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Improved Method for Estimating Soil Moisture Deficit in Oil Palm (*Elaeis guineensis* Jacq.) Areas With Limited Climatic Data

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Abstract

Widespread water deficit is expected to depress growth and yields of oil palms, which sustain daily losses of water through evapotranspiration of 4-5 mm. While accurate predictions for soil moisture deficit are essential for supplying water to plants through irrigation when rainfall is insufficient, soil moisture deficit is difficult to assess. In Malaysia (as in other oil palm-growing countries) rainfall and rain days are the sole climatic parameters recorded; this limited information is insufficient for reliable estimates of water deficit. This paper reports the adoption of a new method of prediction for soil moisture deficit that takes into account the effective rainfall, evapotranspiration, and a correction factor for the water-holding capacity of the soil. Monthly effective rainfall varied from 11% of gross rainfall to 84%. The number of months with soil water deficit varied from 2 to 12 (mean = 9). Values of water deficit obtained were close to those calculated using the Penman equation, thus validating this method of prediction of water deficit.

Keywords: soil water deficit, effective rainfall, evapotranspiration, available water holding capacity, oil palm area, irrigation

1. Introduction

Oil palm (*Elaeis guineensis* Jacq.) grows naturally and is cultivated in the humid tropics of Africa, Latin America and Asia. Its growth and yield are highly correlated to the availability of water, to compensate for water loss through evapotranspiration. The main natural source of water is rainfall, which is limited from time to time. Therefore, it is necessary to determine the water deficit of the soil in the oil palm-growing area so any shortfall can be provided through irrigation.

Water contributes to the integrity of plant cells where it is a solvent for mineral nutrients and foodstuffs to be translocated throughout the plant (Slatyer, 1967). Plants extract water contained in the soil moisture reservoir, which has been defined by Wadleigh et al. (1965) as the inches of available water that may be held per foot of depth multiplied by the depth of rooting of the plant. This water is provided to the soil moisture reservoir by rains. Topping up of the soil moisture reservoir over the course of the cropping season depends on the amount and frequency of precipitation, the nature of the soil and the condition at the soil surface, all of which affect the rate of infiltration, as well as on the management of the soil reservoir for efficient use of water and nutrients. Often, precipitation is unevenly distributed both in terms of timing and location (Renne, 1965), leading to soil water deficits. According to Slatyer (1967), water deficiency (i) reduced the rates of cell division and cell elongation, which affect plant growth; (ii) accelerated breakdown of RNA; (iii) effected changes in total nitrogen, protein nitrogen and amino acids levels; and (iv) led to limited photosynthesis resulting from poor supply of CO_2, reduced utilisation of light energy and low fixation of CO_2.

The optimum rainfall for oil palm is 2000 mm per year. However, the plant can grow and yield well in areas receiving rainfall of at least 1800 mm, provided it is evenly distributed throughout the year without any chronic water deficit in the soil (Hartley, 1988), congruent with Surre (1968) who estimated that a total of 1800-2000 mm of annual precipitation would ensure good foliar emission, a satisfactory production level of number of bunches and a substantial average bunch weight. Water stress is associated with high incidence of juvenile, fused pinnae and retarded growth of seedlings that are discarded at the end-of-nursery culling (Sime & Darby, 2011). Water stress reduces photosynthesis and practically stops oil palm growth (Corley, 1976; Ochs & Daniel, 1976). An annual water deficit of around 700 mm presents a major risk of mortality for oil palms during dry periods in Benin (Chaillard et al., 1983). Symptoms of water stress are gradual in oil palm grown in West Africa. The first stage is the accumulation of 5 to 6 unopened spears rather than the 2 to 3 under optimum moisture circumstances and 2 or 3 green snapped leaves. In the second stage, in addition to the snapping of 4 to 6 leaves, bunches dry out with failure of some of the fruits to achieve ripeness. The drying out of all the leaves at the base of the crown and the toppling of the upper part of the canopy which is comprised of the meristem characterise the third stage. The final stage is the death of the tree (Maillard et al., 1974). Accumulation of unopened spears and yellowing and snapping of leaves are the most evident symptoms of water stress for oil palm in Costa Rica (Villalobos et al., 1992). However, moisture stress and excessive rain during the wet season can also contribute to depressing oil palm yield through the reduction of evapotranspiration and photosynthesis (Kee et al., 2000). The extent of the water deficit depends on the water retention capacity of the soil. In Benin where oil palm was the main cash crop, precipitation was less than 1200 mm with 4-5 months of drought (Hartley, 1977), but water stress was moderate and did not exclude oil palm cultivation thanks to the high water retention capacity of the soils (Purseglove, 1972).

In oil palm, the sex-differentiation is strictly water-dependent. Moisture stress induces the abortion of female inflorescences, thereby depressing bunch yield. In West Africa, studies on the impact of water stress on oil palm yield showed that an increase of 100 mm reduces the oil-to-mesocarp ratio (Ochs & Daniel, 1976). Several measures of improving soil moisture during prolonged dry season have been tried, but unfortunately they were found to lead to less than spectacular yield increase in comparison with irrigation (IRHO, 1969). In fact, only irrigation has assured returns to farmers by permitting the establishment of highly productive agriculture in areas where rainfall is inadequate or unreliable. In oil palm, fresh fruit yields of 26 t/ha have been obtained in the Ivory Coast with irrigation compared to 7.5 t without irrigation (Desmarest, 1967). Irrigation work carried out by IRHO (Institut de Recherches pour les Huiles et Oléagineux) showed that a supply of 1 mm of water increases yield by 26 kg/ha /tree, i.e. 13.5 t/ha for a minimum daily supply of 4 mm (IRHO, 1969). Corley's (1996) review of various irrigation projects in oil palm cultivation found an increase in fruit bunch yield of 50% , on average, over the control, mostly due to increased bunch number (33%), irrespective of the irrigation system. But the increment of mean bunch weight was relatively low (8%). In Malaysia, Roslan, and Haniff (2004) obtained an increase in fruit bunch yield of 14% at the water rate of 120 l/oil palm against 23% at 240 l/oil palm.

One determining factor governing the success of the irrigation in oil palm is a good prediction of the prevailing water deficit of the soil, i.e. the quantity of water to be supplied via irrigation. Using the Penman equation of calculation of ETc (Evapotranspiration) provided reliable estimates of water deficit in the assessment of current and potential yield from oil palm (*Elaeis guineensis* Jacquin) cultivation in the coastal zone and in N'gusti in Cameroon (Bakoumé, 1987, 2011). Similarly satisfactory results were obtained in the assessment of changes in evapotranspiration from an oil palm stand exposed to seasonal soil water deficits in La Me (Côte d'Ivoire) using the Penman equation (Dufrene et al., 1992). The Penman equation-based estimates of soil moisture deficit were comparable to those derived from a lysimeter in Malaysia (Corley, 1996). The Penman equation requires detailed meteorological data including (i) temperature (minimum, maximum, average), (ii) rainfall, (iii) rain days, (iv) relative humidity, (v) wind speed, (vi) ratio of day wind speed-to-night wind speed, (vii) saturation vapour pressure, (viii) extra-terrestrial radiation, and (ix) mean daily maximum possible sunshine hours, to name a few. Currently, in Malaysia, as in most oil palm areas, only rainfall and number of rain days are recorded. The Penman equation which had provided good estimates of the water deficit was abandoned mainly due to limited available climatic data. Therefore, simpler methods based on the rainfall and rain days only are commonly used in which evapotranspiration in oil palm area is assumed (IRHO, 1969). Effective rainfall (ER) is derived from the gross rainfall minus [runoff + deep percolation + interception by the vegetation] (Kee et al., 2000). Interception is subjective because water interception depends on the age of the oil palm and the management of the foliage (pruned or non-pruned). Furthermore, ER does not take into account the fact that only a fraction of the available water-holding capacity is effectively accessible to the oil palm. Other studies simply use the gross rainfall in the calculation of the soil water deficit (Univanich irrigation project, cited by Corley, 1996).

Any reliable method for assessment of soil water deficit would have to generate values comparable to those generated by Penman equation-based calculation. Effective rainfall, one of the two factors used in the calculation of the soil water deficit, is well predicted by a formula which allows the integration of more factors contributing to the rainfall losses. In addition, the method would best incorporate the available water holding capacity (AWHC) of the soils in the assessment of ER. Evapotranspiration (ETc) calculated using the Penman equation, must be corrected using the cropping factor for application to the oil palm area. The method used in the current work envisages reducing the gaps between values of water deficit obtained and those that could have been generated using the Penman equation in the calculation of the evapotranspiration. Therefore, it takes into account the effective rainfall, the available water holding capacity of the oil palm area, and the cropping factor.

2. Materials and Methods

Climatic data and soil available water holding capacities (AWHC) belonging to twelve oil palm areas from Malaysia and one from Cameroon were used to calculate water deficits. The 13 oil palm areas were regularly subjected to two to three consecutive dry months per year. In the current work, a dry month is a month which receives less than 125 mm/month of rainfall with more than 60% probability of occurrence. In Malaysia, one or two oil palm areas were selected from each of the following states: Johor, Kedah, Melaka, Pahang, Perak, Selangor, and Negeri Sembilan. Rainfall and rain days were averaged monthly over 12- to 24 year-records with the exception of Johor's oil palm area, for which records cover 8 years. Values of AWHC were those obtained by Foster (1984) and Mathew et al. (2006) for different soil series and soil groups in Malaysia.

The water deficit was obtained by comparing the potential evapotranspiration of oil palm (ETc) to efficient rainfall (ER). IRHO's predicted ETc was used because rainfall and rain days were the only climatic parameters recorded and available. In this respect, ETc was considered to be 150 mm/month in a month with less than 10 days of rain and 120 mm/month for 10 days and above of rain, as in previous work by Chaillard et al. (1983), Corley (1996) and Roslan and Haniff (2004). The cropping factor allows conversion of evapotranspiration obtained using the Penman equation; applicable for soils covered with a uniform cover of grass to evapotranspiration in an oil palm area was considered to be one (1.00) (Sys et al., 1978). Monthly ER values were calculated as a function of the rainfall (Rm) and ETc in a given month, according to the equation developed by Troch (1986). A correction factor (*f*) was applied to take into account the AWHC of the soils of the oil palm area. The correction concept is based on the fact that only 2/3 of the water from the soil water reserve is accessible to the oil palm (Sys et al., 1978). The value of *f* is equal to one (1) when AWHC is 75 mm. *f* varies from 0.73 when AWHC is 20 mm to 1.08 when AWHC is 200 mm. Therefore, Troch's equation for calculation of ER was formulated after improvement as follows:

$$ER_{(AWHC)} = [Rm^2 \times (0.025/ETc - 0.001) + Rm \times (0.6 + 0.0016\ ETc)] \times f$$

where ETc is evapotranspiration of oil palm in the month; Rm is the rainfall value of the month; and *f* is the correction factor dependent on AWHC.

The rainfall losses (L_r) through surface runoff, interception by vegetation (precisely the oil palm tree canopy) and infiltration into the soil, to name a few, were calculated as a function of Rm as follows:

$$L_r = [(Rm-ER)/Rm] \times 100$$

where Rm is the rainfall value of the month, and ER is the effective rain in a given month.

N'gutsi, a West Cameroon oil palm area, was incorporated in the current study. In a previous study of water deficit in this area, more detailed climatic parameters recorded over 23 years in addition to rainfall and rain days were available. With such an advantage, the Penman equation (FAO, 1976) was used to predict ETc. N'gusti was included in the work to enable comparison of water deficit values generated by Penman equation-based evapotranspiration to those generated by the new improved method for use in the case of limited available climatic data.

3. Results and Discussion

3.1 Effective Rainfall

Effective rainfall refers to the percentage of rainfall which becomes available to plants and crops, i.e. oil palms in the case of the current study. ER and L_r values for the different oil palm areas are shown in Table 1. Water losses (L_r) ranged from 16% in Bagan Datoh (Perak) in June and August with 72 mm and 76 mm of rainfall, respectively, with a soil's AWHC estimated at 213 mm to 89% in N'gusti (West Cameroon) in August, the rainiest month (865 mm) with only 90 mm of AWHC. Globally, in absolute terms, rainfall losses were low in areas with relatively high AWHC for comparable monthly (or annual) rainfalls. N'gusti (West Cameroon) and Bukit Badong (Selangor) received the same amount of rainfall (208 mm) in June and in April, but values of L_r were 37% and 32%, respectively. The difference was probably related to differences in the AWHC of their respective soils (90 mm in N'gusti vs. 253 mm in Bukit Badong). October in Bukit Badong (Selangor) and May in Main (Kedah) is another example of oil palm areas with comparable rainfall but different values of L_r. Similarly, Ayer Tekah (Melaka) with an annual rainfall of 1319 mm and an AWHC of 77 mm recorded relatively higher rainfall losses than did Bagan Datoh (Perak) with an annual rainfall 1477 mm and an AWHC of 213 mm.

Table 1. Effective rainfall and rainfall losses in different oil palm areas

State	Area name	AWHC (mm)	Climatic parameter	Month												Year total
				Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
Johor	Simpang Kiri	100	Rainfall (mm) (8 yr)	160	49	159	117	112	120	145	88	100	131	149	177	1506
			Rain days (8 yr)	10	7	12	12	11	11	13	10	11	14	15	12	136
			ER (mm)	108	40	108	83	80	86	100	65	72	92	102	117	1055
			L_r (%)	32	18	32	29	28	29	31	26	27	30	31	33	30*
Kedah	Main	98	Rainfall (mm) (24 yr)	85	120	190	267	266	194	199	235	320	385	292	166	2720
			Rain days (24 yr)	7	7	13	15	14	12	12	15	17	20	16	11	159
			ER (mm)	67	90	124	158	158	127	129	145	176	191	167	112	1644
			L_r (%)	22	25	35	41	41	35	35	38	45	50	43	33	40*
	Katumba	98	Rainfall (mm) (11 yr)	77	78	182	211	212	197	215	241	269	311	243	130	2367
			Rain days (11 yr)	5	5	9	11	11	10	11	12	13	17	15	9	128
			ER (mm)	61	62	129	136	136	129	138	149	161	175	150	98	1524
			L_r (%)	20	20	29	36	36	34	36	38	40	44	38	25	36*
Melaka	Ayer Tekah	77	Rainfall (mm) (24 yr)	93	59	133	127	99	82	76	73	74	138	197	167	1319
			Rain days (24 yr)	6	4	9	9	7	6	6	7	7	9	11	9	92
			ER (mm)	71	47	97	93	75	63	59	57	58	100	125	117	962
			L_r (%)	24	21	27	27	24	23	22	22	22	28	36	30	27*
Pahang	Mentakab	97	Rainfall (mm) (24 yr)	135	103	155	180	167	129	117	138	180	195	250	226	1974
			Rain days (24 yr)	9	6	9	9	9	7	8	8	10	11	13	13	111
			ER (mm)	100	79	112	126	120	96	88	102	119	127	152	141	1363
			L_r (%)	26	23	27	30	29	25	24	26	34	35	39	37	31*
	Lanchang	97	Rainfall (mm) (19 yr)	108	97	173	151	155	118	141	129	158	210	254	178	1873
			Rain days (19 yr)	9	6	9	8	8	7	8	8	9	11	13	12	110
			ER (mm)	83	75	123	110	112	89	104	97	114	134	153	118	1312
			L_r (%)	23	23	29	27	27	24	26	25	28	36	40	34	30*
Perak	Bagan Datoh	213	Rainfall (mm) (24 yr)	118	97	148	126	94	72	84	76	153	160	196	154	1477
			Rain days (24 yr)	8	6	9	8	6	5	6	7	9	11	12	10	99
			ER (mm)	94	79	115	100	77	60	70	64	118	115	135	111	1138
			L_r (%)	20	18	23	21	18	16	17	16	23	28	31	28	20
	Melentang	213	Rainfall (mm) (24 yr)	139	107	130	143	108	85	97	108	134	169	198	184	1602
			Rain days (24 yr)	8	7	8	8	7	6	6	7	9	10	12	11	100
			ER (mm)	109	87	103	111	87	70	80	87	105	120	136	128	1225
			L_r (%)	22	19	21	22	19	17	18	19	21	29	31	30	24*
Selangor	Bukit Badong	253	Rainfall (mm) (24 yr)	183	140	194	208	183	96	128	162	184	264	305	220	2268
			Rain days (24 yr)	8	6	9	10	7	5	6	7	9	10	13	9	98
			ER (mm)	136	110	142	141	136	79	101	123	136	166	181	156	1608
			L_r (%)	26	22	27	32	26	18	21	24	26	37	41	29	29*
	Bukit Belimbing	253	Rainfall (mm) (24 yr)	185	125	150	133	87	94	112	157	178	219	262	243	1949
			Rain days (24 yr)	10	6	8	8	6	6	6	7	8	11	12	11	99
			ER (mm)	129	100	116	105	72	77	90	120	133	146	166	157	1413
			L_r (%)	30	21	23	21	17	18	19	23	25	33	37	35	27*
Negeri Sembilan	Main	81	Rainfall (mm) (12 yr)	144	64	205	159	176	122	120	106	150	194	258	214	1912
			Rain days (12 yr)	9	5	10	9	9	7	7	7	9	11	14	11	107
			ER (mm)	103	50	129	112	122	90	89	80	107	124	152	133	1292
			L_r (%)	28	21	37	29	31	26	26	25	28	36	41	38	32*
	Kelamah	81	Rainfall (mm) (13 yr)	120	58	153	134	102	103	97	109	104	157	204	199	1540
			Rain days (13 yr)	8	3	9	8	6	7	8	8	8	10	12	10	96
			ER (mm)	89	46	109	98	77	78	74	82	78	111	137	134	1112
			L_r (%)	26	21	29	27	24	25	24	25	25	29	33	33	28*
West Cameroon	N'gutsi	90	Rainfall (mm) (23 yr)	59	80	208	319	460	552	840	865	703	580	318	99	5084
			Rainy days (23 years)	4	6	14	17	19	22	24	27	25	23	17	6	205
			ERc (mm)	47	62	132	174	199	198	108	93	167	195	174	76	1625
				52	*70*	*162*	*217*	*251*	*221*	*125*	*125*	*190*	*230*	*208*	*83*	*1934*
			L_r (%)	20	22	37	46	57	64	87	89	76	66	45	24	68*

AWHC: available water holding capacity; ER: Effective rainfall; L_r (%): percentage of rainfall loss; *: mean annual rainfall loss; Note: Daily potential evapotranspiration is 5 mm if they are less than 10 rain days in the month and 4 mm if 10 rain days or more; In italics are N'gusti's values of ER derived from Penman equation.

Mean annual L_r varied from 20% in Bagan Datoh (Perak) to 68% in N'gusti (West Cameroon). It ranged from 20% to 40% (16% to 50% monthly) when only Malaysian oil palm areas were considered. The range of rainfall losses found in this work was wider than that (35-40%) obtained by Kee et al. (2000). If the high rainfall – which could be an additional explanation for high rainfall losses – in N'gusti (West Cameroon) were to be excluded from the analysis, the ultimate reason for the wide range of water losses was the wide range of AWHC across all oil palm areas, which this current method of estimation of ER took into account.

Results obtained showed that ER depends on rainfall intensity. Monthly rainfall beyond 200 mm resulted in water losses between 35% and 89%; that is to say, they resulted in less effective rainfall. In fact, such excessive rainfall is harmful as it hinders plant growth and subsequently crop yields by leaching nutrients (Hillel, 1971). Other features such as the duration of the rainfall, the terrain, the initial water content of the soils, all of which also affect the effective rainfall, were not taken into consideration in this work as well as almost all previous works. High initial water content of the soil could have led to lessening of the effective rainfall. The difference between values of ER in N'gusti obtained in previous work (indicated by italics in Table 1) and those obtained in the current study may be due to the fact that, in the previous work, ETc was calculated taking into account climatic factors such as radiation, temperature, humidity, and day and night wind speeds, to name a few, which control plant transpiration.

3.2 Water Deficit

Water deficit is a result of an interaction between soil water (mostly provided by rainfall), atmospheric demand (evaporation) and the plant (transpiration) (Shaw & Laing, 1965). Water deficits in different oil palm areas studied are presented in Table 2. In the current work, a water deficit was found in a month when the ETc was greater than the ER. The method of prediction of water deficit reported in this paper showed that oil palm could have received insufficient water for a considerable number of months in a year. The number of months with water deficit varies from 2 in Main (Kedah) to 12 in Simpang Kiri (Johor) (mean = 9). Concurrently, in Malaysia, in absolute terms, the lowest annual water deficit (143 mm) was recorded in Main (Kedah) and the highest (808 mm) in Ayer Tekah (Melaka) over 11 months. Water deficit revealed in N'gusti (West Cameroon) (136 mm) over 4 months was close to the 152 mm obtained using the Penman equation in the calculation of ETc. In fact, water deficit is in line with the ER calculated based on the prediction of an ETc of 150 mm/month if there were fewer than 10 rain days in the month and 120 mm if there were 10 or more rain days. Surre (1968) recognized that IRHO's method of prediction of water deficits when data on only rainfall and rain days are available was useful in the determination of the water balance. Furthermore, the method used in this work is more holistic than the IRHO's method because it takes into account the AWHC, which is correlated both with soil texture (Foster 1984) and with soil structure (Bakoumé, 1987). Surre and Ziller (1963) have found that the available water domain remains constant where the content of fine soil particles varies from 20 to 50% and also when the suitable texture corresponds in general to 25-30% content of fine particles. Differences in clay and silt rates between horizons or between profiles translate into variations in water content between horizons on the one hand and between profiles on the other.

Results revealed that although Simpang Kiri (Johor) and Kelamah (Negeri Sembilan) recorded comparable mean annual precipitations of 1506 mm and 1540 mm, respectively, the water deficit in Kelamah (574 mm) represented 140% of that of Simpang Kiri. This phenomenon could result from the 10 months with 10 or more rain days experienced in Simpang Kiri versus only 3 months with 10 or more rain days in Kelamah. On the same note, Bukit Badong (Selangor) and Main (Negeri Sembilan) with comparable rainfall (1949 mm vs. 1912 mm) and 4 months with 10 or more rain days each but very distinct AWHC (253 mm vs. 81 mm) recorded almost the same water deficits (377 mm vs. 380 mm). Thus, water deficit was shown to be dependent on number the rain days per month. For the same annual rainfall, water deficit was high in oil palm areas where the number of rain days recorded was low, an indication of the extent to which the rain is evenly distributed throughout the year. The higher the number of rain days, the better the rainfall distribution. The method of water deficit prediction used in the current work supports the finding of Bakoumé (1987) from a similar study using a modified Penman equation for determination of ETc in the estimation of water deficit. That study found that water deficit was indicative of a good or a bad distribution of precipitation throughout the year. Good rainfall distribution leads to low water deficit.

Table 2. Water deficits in different oil palm areas studied

State	Area name	AWHC (mm)	Climatic parameter	Month												Annual water deficit (mm)
				Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
Johor	Simpang kiri	100	ETc (mm)	150	150	120	120	120	120	120	120	120	120	120	120	
			ER (mm)	108	40	108	83	80	86	100	65	72	92	102	117	
			Water balance	-12	-110	-12	-37	-40	-34	-20	-55	-48	-28	-18	-3	413
Kedah	Main	98	ETc (mm)	150	150	120	120	120	120	120	120	120	120	120	120	
			ER (mm)	67	90	124	158	158	127	129	145	176	191	167	112	
			Water balance	-83	-60	4	38	38	7	9	25	56	71	47	-8	143
	Katumba	98	ETc (mm)	150	150	120	120	120	150	120	120	120	120	120	150	
			ER (mm)	61	62	129	136	136	129	138	149	161	175	150	98	
			Water balance	-89	-88	9	16	16	-21	18	29	41	55	30	-52	176
Melaka	Ayer Tekah	77	ETc (mm)	150	150	150	150	150	150	150	150	150	150	120	150	
			ER (mm)	71	47	97	93	75	63	59	57	58	100	125	117	
			Water balance	-79	-103	-53	-57	-75	-87	-91	-93	-92	-50	5	-33	808
Pahang	Mentakab	97	ETc (mm)	150	150	150	150	150	150	150	150	150	120	120	120	
			ER (mm)	100	79	112	126	120	96	88	102	119	127	152	141	
			Water balance	-50	-71	-38	-24	-30	-54	-32	-18	-1	7	32	21	326
	Lanchang	97	ETc (mm)	150	150	150	150	150	150	150	150	150	120	120	120	
			ER (mm)	83	75	123	110	112	89	104	97	114	134	153	118	
			Water balance	-67	-75	-27	-40	-38	-61	-46	-53	-36	14	33	-2	398
Perak	Bagan Datoh	213	ETc (mm)	150	150	150	150	150	150	150	150	150	120	120	120	
			ER (mm)	94	79	115	100	77	60	70	64	118	115	135	111	
			Water balance	-56	-71	-35	-50	-73	-90	-80	-86	-32	-5	15	-9	573
	Melentang	213	ETc (mm)	150	150	150	150	150	150	150	150	150	120	120	120	
			ER (mm)	109	87	103	111	87	70	80	87	105	120	136	128	
			Water balance	-41	-63	-47	-39	-63	-80	-70	-63	-45	0	16	8	485
Selangor	Bukit Badong	253	ETc (mm)	150	150	150	120	150	150	150	150	150	120	120	150	
			ER (mm)	136	110	142	141	136	79	101	123	136	166	181	156	
			Water balance	-14	-40	-8	21	-14	-71	-49	-27	-14	46	61	6	201
	Bukit Belimbing	253	ETc (mm)	120	150	150	150	150	150	150	150	150	120	120	120	
			ER (mm)	129	100	116	105	72	77	90	120	133	146	166	157	
			Water balance	9	-50	-34	-45	-78	-73	-60	-30	-17	26	46	37	377
Negeri Sembilan	Main	81	ETc (mm)	150	150	120	150	150	150	150	150	150	120	120	120	
			ER (mm)	103	50	129	112	122	90	89	80	107	124	152	133	
			Water balance	-47	-100	9	-38	-28	-60	-61	-70	-43	4	32	13	380
	Kelamah	81	ETc (mm)	150	150	150	150	150	150	150	150	150	120	120	120	
			ER (mm)	89	46	109	98	77	78	74	82	78	111	137	134	
			Water balance	-61	-104	-41	-52	-73	-72	-76	-68	-72	-15	9	6	574
West Cameroon	N'gusti	90	ETc (mm)	150	150	120	120	120	120	120	120	120	120	120	150	
			ERc (mm)	47	62	132	174	199	198	108	93	167	195	174	76	
			Water balance	-103	-88	12	54	79	78	-12	-27	47	75	54	-74	136
				-136	*-124*	*-45*	*7*	*45*	*66*	*2*	*21*	*34*	*56*	*18*	*-97*	*152*

AWHC: available water holding capacity; ETc: potential evapotranspiration of the crop (oil palm); ER: Effective rainfall; Note: Daily potential evapotranspiration is 5 mm if they are less than 10 rain days in the month and 4 mm if 10 rain days or more; In italics are N'gusti's values of annual water deficit derived from a modified Penman equation for calculation of ETc.

Oil palm areas in Simpang Kiri (Johor) and Main (Kedah) recorded similar rainfall distribution and their soils had a similar AWHC (100 mm vs. 98 mm), but the water deficit was higher in Simpang Kiri compared to that in Main (413 mm vs. 143), in absolute terms. The most relevant feature was found to be the rainfall, which was relatively higher in Main (2720 mm vs. 1506 mm). The method of estimation of water deficit used in the work demonstrated that water deficit depends not only on the rainfall distribution but also on the rainfall intensity. High rainfall intensity results in low water deficit. Katumba (Kedah) and Bukit Badong (Selangor) received almost the same rainfall in October and November (311 mm vs. 305 mm, respectively), but the water reserve (positive value of ER-ETc) was higher in Bukit Badong despite the good rainfall distribution in Katumba (17 rain days in Katumba vs. 13 in Bukit Badong) because of a high AWHC of the soil in Bukit Badong (253 mm vs. 97 mm). In Lanchang (Pahang) and Main (Negeri Sembilan) with same rainfall intensity in October (254 mm vs. 258 mm) and with a slightly better distribution in Main (14 rain days vs. 13), there was a slightly higher water reserve in Lanchang (14 mm vs. 4 mm) due to the relatively higher AWHC of its soils (97 mm vs. 81 mm). It was observed that although water deficit depended on AWHC of the soil of the oil palm area, water deficit was in fact a function of ETc and ER, and ER is a function of AWHC. High AWHC implies high ER and low water deficit.

The method used in this work has been shown to be efficient in that it takes into account the rainfall intensity and its distribution and the AWHC of the soils of the oil palm area on which water deficit depends. Furthermore, the relative similarity between the values of water deficit in N'gusti (West Cameroon) calculated using a previous work and the one issued from the current method validates the method of prediction of water deficit reported in this paper, suggesting that the annual water deficit as estimated by this method can be used in the yield prediction using one of the equations developed by IRHO (1977), Caliman (1992), and Bakoumé (2011) for Africa and the equation developed by Corley (1996) for South-east Asia. In the above mentioned equations, oil palm yield is seen as a function of water deficit in view of the high correlation between water deficit and fresh fruit bunch yield. Bakoume's (2011) formula was developed for oil palm planting materials of the second cycle of recurrent reciprocal selection. The maximum African annual yield of fresh fruit bunches under satisfactory soil moisture throughout the year is 28 t/ha. Estimated yield in N'gusti using the formula described by Bakoumé (2011) and the water deficit derived from, on the one hand, the modified Penman equation and, on the other hand, the method reported in this paper are 25.9 t/ha and 25.7 t/ha, respectively. Finally, the method here reported provides reliable estimates of the irrigation component of the day-to-day water balance defined by Prioux (1989) as follows: Initial reserves + Rain + Irrigation + ETc = Provision of water for growth and production of oil palm. Water deficits would provide good estimates of water needed for irrigation for optimum yield. This requirement is well supported by the reported method of prediction of water deficit, which takes into account both the initial reserves and the water deficit.

The method has revealed the likelihood of water deficits in months receiving up to 180 mm. Generally, in oil palm, a dry month is considered as a month with less than 100 mm of rainfall. In Malaysian oil palm areas studied, the number of months with water deficit is 9 on average. The wide spread of water deficit throughout the year could result in yield depression even if the values of the water deficit are relatively low (< 50 mm). Failure to accommodate water deficits could explain the gap between targeted yield of 30 t/ha (Corley, 1996) in the 1990s and the lower yields obtained by the plantations despite good agricultural practices. The author has predicted a yield decline of 2.88 t/ha of fresh fruit bunches per 100 mm of water deficit in southeast-Asia. Given the limited source of natural water for irrigation, it is likely that research should opt for the selection of progenies tolerant to drought among the wide range of available planting material from different genetic backgrounds.

4. Conclusion

Water deficits as calculated in this work were close to those obtainable using the Penman equation for the determination of evapotranspiration from an oil palm area. The originality of the method resides in the fact that, not only does it operate with in fact very little climactic data, but it also takes into account the available water-holding capacity of the soil in the estimation of the effective rainfall. Furthermore, the water deficit is not a direct function of the gross rainfall but of the efficient rainfall, which is a product of the available water holding capacity of the soils, rainfall intensity and rainfall distribution. More reliable values of monthly water deficit and monthly water reserves are generated which allow planning for water demands for irrigation of oil palms during periods of soil moisture deficit for enhanced growth and increased yields. Given the fact that water is used for many purposes and also source of conflicts between irrigated agriculture with other nonagricultural users of same water source, it is necessary for needs of water for irrigation to be as accurate as possible and very close to the needs for oil palm growth and production of fresh fruit bunches. Hence, accurate predictions of water deficit would prevent water wastage by excessive irrigation as well as avoid insufficient watering. The wide spread of water deficit in oil palm areas in Malaysia and the failure to accommodate to it may be one of the factors for the gaps between expected and recorded yields of the oil palm industry, even under best agricultural practices.

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