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WATER USE OF IRRIGATED OIL PALM AT THREE DIFFERENT ARID LOCATIONS IN PENINSULAR INDIA

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ABSTRACT

The water requirement of irrigated oil palm (Elaeis guineensis *Jacq.*) *in the three Indian states of Andhra Pradesh, Karnataka and Maharashtra were estimated using the Penman-Monteith equation. Microclimate parameters measured using an automated weather station showed that the three geographically separated sites had climatic differences also. The temperature at the study sites ranged between 12°C and 35°C and the vapour pressure deficit (VPD) of the atmosphere ranged between 0.3 and 4.5 kPa. Stomatal conductance measured on fully irrigated plants showed a maximum of 500 mmol* m^{-2} s^{-1}*. The stomatal conductance was highly correlated with the VPD. Closure of stomata started when the VPD was greater than 1.0 kPa. The stomatal conductance was severely reduced when the VPD reached values >1.9 kPa. All the sites had a prolonged dry season. At none of the sites could oil palm be grown as a rain-fed crop. Water loss by transpiration as estimated for a dry day (without rain) ranged from 2.0 to 5.5 mm. The transpiration/evaporation ratio was approximately 0.8 at all the three locations.*

Keywords: oil palm, water requirement, transpiration, microclimate, India.

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INTRODUCTION

The history of oil palm in India goes as far back as 1836 when this tree was first introduced to the National Botanic Garden, Calcutta. Ever since, gradual introduction of this oil-yielding palm has been taking place in the different states of India. However, the first large-scale plantations in Kerala and the Andaman Islands had problems of low yield.

To achieve self-sufficiency in edible oils, the Department of Biotechnology, Government of India introduced oil palm on an experimental basis in 1989 into three Indian states - Andhra Pradesh, Karnataka and Maharashtra. All these states have an annual dry season that lasts nearly six months. However, the ground water resources are rich in these locations and they can be used to provide irrigation during these dry periods. Apart from some plantations in Benin, this is one of the first few attempts to grow oil palm on a large-scale as an irrigated crop. The water requirement of oil palm is relatively unknown. Moreover, it is necessary to work out the water requirement for each geographical location. It is also important to evaluate the ecophysiological performance of a tree before introducing it to a new site on a large-scale (Kallarackal and Somen, 1997a).

In this paper, we present the details of the work done on oil palm in the three locations over two years. Using hourly microclimate data and stomatal conductance measurements, transpiration from the irrigated plantation using the Penman-Monteith equation. This was then related to Penman potential evaporation to predict the irrigation requirements.

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EXPERIMENTAL

Plantation Site Details

Experimental plots of oil palm were established in 1988-1999 in the three peninsular Indian states of Andhra Pradesh (A.P.), Karnataka and Maharashtra with the intention of demonstrating the feasibility of oil palm cultivation under irrigated conditions over an area of 1000 ha in each of the three states. *Tenera* sprouted seeds imported from ASD Costa Rica and indigenous material from the Central Plantation Crops Research Institute (CPCRI), Palode in the ratio 4:1 were used as the planting materials. The site in A.P. was a 15-ha plantation at Pothepally (Site 1) (lat. 16° 47′ and long. 81° 5′) in West Godavari district. The elevation of the site was approximately 80 m above sea level. In Karnataka, the site was a 10-ha plantation at Bhadravati Taluka (Site 2) (lat. 14° 3′ and 74° 36′ long.) in Shimoga district. The elevation of the site was approximately 650 m. In Maharashtra, the site was a 263-ha plantation at Osram (Site 3) (lat. 16° 4′ and long. 73° 39′) in Sindhudurg district. The elevation of the site was approximately 100 m above mean sea level. The general climatic data from nearby weather stations and the microclimate data collected within the plantations for the three sites are depicted in *Table 1*. All the three sites were characterized by a non-uniform rainfall distribution during the year. Most of the rainfall was received during the southwest monsoon from June to October. All the sites experienced a prolonged dry season from December to May. The soil at Site 1 is deltaic alluvium, very deep 3 to 6 m, and well drained. The soil is very fertile. Site 2, with red loamy soils, has a loam to silt loam texture, and is deep, acidic, rich in organic matter with good aggregating ability. They are good for irrigation. The soils at Site 3 are laterites derived from basalt, red to reddish-brown, well drained, with low water-holding capacity.

The three sites had oil palm planted 9 m apart in a triangular system, accommodating 143 palms ha^{-1}. Basin irrigation using water pumped from underground sources was used in the first two sites, whereas the third site was irrigated from a nearby river. Irrigation to field capacity was ensured at all the three sites during the entire period of the study.

Microclimate

A 5 m high, steel scaffold tower was installed in each of the sites to mount the meteorological equipment above the canopies of the palms. The meteorological sensors were mounted at the top of these towers. Temperature and relative humidity were measured using a shielded thermistor and a carbon electrode RH chip (Model 207 temp. and RH probe, Campbell Scientific Inc., Utah, USA). Wind speed was measured using a cup counter anemometer (Model 014A, Met One, Sunnyvale, CA, USA) with a switch closure mechanism. Net radiation was measured using a net radiometer of the Fritschen type (REBS Inc., Washington, USA). Photon flux density (PFD) was measured using a quantum sensor (Model LI 190SA, Li-Cor, Nebraska, USA). Soil temperature was measured at two depths, 100 mm and 300 mm, using a thermocouple sensor (Model 107, Campbell Scientific Inc., Utah, USA). Soil heat flux was monitored by a flux plate (HFT-1, REBS Inc., USA) buried 50 mm below the soil surface, in between the rows of palms. All the sensors were connected to a data logger (Model CR10, Campbell Scientific Inc., Utah, USA). The vapour pressure deficit (*D*) was calculated hourly using the temperature and relative humidity data. Logging was for every 5 s and hourly averages were stored. Details of the set-up can be found in Kallarackal and Somen (1997b). The microclimate was monitored continuously for two to three days, during each visit, for two consecutive years.

TABLE 1. ANNUAL AVERAGES/MAXIMA OF THE MICROCLIMATE DATA COLLECTED AT THE THREE EXPERIMENTAL SITES

Parameter	Andhra Pradesh	Karnataka	Maharashtra
Atmos. temperature (°C)	20 – 35	15 –35	12 – 35
VPD (D) (kPa)	0.4 – 4.5	0.3 – 4.5	0.3 – 4.5
Wind velocity (m s^{-1})	0.4 – 3.5	0.5 – 4.5	0.5 – 2.0
PFD max. (µmol m^{-2} s^{-1})	1 500	1 700	1 600
Net radiation max. (W m^{-2})	600	600	600
Rainfall annual avg. (mm)	1 048	1 144	4 000
Pan evaporation (mm)	2 162	2 102	1 600
Soil heat flux max. (W m^{-2})	80	60	50

The daily potential evaporation (E_p) for each site in the days of measurements was calculated using Penman's combination equation (Penman, 1956) as modified by Van Bavel (1966):

$$E_p = E_{pr} + E_{pc} \quad (1)$$

where,

$$E_{pr} = \Delta R_n \;/\; [\lambda(\Delta + \gamma)] \quad (2)$$

$$E_{pc} = (\rho\, c_p\, D\, g_a) \;/\; [\lambda\,(\Delta + \gamma)] \quad (3)$$

where, E_{pr} is the radiative term in the Penman equation representing the steady state, the asymptotic limit approached by a closed atmosphere over a large expanse of vegetation with fixed surface resistance (Mcnaught and Jarvis, 1983), E_{pc} the convective term in the Penman equation as modified by Van Bavel (1966), R_n = net radiation (W m^{-2}), g_a = aerodynamic conductance of the canopy (mol m^{-2} s^{-1}) calculated using equation (7), λ = psychrometer constant (0.066 k Pa K^{-1}), D = vapour pressure deficit (mb), Δ = slope of the saturated vapour pressure versus temperature curve (k Pa K^{-1}), γ = latent heat of water (44 200 J mol^{-1} at 20°C).

Gas Exchange Measurements

Four-year-old palms were used for this study. Preliminary measurements had shown that leaf No. 8 or 9 (numbered from youngest to the oldest) shows the maximum stomatal conductance (g_s) (Jeyakumar and Kallarackal, 1994). The g_s was measured using a portable infrared gas analyser system (Li 6200, Li-Cor, Nebraska, USA) along with net photosynthesis. A 1-litre chamber was used to enclose the leaf for measurement. A leaf lamina area of 1200 mm^2 was enclosed in the chamber. The measurements were programmed in such a way that the leaf lamina did not remain inside the chamber for more than a minute. All the diurnal measurements were made in natural daylight. The g_s was calculated using the software supplied with the instrument. Additionally, the instrument also measured the leaf temperature using a thermocouple attached to the chamber.

Water Potential

The water status of the plants was monitored by measurements of the leaf water potential (Ψ). A Scholander pressure chamber (PMS Instrument Co., Corvallis, USA) was used for the measurement of Ψ. Since the leaflets were very long for the chamber, they were rolled while kept in a plastic bag before detachment from the plant. The leaflets were inserted in the bag just before detachment. Measurements were made at one- or two-hourly intervals starting from pre-dawn till dusk.

Transpiration

Estimation of the canopy transpiration was done using the Penman-Monteith equation (Monteith, 1965):

$$E_c = \frac{s(R_n - G) + C_m\, g_a\, D}{\lambda[s + \gamma(1 + g_a / g_c)]} \quad (4)$$

where, E_c = canopy transpiration (mol m^{-2} s^{-1}), R_n = net radiation (W m^{-2}), G = soil heat conduction flux (W m^{-2}), C_m = mole specific heat of air (J mole^{-1}), g_a = aerodynamic conductance of the canopy (mol m^{-2} s^{-1}), λ = psychrometer constant (0.066 k Pa K^{-1}), D = vapour pressure deficit (mb), s = slope of the saturated vapour pressure versus temperature curve (k Pa K^{-1}), γ = latent heat of water (44 200 J mol^{-1} at 20°C), g_c = canopy conductance (mol m^{-2} s^{-1}).

In the above equation, parameters R_n, G and D were obtained from the microclimate measurements. Tabled values were used for C_m. Canopy conductance, g_c was obtained by the equation:

$$g_c = \sum g_s\, L \quad (5)$$

where, g_s = the porometer values for stomatal conductance, L = the leaf area index measured by the equation (Hardon *et al*., 1969):

$$L = b\,(n\, lw) \quad (6)$$

where, b = correction factor (0.55), n = number of leaflets, lw = mean of length times middle width for a sample of the largest leaflets.

The aerodynamic conductance, g_a, was obtained by:

$$g_a = (k^2 uP) / \ln^2\, [(z\text{-}d)/z_0] \quad (7)$$

where, k = von Karman's constant (0.41), u = mean wind speed measured 2 m above the canopy (ms^{-1}), z = anemometer reference height (5 m), d = zero plane displacement - calculated as 0.64 h (where h = crop height in metres), z_0 = the roughness length (= 0.13 h), P = mole density of air (mol m^{-3}).

The hourly averaged wind speed data formed the most important variable for the calculation of g_a. The slop of the saturated vapour pressure versus temperature curve, s was calculated using the equation:

$$s = \frac{\lambda\, e_s\,(T)}{R(T + 273)^2} \quad (8)$$

where, e_s = saturation vapour pressure at temperature T, R = universal gas constant (8.314 J mol^{-1} K^{-1}). The values of E_t were worked out on an hourly basis for each site for each visit. The values obtained in mol m^{-2} s^{-1} were converted to depth equivalents (mm h^{-1}) for convenience.

Leaf Area and Leaf Area Index (L)

The leaf area per palm was equal to the mean area per leaf multiplied by the number of leaves per palm. Mean area per leaf was estimated as described by Hardon *et al*. (1969) from equation (6). The average leaf area developed per month was worked out from the product of new leaves produced, and the area per leaf worked out by the above equation. The *L* was calculated by dividing the mean leaf area per tree by the land area occupied by the tree. In the present case, 143 trees ha $^{-1}$ was the planting density.

RESULTS AND DISCUSSION

Microclimate

The maximum atmospheric temperature at all the three sites rarely exceeded 35ºC (*Table 1*). However, the minimum temperature at Sites 2 and 3 dropped considerably below the ideal minimum temperature of 20ºC recommended for oil palm growing. At all the three sites, the range of *D* was large, from 0.4 to 4.5 kPa, which shows the wide variation in atmospheric vapour pressure deficit. The light availability at all the three sites was not limiting, although the high seasonal rainfall and cloudiness at Site 3 restricted sunshine hours to less than 5 hr a day for several days during the monsoon period.

Gas Exchange Measurements

Preliminary measurements had shown that leaf No. 8 or 9 gave the maximum values for the gas exchange parameters (Jeyakumar and Kallarackal, 1994). This agreed with measurements done by other investigators (Dufrene and Saugier, 1993). The maximum values of g_s measured at all the three sites showed ≈500 mmol m^{-2} s^{-1}. Diurnal measurements of g_s showed that they peaked in the morning (*Figure 1*). If we look at the figure along with the microclimate data collected at all the stations, the reduced conductance towards afternoon was not due to insufficiency in PFD but to the changes in *D*. Hence, *D* measured hourly was regressed against g_s from the three sites pooled together. *Figure 2* gives us the indication that invariably at all the three sites g_s was regulated by *D*. By using g_s data collected at or above the light saturation level in the figure, it is apparent that the regulation of stomatal function is mainly due to *D*. At lower values of *D* (<1.5 kPa), the g_s decrease was negatively exponential. However, with further increase in *D* (>1.5 kPa), the decrease in g_s was more or less linear, but coming to a steady state at around 100 mmol m^{-2} s^{-1}. No complete stomatal closure was observed at any of the three sites with further increase in *D*.

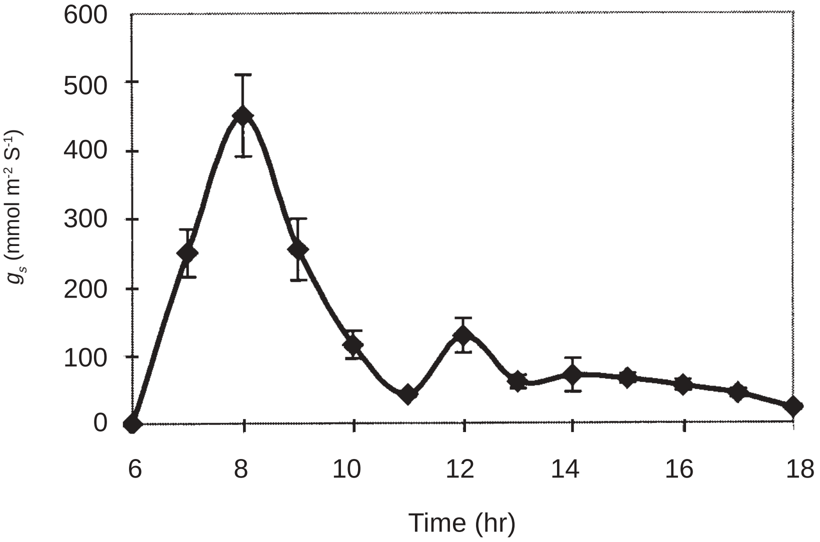

Figure 1. A typical diurnal curve of the g_s measurements done at one of the locations on a sunny day at Site 2, showing the morning peak, after which the values drop down drastically throughout the day. This was the trend at all the three sites.

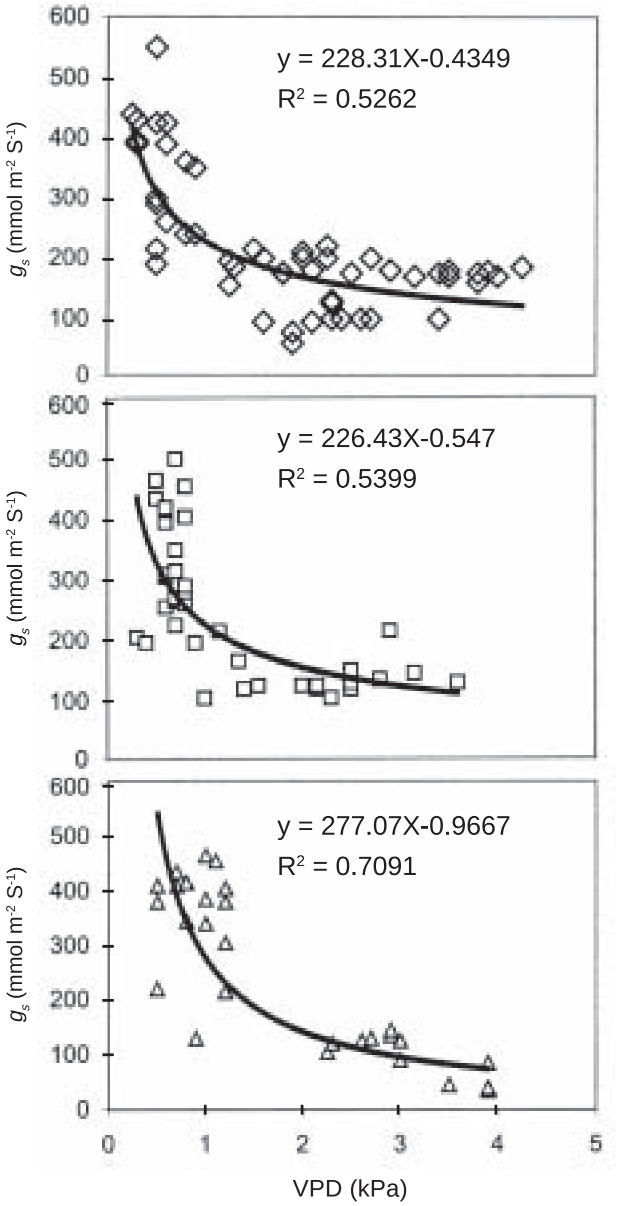

Figure 2. Stomatal conductance (g_s) measurements taken at the three sites to show the trend in stomatal conductance as a function of the atmospheric vapour pressure deficit (D). The conductance values drop down drastically as D reaches approximately 1.5 kPa. The equations for fitting the data are also given along with the R^2 value (◇Site 1, □Site 2, △Site 3).

Dufrene and Saugier (1993) reported the nearly complete closure of stomata ($g_s = 50$ mmol $m^{-2} s^{-1}$) at a *D* value of 4.5 kPa. High VPD resulting from low air humidity and high air temperature has been shown to cause stomatal closure in many plants (Schulze and Hall 1982; El Shakawi *et al.*, 1984; Chiariello, 1984; Kallarackal and Somen, 1997b). This is referred to as feedback control of the environment on stomatal conductance with feed forward control of stomata on plant water relations (Cowan, 1977; Farquhar, 1978). Smith (1989) concluded that stomatal closure in oil palm is induced by high VPD, which is further enhanced by any soil water deficit. Stomatal closure due to increasing atmospheric VPD has been reported in oil palm from Nigeria (Rees, 1961), Colombia (Smith, 1989) and Ivory Coast (Dufrene and Saugier, 1993).

Reduction in g_s due to stomatal closure can considerably reduce the diffusion of CO_2 through the stomata, thereby reducing photosynthesis. However, the threshold g_s at which photosynthesis is affected varies in plants. Smith (1989) indicated that photosynthesis in oil palm begins to be significantly limited at a g_s <125 mmol $m^{-2} s^{-1}$, which requires a VPD >3.8 kPa. This was found to be true with the air temperature at 38ºC and R.H. below 40%.

Dufrene and Saugier (1993) observed that the transpiration rate decreased exponentially when the VPD increased from 0.4 to 1.8 kPa, but then decreased linearly. The decrease in A_{max} was only about 10% when $g_{s\,max}$ decreased by 50% (from 750 to 350 mmol m^{-2} s^{-1}) with VPD changing from 1 to 1.8 kPa. Thus, it is apparent that the three parameters - A, g_s and VPD - are highly correlated in oil palm. All the available investigations show that g_s is strongly affected by VPD. However, g_s at which A is strongly impaired varies in different locations. The values reported by Dufrene and Saugier (1993) seem to show maximum similarity to the values reported in this investigation.

Water Relations

Diurnal measurements of the water potential (Ψ) showed that it decreased from the morning till 14:00 hr, after which the values started to increase. The midday water potential was a good indicator of the maximum water stress the palms were subjected to in the newly introduced localities. *Figure 3* shows the pre-dawn and midday water potentials prevailing at the three sites on a typical summer day. From the pre-dawn values, it is apparent that the water status of the plants at the three sites was relatively high. The midday water potential also did not indicate any extreme level of stress.

Transpiration

The E_t, as calculated using the Penman-Monteith equation, showed that the hourly daytime canopy transpiration ranged between 0.1 and 1.0 mm hr $^{-1}$ on a land area basis. This, when cumulated on a daily basis, showed that the daily transpiration varied between 2.0 and 5.5 mm day $^{-1}$ (*Table 2*). If this were converted to litres day^{-1} plant^{-1} (for 143 plants ha^{-1}), it would work out to 140 to 385 litres day^{-1} plant^{-1}. It would seem that the transpiration loss was extremely high. However, it should be remembered that the plants in the present sites were fully irrigated. Hence, there was no soil water limitation to achieving full transpiration. In the unirrigated condition, the transpiration can be expected to be much lower. The transpiration calculated by the Penman-Monteith equation is the water loss from the dry canopy. The E_p, calculated for the different months at the three sites, is also shown in *Table 2*. The ratio E_t/E_p indicates that E_t was between 70% and 90% of E_p (*Table 2*). The oil palm plantations under investigation here had not yet achieved full canopy closure because they were only 4 to 5 years old. Hence, the soil heat flux measured in this study would have been much more than that in a fully closed-canopy plantation.

It would be expected that the water consumption by the oil palm would be less when complete canopy closure occurs. This is because of the reduced ventilation within the canopy, which would decrease the boundary layer conductance. From that stage, it is expected that the water use would get stabilized. Very few studies have been made on evapotranspiration in oil palm stands. One such study conducted by Dufrene *et al*. (1992) at La Mé in Ivory Coast has showed that evapotranspiration from the dry canopy was 81% of the potential evapotranspiration. The daily transpiration in their study ranged between 1.25 mm day^{-1} to 2.31 mm day^{-1}. However, the plants were unirrigated. This should explain the lower values obtained by them compared to the values obtained

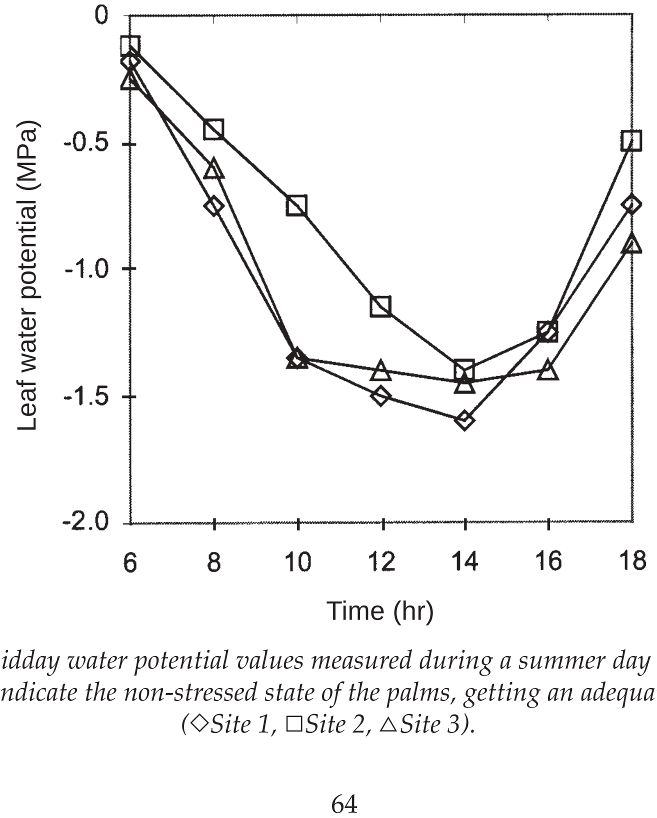

Figure 3. Pre-dawn and midday water potential values measured during a summer day at the three sites. The high pre-dawn values indicate the non-stressed state of the palms, getting an adequate supply of water (◇Site 1, □Site 2, △Site 3).

TABLE 2. RATIO OF TRANSPIRATION (mm day^{-1}) AND EVAPORATION (mm day^{-1}) MEASURED AT THE THREE SITES

Month	E_t			E_p			E_t/E_p		
	Site 1	Site 2	Site 3	Site 1	Site 2	Site 3	Site 1	Site 2	Site 3
January	2.82	-	3.45	3.66	5.65	4.77	0.68	0.77	0.73
February	-	4.36	-	-	-	-	-	-	-
March	-	-	5.45	-	-	6.65	-	-	0.82
April	4.93	-	-	6.35	-	-	0.77	-	-
May	-	3.91	-	-	4.65	-	-	0.84	-
June	-	-	3.12	-	-	3.93	-	-	0.79
July	1.30	-	-	2.18	-	-	0.76	-	-
August	2.44	2.34	2.22	3.01	3.37	2.68	0.81	0.70	0.83
September	3.95	1.15	-	4.67	1.56	-	0.85	0.74	-
October	2.48	4.23	5.54	3.66	5.15	6.20	0.68	0.82	0.89
November	-	2.34	3.20	-	3.07	4.99	-	0.76	0.64
December	3.30	4.05	2.47	4.27	4.99	3.21	0.77	0.81	0.77

Note: The empty cells denote when measurements were not taken.

in this investigation. It may be also noticed from *Table 2*, that the transpiration rates were much lower in the dry season (December to May) than during the wet season. This was due to the atmospheric dryness which caused stomatal closure, even with water available in the soil.

Oil palm is successfully cultivated in areas of very heavy to moderate rainfall. In areas with very high rainfall (>5000 mm), the rainfall is usually in excess of evapotranspiration. In such locations, constant cloudiness could limit the productivity. This is found along the Pacific plain of tropical South America (Hartley, 1977). However, in the three states in India under study, the rainfall amount varies from a little more than 1000 mm in Karnataka to more than 4000 mm in the Maharashtra sites. From a survey of the rainfall data in the major oil palm growing areas of Asia, Africa and America, it may be noted that oil palm is not grown in any location with rainfall as low as that of A.P. and Karnataka. The most similar location is probably Dahomey in Africa where the annual rainfall is 1232 mm. Like in the Indian peninsular locations, four months (November to February) are almost devoid of rain (Hartley, 1977). However, the productivity of the palms in Dahomey is reasonably good which is ascribed due to the high water‑holding capacity of the soil.

An estimate of the water deficits at the various sites can be worked out using the following formula:

$$B = Res + R - E_{tp} \qquad (9)$$

where,

B = the water deficit at the end of the period,
Res = soil reserve at the beginning of the period,
R = rainfall, and
E_{tp} = potential evapotranspiration during the period.

Using the above equation, it was possible to work out the water deficits at the end of the drought period in all the three sites under study. In calculating this, we have assumed the soil water reserve (*Res*) at the beginning of November to be at field capacity, or 250 mm. The same value was taken for all the three sites. The Penman potential evapotranspiration (E_{tp}) for the sites was taken from the published values of Rao *et al*. (1971). The results are presented in *Table 3*.

TABLE 3. WATER DEFICITS (mm) AT THE THREE SITES BY THE END OF THE DRY PERIOD (May) AS WORKED OUT BY EQUATION (9)

Site	Res	R	E_{tp}	B
Andhra Pradesh	250	123	997	-624
Karnataka	250	133	875	-492
Maharashtra	250	100	1 003	-653

Note: See text for abbreviations.

From *Table 3*, it is apparent that in all the three sites, there was a drought period, at the end of which the water deficits were considerable. This means that oil palm cannot be successfully grown at any of these sites as a rain-fed crop. Proper irrigation is necessary to get better growth and yield from the palms. The oil palm has the capacity to use water from great depths. For example, in Ivory Coast, the plant was found to extract water from 5.2 m depth (Dufrene *et al.*, 1992). They also found that the fraction of extractable water in the soil was never reduced below 0.40 even during the dry season. This was due to early stomatal closure which occurred when the fraction of extractable water of the top 80 cm of soil decreased below 0.60. Stomatal closure induced a decrease in the transpiration rate.

Water supply has been found to be the major limiting factor for oil palm yield (Cornaire *et al*., 1994). When subjected to severe stress, the trees not only reduce production to less than 5 t FFB ha^{-1}, but also suffer vegetative damage. A very good example for this can be found in the state of Kerala, India, where 3700 ha have been brought under oil palm mainly in hilly areas. The average yield from these plantations is reported to be below 1 t oil ha^{-1} yr^{-1} (5 t ha^{-1} yr^{-1}) (Rethinam, 1994). In Kerala, there exists a dry period lasting not less than four to five months, and the crop is not irrigated. The productivity is even less than in the Andamans where oil palm was introduced in 1976 (Thampan, 1992).

CONCLUSION

Analysis of the microclimate shows that the maximum temperatures at all the three sites were well within the boundary when compared to suitable oil palm growing areas elsewhere. However, the minimum temperatures at Sites 2 and 3 were much lower than the recommended value. The VPD at all the three sites were at a maximum of 4.5 kPa. Except for some months, the VPD at all the sites exceeded the 1.8 kPa, which resulted in stomatal closure. The irrigated oil palms at all the three sites were not suffering from any water stress as indicated by the water potential measurements. Estimation of the soil water deficits in all the sites indicated that the prolonged dry period created a severe water deficit. Estimation of transpiration by the Penman-Monteith method indicated a transpiration of 2.0 to 5.5 mm day^{-1} for all the plantations.

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