

**University of São Paulo
“Luiz de Queiroz” College of Agriculture**

**Water requirement of oil palm in two different edaphoclimatic conditions
in Brazil**

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Thesis presented to obtain the degree of Doctor
in Science. Area: Agricultural Systems
Engineering

**Piracicaba
2019**

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Water requirement of oil palm in two different edaphoclimatic conditions in Brazil
versão revisada de acordo com a resolução CoPGr 6018 de 2011

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1. *Elaeis guineensis* Jacq. 2. Balanço hídrico 3. Sensoriamento remoto 4. Irrigação I. Título

*I dedicate with love to
my parents Josevaldo and Dulcineia,
my brother Júlio César and my sister Hellen,
the memory of my grandparents Otávio, Josefa, Aroaldo, José Ribeiro, and Nadir,
and my fiancée Amanda.*

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*“Thou meetest him that joyfully works righteousness,
those that remember thee in thy ways.”*

Isaiah 64, 5

“...you were bought with a price. So glorify God in your body.”

I Corinthians 6, 20

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RESUMO

Necessidade hídrica da palma de óleo em duas condições edafoclimáticas no Brasil

A palma de óleo, ou dendezeiro, é uma cultura perene que se destaca pela maior produção de óleo por área plantada entre as oleaginosas. O principal objetivo desta Tese foi determinar a exigência de água pela palma de óleo em duas condições edafoclimáticas brasileiras distintas. Especificamente, este estudo objetivou: (i) quantificar a evapotranspiração real (ET_a), obter coeficientes de cultura (K_c e K_{cb}) e determinar a relação entre o coeficiente de cultura basal (K_{cb}) e índice de área foliar (IAF) de plantas jovens de palma de óleo irrigadas em condições subtropicais úmidas; (ii) determinar a variação espaço-temporal da evapotranspiração da palma de óleo a partir de imagens de satélite ajustadas, bem como o coeficiente de cultura ajustado (K_{cadj}) e seus componentes sob condições climáticas da Amazônia. A necessidade hídrica de dendezeiros jovens foi determinada a partir de leituras feitas por um lisímetro de pesagem de precisão (4,0 m de diâmetro x 1,3 m de profundidade) instalado em Piracicaba, SP, Brasil. Os coeficientes de cultura foram obtidos dividindo-se as medidas lisimétricas no período de 24 h pela evapotranspiração de referência (ET_o) calculada pelo método de Penman-Monteith (FAO-56) e as medidas de IAF foram realizadas por meio do analisador de área foliar LAI-2200. As medidas lisimétricas mostraram que a ET_a e a transpiração da palma de óleo jovem foram $2,50 \pm 1,39 \text{ mm d}^{-1}$ e $1,43 \pm 1,09 \text{ mm d}^{-1}$, respectivamente, e os correspondentes K_c e K_{cb} foram 0,71 e 0,41, respectivamente. K_{cadj} médio para plantas entre 18 e 33 meses de idade foi de 0,08 e é recomendado apenas para irrigação por gotejamento, uma vez que é o resultado de um ajuste dependente da cobertura do solo e do espaçamento entre culturas. A relação K_{cb} - IAF obtida para palma de óleo foi $K_{cb} = 0,5895 IAF - 0,6674$ ($R^2 = 0,9856$) e pode ser útil para estimar o uso de água de dendê a partir de medidas de IAF . Para determinar o consumo hídrico da palma de óleo na Amazônia Oriental Brasileira, um modelo de balanço hídrico baseado em dados de sensoriamento remoto foi utilizado durante um período de 8 anos consecutivos em um cultivo comercial de palma de óleo no município de Moju, Pará, Brasil. Os resultados revelaram que, sob a influência do clima na Amazônia, a média plurianual da ET_a diária e total foi de cerca de $3,4 \pm 0,4 \text{ mm d}^{-1}$ e $1229 \pm 127,2 \text{ mm ano}^{-1}$. As necessidades hídricas da palma de óleo foram menores durante a estação seca ($364,7 \pm 88,94 \text{ mm}$) em relação ao período chuvoso ($864,4 \pm 80,91 \text{ mm}$) em decorrência de eventuais situações de estresse hídrico. O K_{cadj} médio de todo o período foi $0,87 \pm 0,42$. O K_{cb} foi caracterizado por um contínuo crescimento nos dois primeiros anos de cultivo (média de $0,78 \pm 0,29$), o qual se estabilizou a partir do terceiro ano com valores médios $1,16 \pm 0,04$. A correlação entre os rendimentos de cachos de frutos frescos (CFF) medidos *in situ* e modelados foi descrita por uma função linear ($Prod_{mod} = 0,7626.Prod_{med} + 538,64$; $R^2 = 0,9913$). Por fim, esta Tese apresenta resultados interessantes sobre as necessidades de óleo de dendê em duas regiões brasileiras, os quais podem ser de fundamental importância no estabelecimento de estratégias para melhorar a eficiência do uso da água em plantações de dendê.

Palavras-chave: *Elaeis guineensis* Jacq., Balanço hídrico, Sensoriamento remoto, Irrigação, Lisímetro

ABSTRACT

Water requirement of oil palm in two different edaphoclimatic conditions in Brazil

Oil palm is a perennial evergreen crop which stands out as the crop with the highest oil production per planted area among the oilseeds. The main objective of this thesis was to determine the oil palm water requirement in two different edaphoclimatic Brazilian conditions. Specifically, this study aimed to: (i) quantify actual evapotranspiration (ET_a), develop crop coefficients (K_c and K_{cb}), and determine the relationship between the basal crop coefficient (K_{cb}) and leaf area index (LAI) of young irrigated oil palm growing under the Brazilian Humid Subtropical conditions; (ii) determine the spatiotemporal variation of oil palm evapotranspiration from adjusted satellite images, as well as the adjusted crop coefficient (K_{cadj}) and its components under Amazon climate conditions. To compute the water requirement of young oil palm trees, we used a large and precise weighing lysimeter (4.0 m diameter x 1.3 m depth) installed in Piracicaba, SP, Brazil. Crop coefficients were obtained by dividing lysimetric measurements over 24 h period by reference evapotranspiration (ET_o) calculated by the Penman-Monteith method (FAO-56) and LAI measurements were performed by using the LAI-2200 Plant Canopy Analyzer. Lysimetric measurements showed that ET_a and transpiration young oil palm were $2.50 \pm 1.39 \text{ mm d}^{-1}$ and $1.43 \pm 1.09 \text{ mm d}^{-1}$, respectively, and the corresponding K_c and K_{cb} were 0.71 and 0.41, respectively. Average K_{cadj} for plants between 18- and 33-month-old was 0.08 and is recommended only for drip irrigation as it is the result of an adjustment that depends on ground coverage and crop spacing. The K_{cb} - LAI relationship obtained for oil palm was $K_{cb} = 0.5895 LAI - 0.6674$ ($R^2 = 0.9856$) and can be useful to estimate oil palm water use from LAI measurements. To determine the oil palm water use in the Eastern Brazilian Amazon, a remote-sensing-based ET and water balance model was performed over an 8-year consecutive period in a commercial oil palm site near Moju, Pará, Brazil. The results of the water balance model revealed that under Amazon climate influence, the multi-year average of daily and total ET_a was about $3.4 \pm 0.4 \text{ mm d}^{-1}$ and $1229 \pm 127.2 \text{ mm yr}^{-1}$. The oil palm water requirements were lower during the dry season ($364.7 \pm 88.94 \text{ mm}$) comparing to the rainy period ($864.4 \pm 80.91 \text{ mm}$) as a result of eventual water stress. In an annual average basis, K_{cadj} was 0.87 ± 0.42 , K_{cb} for the two first growing years was 0.78 ± 0.29 , reaching an average of 1.16 ± 0.04 from the third cropping year. The correlation between *in situ* measured and modeled oil palm fresh fruit bunches (FFB) yields was described by a linear function ($Yield_{mod} = 0.7626 Yield_{meas} + 538.64$; $R^2 = 0.9913$). In summary, this thesis presents interesting results on palm oil needs in two Brazilian regions, which may be of fundamental importance in establishing strategies to improve the efficiency of water use in palm plantations.

Keywords: *Elaeis guineensis* Jacq., Water balance, Remote sensing, Irrigation, Lysimeter

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LIST OF ABBREVIATIONS

A_c	canopy cover area
A_E	evaporation of water from the soil outside the lysimeter
A_L	lysimeter area
A_t	total area
CN	curve number
CWP	crop water productivity
D	drainage
d	Willmott index of agreement
D_e	weight for evaporated depth
D_r	weight for depletion
D_{REW}	weight for skin evaporated depth
E	evaporation
E_d	evaporation from the dry soil area
ET	evapotranspiration
ET_a	actual evapotranspiration
ET_c	crop evapotranspiration
ET_o	reference evapotranspiration
E_V	evaporation from the soil inside the lysimeter
E_w	evaporation from wetted soil area
f_c	fraction cover
FFB	fresh fruit bunch
GC	ground coverage
GDD_{base}	growing degree days base temperature
$h_{c \max}$	maximum crop height
$h_{c \min}$	minimum crop height
HI	harvest index
Irr	irrigation
$K_{c \max}$	maximum crop coefficient
K_c	crop coefficient
K_{cadj}	adjusted crop coefficient
K_{cb}	basal crop coefficient
K_{cbrf}	reflectance-based Crop coefficient

K_e	evaporation coefficient
K_{e1}	coefficient of evaporation of water after irrigation
K_{e2}	coefficient of evaporation of water after rainfall
K_s	stress coefficient
K_{sat}	saturated hydraulic conductivity
K_{st}	temperature stress coefficient
K_{sw}	water stress coefficient
L5-TM	Landsat 5 Thematic Mapper
L7-ETM+	Landsat 7 Enhanced Thematic Mapper Plus
L8-OLI	Landsat 8 Operational Land Imager
LAI	leaf area index
MAD	management allowable depletion
$NDVI$	normalized difference vegetation index
p	soil depletion fraction
PA	Pará
P_p	precipitation
R^2	coefficient of determination
RH	relative humidity
$RMSE$	root mean square error
R_n	net solar radiation
R_s	global solar radiation
$SAVI$	soil adjusted vegetation index
SD	standard deviation
$SETMI$	Spatial EvapoTranspiration Modelling Interface
T	transpiration
T_{adj}	adjusted crop transpiration
T_{ave}	average temperature
$T_{base\ st}$	base temperature stress
TEW	total evaporable water
T_{max}	maximum temperature
T_{min}	minimum temperature
$T_{upper\ st}$	upper limit temperature stress
TWC	total water consumption
U_2	2-meter wind speed

V	volume
VI	vegetation index
VPD	vapor pressure deficit
WUE_B^*	normalized water use efficiency
Y_{meas}	measured yield
Y_{mod}	modeled yield
Z_e	evaporation layer
θ_{FC}	field capacity
θ_{vini}	initial profile average volumetric water content
θ_{vL}	weight for lower soil layer volumetric water content
θ_{vsat}	saturated volumetric water content
θ_{WP}	permanent wilting point

LIST OF SYMBOLS

%	percentage
°	degree
°C	degrees Celsius
CO ₂	carbon dioxide
g cm ⁻³	gram per cubic centimeter
g m ⁻²	gram per square meter
h d ⁻¹	hour per day
ha yr ⁻¹	hectare per year
ha	hectare
kg m ⁻³	kilogram per cubic meter
kg	kilogram
kPa	kilopascal
L d ⁻¹	liter per day
L h ⁻¹	liter per hour
m s ⁻¹	meter per second
m	meter
m ²	square meter
m ³	cubic meter
min	minute
MJ m ⁻² d ⁻¹	megajoule per square meter and per day
mm d ⁻¹	millimeter per day
mm m ⁻¹	millimeter per meter
mm yr ⁻¹	millimeter per year
mm	millimeter
N	North
S	South
t ha ⁻¹ yr ⁻¹	tones per hectare per year
US\$	American dollar
W	west

LIST OF INITIALS

ABRAPALMA	Brazilian Association of Palm Oil Producers
DWFI	Daugherty Water for Food Institute
EMBRAPA	Brazilian Agricultural Research Corporation
ESALQ	“Luiz de Queiroz” College of Agriculture
FAO	Food and Agriculture Organization of the United Nations
MAPA	Ministério da Agricultura, Pecuária e Abastecimento
SAGRI	Secretaria de Agricultura do Estado do Pará
UNL	University of Nebraska-Lincoln
USDA	United States Department of Agriculture
USP	University of São Paulo

1 GENERAL INTRODUCTION

Expectations of population growth and accelerated growth of animal protein consumption as a result of the recent social rise of hundreds of millions of people in emerging countries projected a rise of up to 70% in demand for food by 2050. Moreover, in face of the current issues such as the depletion of fossil fuels and environmental degradation, the use of renewable fuels and the need to improve energy efficiency (Kumar *et al.*, 2012) have intensified the search for alternative sources of energy (Suarez and Meneghetti, 2007; Pousa *et al.*, 2007) such as biofuels. Biodiesel is considered one of the most important liquid biofuels used in the last years along with bioethanol and it is derived from agricultural crops such as oil palm.

Oil palm (*Elaeis guineensis* Jacq.) is a perennial crop member of the monocotyledonous palm family *Arecaceae*. This oilseed is originating in humid lowland tropics West Africa that was introduced initially in Brazil in the late sixteenth century in the state of Bahia, and later in the Amazon region where the largest cultivated areas are located (Villela *et al.*, 2014; Venturieri *et al.*, 2009). This crop is one of the most productive oil crops in the world and it is widely used as feedstock for food, hygiene, and chemical industry, especially biodiesel production (World Bank, 2010; Schwaiger *et al.*, 2011; Villela *et al.*, 2014, Paterson and Lima, 2018).

Oil palm is largely dependent on climatic factors, growing well in humid and flat tropical regions. The rainfall is the most important climatic factor for this oilseed, with an average rainfall of 2000 mm well distributed throughout the year (Hartley, 1988; Lim *et al.*, 2008). In addition, the oil palm can reach good productive indices in areas that receive at least 1800 mm without soil water deficit (Hartley, 1988).

According to Corley and Tinker (2016), it is a crop susceptible to large temperature variations, having a good development in places where the average annual temperature is between 25 and 27 °C, without the occurrence of minimum temperatures below 17 °C for long periods. However, when grown at high altitudes as well as in areas located at latitudes below 15 ° (N or S), it can grow with minimum average temperatures below 20 °C. The effects of low temperatures on the plant are the increase in flower abortion and slow plant growth (Foong, 1993). The relative humidity of the air should be kept at or greater than 85%, equivalent to a saturation deficit of less than 0.6 kPa.

The oil palm is also a demanding crop in solar radiation. According to Corley and Tinker (2016), besides influencing the photosynthetic rate, solar radiation can interfere with the maturation of the bunches and the oil content in the fruit. Considering that this plant has a high photosynthetic capacity, the insolation required for the oil palm to express its productive potential lies between 1500 and 2000 annual hours distributed evenly, with a minimum of 5 h d^{-1} , and may even require 7 h d^{-1} in a few months, or solar radiation around 16 and $17 \text{ MJ m}^{-2} \text{ d}^{-1}$ (Hartley 1988, Lim *et al.*, 2008, Verheye, 2010, ABRAPALMA, 2016).

Palm oil production can reach about $4 \text{ to } 7 \text{ t ha}^{-1} \text{ yr}^{-1}$, representing up to ten times more oil production compared with soybeans, for example and the oil palm potential can be confirmed after this oilseed take on world leadership in oil production and consumption in 2005, surpassing soybean oil production (Pina, 2010; Teles *et al.*, 2016). Indeed, palm oil production accounts for more than 30% of the world's vegetable oil production (FAO, 2013) and it is a valuable industry worth over US\$ 50 billion dollars annually (Murphy *et al.*, 2014). Thus, the continuous increase in demand for this crop as well as its economic attractiveness led to increased production (Wicke *et al.*, 2011) and expansion of cultivated areas (FAO, 2016), becoming the most rapidly expanding crop in tropical countries over the last years.

In this sense, according to global biophysical models, Brazil has the largest remaining potential land area suitable for oil palm production among the other oil palm producing countries, particularly in the Amazon region (Ramalho Filho *et al.*, 2010). This region has adequate soil and climate conditions for high oil palm productivity as well as a wide range of native oil palm (La Rovere *et al.*, 2011). In the Legal Amazon region, the Agri-Ecological Zoning of Oil Palm in Deforested Areas of the Amazon (ZAE-Palma) has identified about 30 million hectares suitable for oil palm cultivation (Ramalho Filho *et al.*, 2010).

In this regard, the surface dedicated to oil palm cultivation in Brazil has increased at an average rate of 5000 ha yr^{-1} from 2006, reaching a total cultivated area of about 143000 ha in 2016 (FAO, 2016). Most of this area is on Northeastern Pará state that has become the largest palm oil producing Brazilian state, responsible for about 93% of the palm oil in the country (Souza *et al.*, 2010; Furlan Junior *et al.*, 2006). Throughout the last decade, oil palm plantations in Pará state have been organized in agroindustry that produces feedstock from their own managed lands and small farmers and producers of all sizes (SAGRI, 2013). In particular, the rational use of palm oil as an alternative for energy generation in Amazon region, for instance, is a good opportunity once this vegetable oil has physicochemical properties quite similar to petroleum diesel (Furlan Junior *et al.*, 2004).

In areas traditionally exploited with oil palm cultivation, production is basically based on rainfed cultivation or by using irrigation during periods of drought, in regions with annual total rainfall of less than 1,000 mm, with an irregular distribution. With regard to areas where larger and more intense periods of soil water deficit can occur during the year, it is of particular importance to consider irrigation technology to obtain economic productivity since the plant stand and total photosynthetic efficiency of the canopy are maximized due to the minimization of the water deficit in the soil, verifying the production in these regions.

Although there are several studies on the oil palm water demand in traditional production centers in Southeastern Asia (Lee *et al.*, 2005; Palat *et al.*, 2009; Arshad, 2014, Röhl *et al.*, 2015; Meijide *et al.* (2017), there is still insufficient information about oil palm requirements in non-traditional regions like Brazil, which is considered strategic in the expanding process of this crop in the world. Thus, quantifying actual crop water requirement or evapotranspiration (ET_a) is important for irrigation management or irrigation scheduling. Evapotranspiration is a phenomenon that includes two processes of water losses from surfaces to atmosphere (Doorenbos and Pruitt, 1977): water evaporation (from the soil, water layers or plant surfaces) and plant transpiration (stomata of leaves) (Jensen *et al.*, 1990). Over the years, some methods of estimating ET_a have been developed and used in order to quantify accurately, the crop water requirements using surface meteorological observations (Yang *et al.*, 2014) such as eddy covariance (Meyers and Baldocchi, 2005; Merten *et al.*, 2016; Meijide *et al.*, 2017), Bowen ratio techniques (Bowen, 1926; Andreas *et al.*, 2013; Potter *et al.*, 2011), lysimeters (Howell *et al.* 1985; López-Urrea *et al.*, 2009; Allen *et al.* 2011; Evett *et al.*, 2012) and remotely sensed data (Duchemin *et al.*, 2006; González-Dugo and Mateos, 2008; Cruz-Blanco *et al.*, 2014, Parka *et al.*, 2017)

Lysimeter-based ET determinations are considered the reference method because of its satisfactory accuracy and resolution, features that are used to validate the accuracy of other methods of ET estimate (Green *et al.*, 2003). Weighing lysimeters is the only direct ET_a measurement method since it relies on mass balance so that measurements are possible even during periods of precipitation and irrigation events (Evett *et al.*, 2012) and because ET_a can be computed over intervals shorter than a day (Beeson Junior, 2011).

Recently, the use of these data into models of ET has been considered a promising tool for providing the spatial distribution of ET at the regional scale, minimizing the use of methods that represent only processes in local scale (Xu and Singh, 2005; Venturini *et al.*, 2008; Yang *et al.*, 2014). The reflectance-based crop coefficient (K_{cbrf}) model is one of the general types of remote sensing approaches for estimating crop ET (González-Dugo *et al.*,

2009) and it has been successfully used in the last years for irrigation management and estimates of ET in large areas (Neale *et al.*, 2012). In this approach, the spatially distributed basal crop coefficient (K_{cb}) is estimated from vegetation indices (VI) that traces the crop growth and are used along with reference ET to compute crop evapotranspiration (ET_c) (Bausch and Neale, 1989; Neale *et al.* 1989; Neale *et al.*, 2012; González-Dugo *et al.*, 2009).

In this context, the abovementioned methodologies may be appropriate to test hypotheses about oil palm water needs under different edaphoclimatic conditions in Brazil: (1) since oil palm grows well in humid regions such as the Amazon, irrigation favors cultivation of this oilseed in areas with lower rainfall than those of traditional regions; (2) because prolonged water stress affects oil palm production, irrigation minimizes the effect of water deficit during less rainy periods of the year, even in humid regions.

In order to test the hypotheses of this work, our study aimed to:

- determine the actual crop evapotranspiration, single (K_e) and basal (K_{cb}) crop coefficient of young oil palm growing irrigated under the Brazilian Humid Subtropical conditions, and additionally establish the relationship between K_{cb} and leaf area index (LAI) (**Chapter 2**).
- determine the spatiotemporal variation of oil palm evapotranspiration from adjusted satellite images, the adjusted crop coefficient (K_{cadj}) and its components; and estimate oil palm productivity based on the normalization of water productivity in Eastern Brazilian Amazon (**Chapter 3**).

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2 EVAPOTRANSPIRATION AND CROP COEFFICIENT OF YOUNG OIL PALM TREES IN THE BRAZILIAN HUMID SUBTROPICAL CONDITIONS FROM LYSIMETRIC MEASUREMENTS

Abstract

The oil palm (*Elaeis guineensis* Jacq.) stands out for its high oil productivity, which is the most consumed in the world and represents a promising option for the production of biofuels and food in Brazil. Accurate information about oil palm water requirements for precise and sustainable use of irrigation is a bottleneck for oil palm expansion to non-traditional oil palm production centers. This study aimed to quantify actual evapotranspiration (ET_a) and develop the single (K_c) and basal (K_{cb}) crop coefficients. Also, we aimed to determine the relationship between K_{cb} and leaf area index (LAI) of young oil palm growing irrigated under the Brazilian Humid Subtropical conditions. The experiment was carried out in Piracicaba, São Paulo, Brazil from April 2017 to July 2018 when plants were 18- and 33-month-old, respectively. A large and precise weighing lysimeter (4.0 m diameter x 1.3 m depth) was used to measure ET under drip irrigation. Crop coefficients were obtained by dividing lysimetric measurements over 24 h period by reference evapotranspiration (ET_o) calculated by the Penman-Monteith method (FAO-56). Also, *in situ* LAI measurements were performed using the LAI -2200 Plant Canopy Analyzer. Lysimetric measurements showed that oil palm ET_a and transpiration were $2.50 \pm 1.39 \text{ mm d}^{-1}$ and $1.43 \pm 1.09 \text{ mm d}^{-1}$, respectively, and the corresponding K_c and K_{cb} were 0.71 and 0.41, respectively. K_{cadj} for plants between 18- and 33-months-old was 0.08 and is recommended only for drip irrigation as it is the result of an adjustment that depends on ground coverage and crop spacing. A low irrigation water amount was obtained by using K_{cb} instead of K_c , K_{cadj} and especially $K_{cb} + K_e$, once the latter considers high soil evaporation that increases the amount of water to be applied by irrigation to compensate the soil evaporation. The K_{cb} - LAI relationship obtained for oil palm is $K_{cb} = 0.5895 LAI - 0.6674$ ($R^2 = 0.9856$) and can be useful to estimate oil palm water use from LAI measurements.

Keywords: *Elaeis guineensis* Jacq.; Water requirement; Drip irrigation

2.1 Introduction

The oil palm (*Elaeis guineensis* Jacq.) is a native African species cultivated in humid tropical regions, mainly in Africa, Asia and America (Henderson and Osborne, 2000; Wahid *et al.*, 2004) and it has the highest productivity among the oilseeds planted worldwide. Palm oil average yield (4 to $7 \text{ t ha}^{-1} \text{ yr}^{-1}$) is approximately 10 times the yield of soybean oil average yield (Rocha, 2007), which on average yields 0.5 t ha^{-1} of oil (Pina, 2010). In addition to the productive potential of the oil palm, the cost of producing palm oil is lower than that of other major oilseeds, so it stands out as the species that should be responsible for meeting most of

the growing world demand for vegetable oil, estimated to be 240 million tons by 2050 (Corley, 2009; Zimmer, 2009).

Oil palm cultivation occupies an area of more than 17 million hectares and produces 267.55 million tons of oil worldwide (FAO, 2013), of which Indonesia and Malaysia account for 87%. In Brazil, the crop is well adapted to the climatic conditions of the legal Amazon and the coast of the state of Bahia (Barcelos *et al.*, 2002), regions with high rainfall indices and high temperatures throughout the year (Teles *et al.*, 2016). The highest concentration of cultivated areas is in the state of Pará, which accounts for about 90% of the national palm oil production (USDA, 2011).

According to the Brazilian Association of Palm Oil Producers (ABRAPALMA), the area cultivated in Brazil is about 236,000 hectares, including areas of agroindustry, small and medium-sized owners, and family farmers (BRASIL, MAPA, 2018). Moreover, this amount may increase in the upcoming years once Brazil has about 30 million hectares of non-forest land suitable for growing oil palm (Ramalho *et al.*, 2010), giving to the country a strategic position in face of forecasts of a global increase in demand for palm oil.

On the other hand, there are some issues that should be considered within the context of the oil palm expansion in the Brazilian Amazon such as the challenge of controlling a disease of unknown etiology called Fatal Yellowing (Krug *et al.*, 2013), the high logistics costs of input supply and production flow (Brandão and Schoneveld, 2015; Teles *et al.*, 2016), and the challenges of the sustainable production of this crop (Lameira *et al.*, 2015a). Regarding to this last aspect, Lameira *et al.* (2015b) suggests that the ideal would be that the production of oil palm would be restricted to a maximum of 10% of the agricultural area, as occurs in the areas of sugarcane expansion in the state of Goiás, Brazil, since the municipalities in the palm oil producing region have different development patterns, socioeconomic vulnerability and accentuated socioenvironmental problems.

In view of the aforementioned factors along with the high technological level employed in some regions of Brazil and the high potential yield of oil palm, farmers and research institutions have considered the possibility of growing oil palm in other areas and regions of the country provided that irrigation is feasible. Recently, a yield analysis of oil palm cultivated under Brazilian Savanna conditions revealed the oil yields similar to regions of Indonesia and Malaysia can be achieved by using irrigation (Teles *et al.*, 2016). The literature contains several studies about oil palm water requirement (Lee *et al.*, 2005; Palat *et al.*, 2009; Arshad, 2014), but there is lacking information to manage irrigation satisfactorily. Furthermore, the real oil palm water requirement in non-traditional regions such as

southeastern Brazilian is scarce since there is just one publication reporting the oil palm water use in the Brazilian Tropical Savanna in 7-year-old oil palm trees (Antonini *et al.*, 2015).

In this sense, accurate determination of the crop water requirement or evapotranspiration (ET_c) is important to improving irrigation water productivity, particularly, in regions where restricted rainfall throughout the year is supplemented by irrigation. As ET_c varies widely from crop to crop, during the growth period of the crop and under various local climate conditions (Reddy, 2015; Xu *et al.*, 2018), specific crop coefficients (K_c) are needed in irrigation scheduling for providing precise water applications for different regions. K_c is a coefficient established by Allen *et al.* (1998) which predicts properties of the crop which affect ET. Thus, ET_c can be calculated by multiplying K_c by ET_o ($ET_c = ET_o \cdot K_c$). ET_o represents a standardized reference ET which relies on a version of the Penman-Monteith reference ET equation for a short (12 cm high clipped), smooth “grass” crop, incorporating the effects of weather into the ET estimate (ASCE, 2005).

However, in herbaceous crops, K_c varies only seasonally, whereas in trees K_c is affected by horticultural factors that alter soil cover and, consequently, soil moisture to some extent. (Fereres and Goldhamer 1990; Goodwin *et al.* 2006, Alves Júnior *et al.*, 2007). Therefore, Keller and Karmeli (1974) proposed an equation that adjusted water use rates in the total area to individual canopy cover area irrigated by a drip system. Additionally, Allen *et al.* (1998) considered the effects of specific wetting events by splitting the K_c into two separate coefficients: one that quantifies soil evaporation (K_e), and another associated to crop transpiration denominated basal crop coefficient (K_{cb}). In addition, a stress coefficient (K_s) was included for soil water limiting conditions. By this methodology, ET_c , or ET_a , once considers eventual water stress, is calculated as $ET_a = (K_{cb} \cdot K_s + K_e) \cdot ET_o$. This way, in this paper, evapotranspiration measured in field refers to actual evapotranspiration (ET_a)

In general, ET is the sum of soil evaporation (E) and plant transpiration (T) (Allen *et al.*, 1998). But in sparse crops, ET_a is composed of four components: crop transpiration; rainfall intercepted and evaporated from the canopy; evaporation from the overall soil; and evaporation from the area wetted by the emitters (Orgaz *et al.*, 2006). So, the precise partitioning between T and E is very useful especially in drip irrigation planning, once E does not contribute to crop productivity and should be reduced at maximum in order to conserve agriculture water (Allen, 2000).

Several methods such as Bowen ratio energy balance system (Bowen, 1926; Tanner 1960; Irmak, 2010), eddy covariance method (Reynolds, 1895; Facchi *et al.*, 2013) and lysimetric measurements are often used to determine ET (Howell *et al.* 1985; Allen *et al.*

2011; Tripler *et al.*, 2012). Among them, the weighing lysimeter method is considered the reference method for providing satisfactory accuracy and resolution of the data (Howell *et al.*, 1985; Silva *et al.*, 1999; Allen *et al.*, 2011), which are vital to precise irrigation scheduling and improving crop productivity and water use efficiency.

Thus, the objectives of this study were to: (i) determine the actual crop evapotranspiration of young oil palm growing irrigated under the Brazilian Humid Subtropical conditions; (ii) determine single (K_c) and basal (K_{cb}) crop coefficient; and (iii) derive the relationship between K_{cb} and leaf area index (LAI).

2.2 Material and Methods

2.2.1 Experimental site

The study was carried out at an experimental area belonging to the ‘Luiz de Queiroz’ College of Agriculture, the University of São Paulo (ESALQ/USP), Brazil (22.70°S and 47.64°W, 511 m altitude) during 16 months (April 2017-July 2018) in a 1.0 ha plot cultivated with 18-month-old oil palm trees (*Elaeis guineensis* Jacq.) (Fig. 2.1a). According to the Köppen-Geiger world soil classification (Peel *et al.*, 2007), the local climate is classified as Cfa (subtropical mesothermic with hot summer), with an annual mean temperature of 21.6 °C and annual precipitation of 1328 mm (Marin *et al.*, 2011). The soil is classified as loamy (59.6% clay, 13.7% silt, and 26.6% sand), with 3.2% organic matter content, and density around 1.4 g cm⁻³.

Oil palm plants were cultivated in the experimental area in mid-October 2015, using 12-leaf seedlings previously cultivated in a greenhouse. The cultivar used was BRS C2501, a commercial Tenera hybrid developed by the breeding program of Embrapa Western Amazon (Brazilian Agricultural Research Corporation), originating from African parental varieties of *Elaeis guineensis* (Jacq.) Dura (source Deli) and Pisifera (source La Mé). A spacing of 9 m between plants in equilateral triangles was adopted, totaling 143 plants ha⁻¹ (Fig. 2.1b).

Throughout the execution of the experiment, crop management practices were carried out, encompassing the phytosanitary control of pests, diseases, and weeds. The applications of chemical pesticides were performed from pests and diseases diagnostics in the plants. Regarding the control of the weeds, we used a grubber coupled to a tractor for the control in the interline and manual grubber for the control between plants. After each manual grubbing,

the localized application of a non-selective systemic herbicide was performed. Fertilization was applied according to Rodrigues *et al.* (2002) twice a year.

Irrigation was performed by means of a drip irrigation system (Fig. 2.1c). Five emitters of 8 L h⁻¹ rate (40 L h⁻¹ per plant), spaced 0.85 m apart in a 16 mm polyethylene pipe, were installed per plant. The tube was arranged radially around the plant, making a radius of 0.5 m. The system was checked twice a year for uniformity of discharge. The amount of water to be applied was determined by a lysimeter placed at the center of the experimental area.

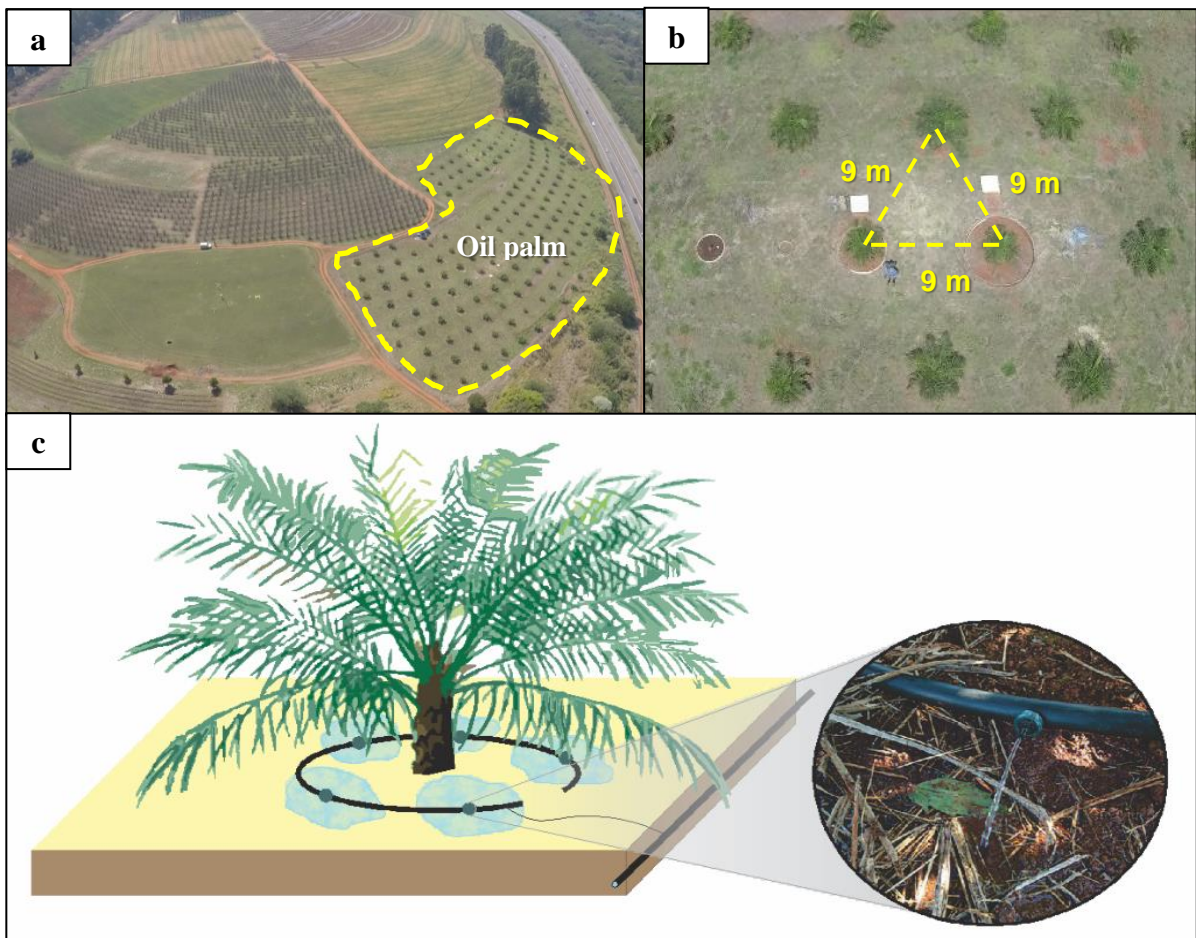


Figure 2.1 Experimental site with a) oil palm cultivation. b) Detail of the arrangement of the plants in field, and c) drip irrigation system.

2.2.2 Lysimeter measurements and reference evapotranspiration

The lysimeter used in our study was deployed and firstly calibrated by Campeche (2002) at the center of the experimental site. Lysimetric calibration was made yearly (between May and August) to ensure the precision of the measurements. The lysimeter was a high

precision (Fig. 2.2a), suspended weighed type (4.0 m diameter x 1.3 m depth) which consisted of a steel container filled with the same characteristics of the surrounding soil. The lysimeter tank was equipped with a drain at the bottom that allowed the drainage of excess water (Fig. 2.2b). The lysimeter was placed on three 13.5-ton load cells (0.1 mm precision) (Fig. 2.2c), which were connected to a data logger (model CR800, Campbell Scientific, Inc., Logan, Utah), programmed to take readings every 5 seconds and recordings every 15 min, hourly, and daily (Fig. 2.2d).

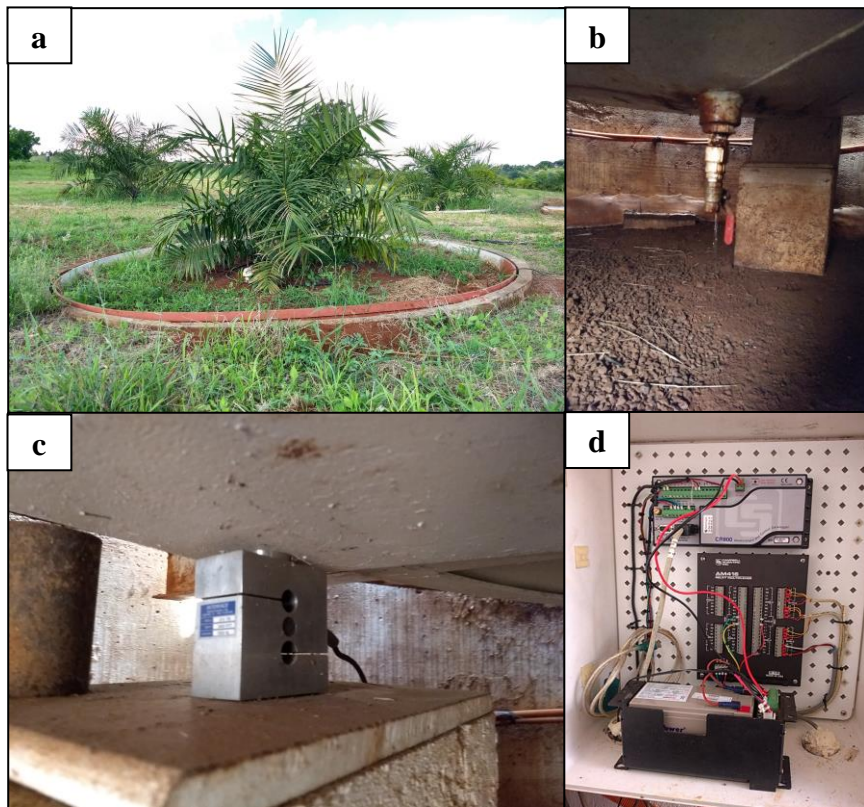


Figure 2.2 Detail of the a) weighing lysimeter containing a oil palm plant, b) drainage system, c) load cell, and d) data logger CR800.

Reference evapotranspiration (ET_o) was calculated by using the FAO Penman-Monteith method (Allen *et al.*, 1998), which uses standard climatic data recorded by an automatic weather (Fig. 2.3a) station installed approximately 70 m from the lysimeter (Fig. 2.3b). The weather station was placed over a surface of green grass of homogeneous height (≈ 0.12 m), actively growing and without water deficit. Meteorological data included air average (T_{ave}), maximum (T_{max}), and minimum (T_{min}) temperature and relative air humidity (RH) (Vaisala Inc., model HMP45C), global (R_s) and net solar radiation (R_n) (Kipp & Zonen, model

NR-Lite), wind speed (Gill, model Windsonic 4) at 2 m height, and precipitation (P_p) (Texas Electronics, model TE525mm). Because it is a relatively flat area, data from the weather station represent well of the lysimeter site. A 15 min, hourly, and daily meteorological data recordings also were made, from readings every second by another datalogger (model CR1000, Campbell Scientific, Inc., Logan, Utah).

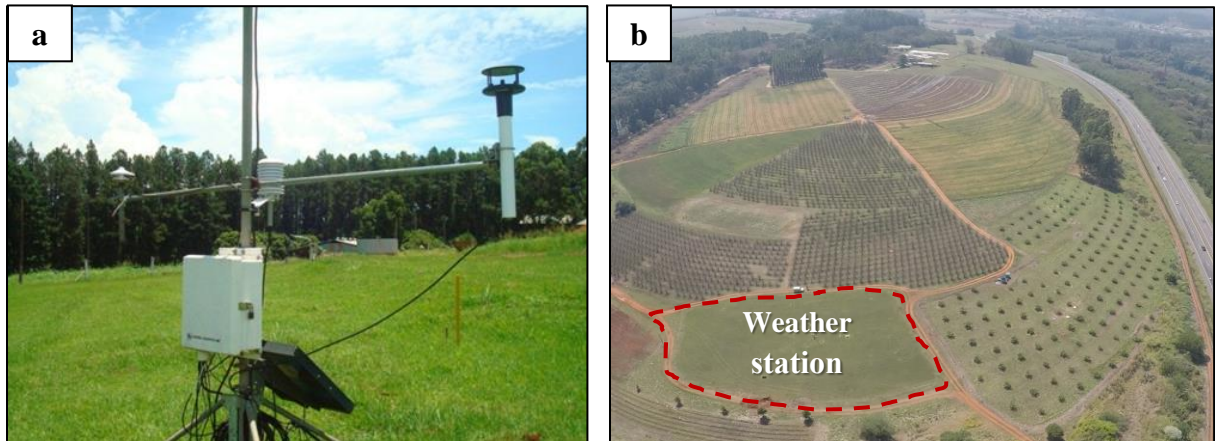


Figure 2.3 Detail of the a) weather station and b) the area covered by short grass where the weather station was installed.

For the computation of the oil palm oil consumption, the difference between the values was recorded at midnight between two consecutive days and when the wind speed was considered weak ($<1.5 \text{ m s}^{-1}$). Daily ET_a values were determined as the difference between lysimeter mass losses (evaporation and transpiration) and lysimeter mass increases (precipitation, or dew) divided by the lysimeter area (12.56 m^2). Irrigation was performed after midnight in order to avoid computing the addition of mass to the lysimeter as well as to minimize excessive evaporation losses due to the incidence of solar radiation throughout the day.

In order to verify the similarity between the lysimeter plant and the other plants in the experimental area, biophysical measurements were performed every two months. The measurements consisted of plant height (m), average canopy diameter (m), trunk perimeter (m), and leaf n° 9 lengths (m) in the lysimeter plant and in 9 plants near the lysimeter (Table 2.1).

Table 2.1 Biophysical measurements of oil palm from April 2017 to July 2018 in Piracicaba, Brazil. (average \pm standard deviation)

Plant	2017					2018		
	Apr	Jun	Aug	Oct	Dec	Feb	Apr	Jun
	Height (m)					Height (m)		
Lysimeter	1.8	1.9	2.0	2.2	2.2	2.3	2.2	2.4
Orchard	1.9 \pm 0.2	2.0 \pm 0.2	2.0 \pm 0.2	2.2 \pm 0.2	2.3 \pm 0.3	2.1 \pm 0.1	2.3 \pm 0.2	2.4 \pm 0.2
	Average canopy diameter (m)					Average canopy diameter (m)		
Lysimeter	2.5	2.6	2.9	2.9	3.1	3.2	3.5	3.5
Orchard	2.6 \pm 0.1	2.8 \pm 0.3	2.9 \pm 0.3	3.1 \pm 0.4	2.9 \pm 0.2	3.3 \pm 0.3	3.4 \pm 0.2	3.5 \pm 0.2
	Trunk perimeter (m)					Trunk perimeter (m)		
Lysimeter	0.9	0.9	1.0	1.1	1.3	1.3	1.4	1.5
Orchard	0.9 \pm 0.1	1.0 \pm 0.1	1 \pm 0.1	1.2 \pm 0.2	1.1 \pm 0.1	1.3 \pm 0.1	1.5 \pm 0.3	1.4 \pm 0.1
	Leaf n° 9 lengths (m)					Leaf n° 9 lengths (m)		
Lysimeter	1.4	1.6	1.7	1.6	1.8	1.6	2.0	2.3
Orchard	1.4 \pm 0.2	1.7 \pm 0.3	1.9 \pm 0.2	1.9 \pm 0.3	2.0 \pm 0.2	1.9 \pm 0.2	1.9 \pm 0.1	2.3 \pm 0.1

2.2.3 Transpiration (T) and basal crop transpiration coefficient (K_{cb})

Transpiration (T) (Eq. 1) and basal crop transpiration coefficient (K_{cb}) (Eq. 2) were estimated from the data recorded by the lysimeter daily, considering the individual contribution of the transpiration of the crop and of the soil water evaporation by replacing the crop coefficient (K_c) by a crop transpiration coefficient, K_{cb} and a soil evaporation coefficient, K_e (Eq. 3) (Allen et., 1998).

$$T = \left\{ \frac{\left[(M_i - M_{i-1}) - D + Irr + (P_p \cdot A_L) \right] - E_v}{A_c} \right\} \quad (1)$$

$$K_{cb} = \frac{T}{ET_o} \quad (2)$$

$$K_e = \frac{E}{ET_o} \quad (3)$$

Where M_{i-1} is the mass of the lysimeter on the previous day (kg); M_i is the current mass of the lysimeter (kg); D is the Drainage (kg); Irr is the irrigation (kg); P_p is precipitation (mm); A_L is the surface of the lysimeter (12.56 m²); E_v is evaporation from the soil inside the lysimeter; A_c is the canopy cover area (m²); ET_o is reference evapotranspiration, and E is the water evaporated from the soil surface (mm);

Soil water evaporation was then determined by equations presented below (Eq.4-6).

$$E_v = E_w + E_d \quad (4)$$

Where E_w is water evaporated from the wetted soil area (mm), and E_d is water evaporated from the dry soil (mm).

E_w (Eq. 5) and E_d (Eq. 6) were estimated by a water evaporation curve of the soil in the experimental area (Silva, 2005), as a function of days after an irrigation or rainfall.

$$E_w = K_{e1} \cdot ET_o \cdot A_w \quad (5)$$

$$E_d = K_{e2} \cdot ET_o \cdot A_d \quad (6)$$

Where K_{e1} is the coefficient of evaporation of water in the soil as a function of the days after irrigation and K_{e2} is the coefficient of evaporation of water in the soil as a function of the days after rainfall; ET_o is the reference evapotranspiration (mm); A_w is the wetted area (2.2 m²), and A_d is the dry area inside the lysimeter (10.36 m²).

2.2.4 Crop evapotranspiration (ET_a) and crop coefficient (K_c)

Crop Evapotranspiration (ET_a) (Eq. 7) was estimated by dividing the total water consumed by the plant by the total area allocated to each plant.

$$ET_a = \frac{TWC}{A_t} \quad (7)$$

Where ET_a is the crop evapotranspiration (mm); TWC is the total water consumption of the plant (L d⁻¹) and A_t is the area allocated for each plant (70.2 m²).

For the daily ET_c , only the instantaneous value, recorded at midnight of each day, was considered when the wind element was zero or less than 1.5 m s⁻¹. In addition, inconsistent values were detected and discarded especially on rainy days.

TWC (L d⁻¹) (Eq. 8) is the sum of soil evaporation and crop transpiration that occurred during the same period in the lysimeter (12.56 m²), added the evaporation of water in the soil from the area outside the lysimeter ($A_E = 57.64$ m²), to complement the lysimeter area, totaling the allocated area for each 70.2 m² plant, as follows.

$$TWC = (T \cdot A_c) + E_v + (K_{e2} \cdot ET_o \cdot A_E) \quad (8)$$

K_c (Eq. 9) was calculated by dividing ET_a by ET_o estimated by the Penman-Monteith method (Allen *et al.*, 1998).

$$K_c = \frac{ET_a}{ET_o} \quad (9)$$

Once the irrigation was performed by using a drip irrigation system, ET_a values were corrected by the percentage of plant cover ($GC = A_c/A_t$). However, the useful area of the crop was 70.2 m^2 (A_t), and A_c , the canopy coverage area (m^2) varied with the oil palm growth. So, K_c was adjusted (K_{cadj}), following a methodology described by Keller and Karmeli (1975) (Eq. 10). According to these authors, the methodology can be reliably used as long as the soil area is dry because the contribution of the external soil is not being determined. In the case of drip irrigation, this methodology is fully acceptable and this equation adjusts the rate of water consumption for canopies with low soil cover.

$$K_{cadj} = \left(\frac{ET_a}{ET_o} \right) \cdot \left(\frac{GC}{0.85} \right) \quad (10)$$

The estimation of the volumes of water to be applied in the irrigation was done through the equations used by Alves Júnior *et al.* (2007) and Barboza Júnior (2007) for ‘Tahiti’ lime tree, in the same lysimeters of the present study.

2.2.5 K_{cb} versus Leaf Area Index (LAI)

LAI information was obtained from measurements taken in 10 plants in the surrounding of the lysimeter, including the plant inside the lysimeter. An LAI -2200 Plant Canopy Analyzer was used to determine the LAI by comparing the intensity of diffuse incident light measured at the bottom of the canopy with that incoming at the top. The LAI measurements were taken near dusk and dawn in order to reduce the effect of scattering on the instrument, following the “isolated plant” methodology suggested by the manufacturer. An assessment between K_{cb} and LAI was performed by using LAI average from the ten plants and the average K_{cb} from 10 days before the LAI determination date in order to reduce the chances of adding non-representative K_{cb} values. A total of six K_{cb} - LAI pairs were used.

2.3 Results

2.3.1 Meteorological conditions

Fig. 2.1 presents the daily average (T_{ave}) and minimum temperatures (T_{min}), average relative humidity (RH), precipitation (P_p), and applied irrigation (Irr) during the experimental period. T_{ave} throughout this period was 21.2 ± 3.1 °C, while maximum and the minimum temperature reached 37.8 and 2.3 °C, respectively. The thermal amplitude over the 487 days of the study had an average of 13.5 °C with maximum and minimum values of 23.6 and 3.3 °C, respectively. Relative humidity levels fluctuated between 14.9 and 99.6% across the months with average RH of 72.5 ± 5.0 %. Total accumulated rainfall was 1322.8 mm, almost all during the spring and summer. Historically, minimal rainfall occurs between the late autumn (May) and late winter (August) in Piracicaba. The plants received 66 irrigations over the study period, especially during the dry season, and the total of applied irrigation water was 380 mm.

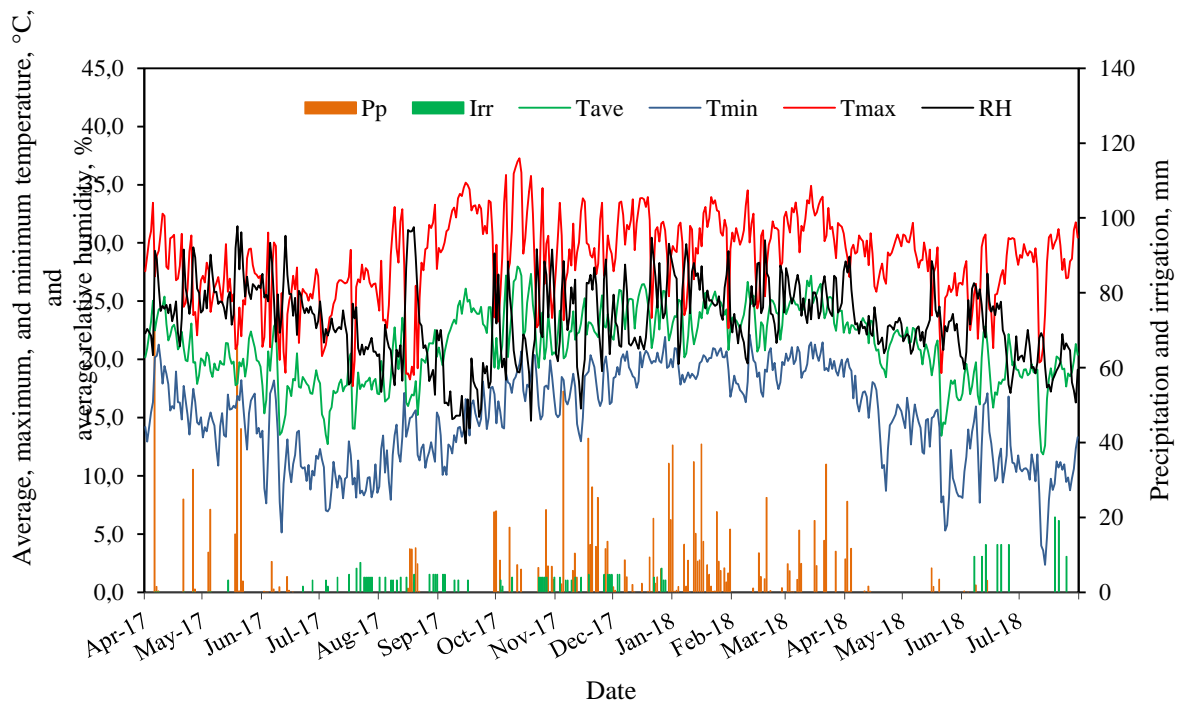


Figure 2.4 Meteorological data summary and irrigation depths between April 2017 and July 2018 at Piracicaba, São Paulo, Brazil. Daily precipitation (P_p), irrigation (Irr), average (T_{ave}), minimum (T_{min}) and maximum (T_{max}) temperatures, and relative humidity (RH).

Wind speed and vapor pressure deficit (*VPD*) are shown in Fig. 2.2. Average wind speed at 2 m height was $1.4 \pm 0.4 \text{ m s}^{-1}$, and values oscillated from 0.75 to 3.1 m s^{-1} . *VPD* was calculated from data temperature (T_{max} and T_{min}) and *RH*. *VPD* is a measure of the evaporating power of the air, having a direct relationship with the evaporation process since it depends on the vapor pressure gradient between the evaporating surface and the air. Thus, the higher its value, the greater the atmospheric demand and, consequently, the greater the evapotranspiration. *VPD* ranged from 0.05 to 2.28 kPa over the 16 evaluated months and average *VPD* was $0.81 \pm 0.38 \text{ kPa}$.

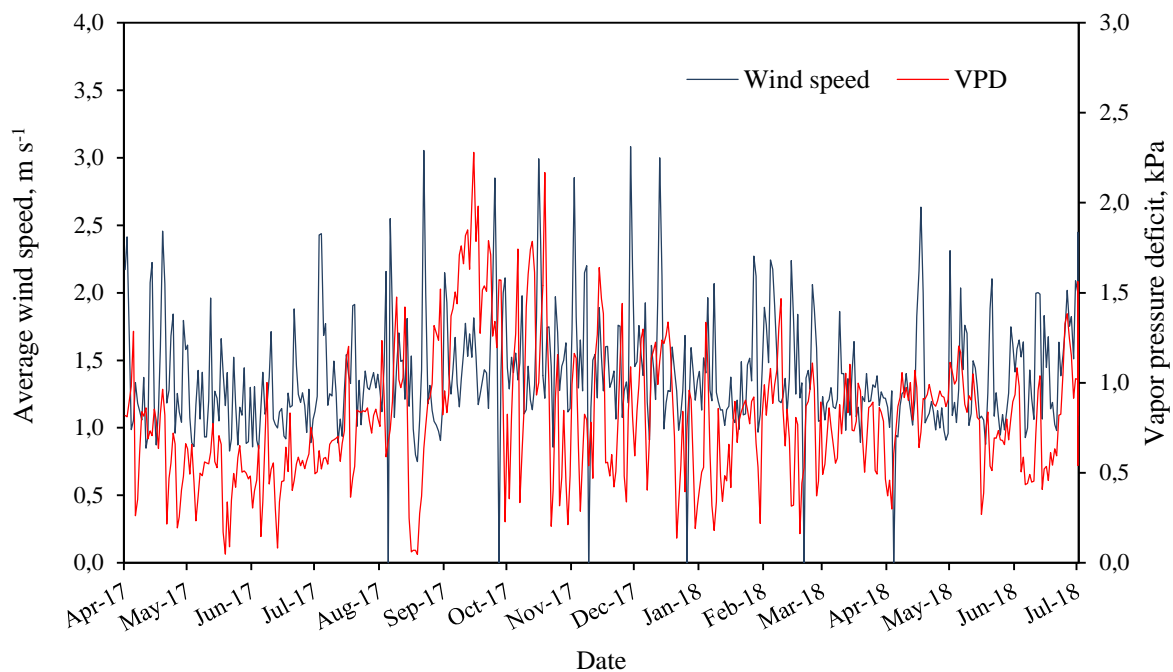


Figure 2.5 Daily average 2-m wind speed and vapor pressure deficit (*VPD*) between April 2017 and July 2018 at Piracicaba, Brazil.

Global (R_s) and net solar radiation (R_n) levels displayed larger variability along the time (Fig. 2.3). Average R_s was $17.1 \pm 5.9 \text{ MJ m}^{-2} \text{ d}^{-1}$, ranging from a low of $1.9 \text{ MJ m}^{-2} \text{ d}^{-1}$ in late winter 2017 (August) to a high of $31.4 \text{ MJ m}^{-2} \text{ d}^{-1}$ during the late spring 2017 (November). On the other hand, average R_n was $7.7 \pm 3.75 \text{ MJ m}^{-2} \text{ d}^{-1}$, so that the highest R_n ($16.6 \text{ MJ m}^{-2} \text{ d}^{-1}$) occurred in January 2018 in mid-summer, and the minimum R_n ($-1.0 \text{ MJ m}^{-2} \text{ d}^{-1}$) value was registered in mid-spring 2017 (October).

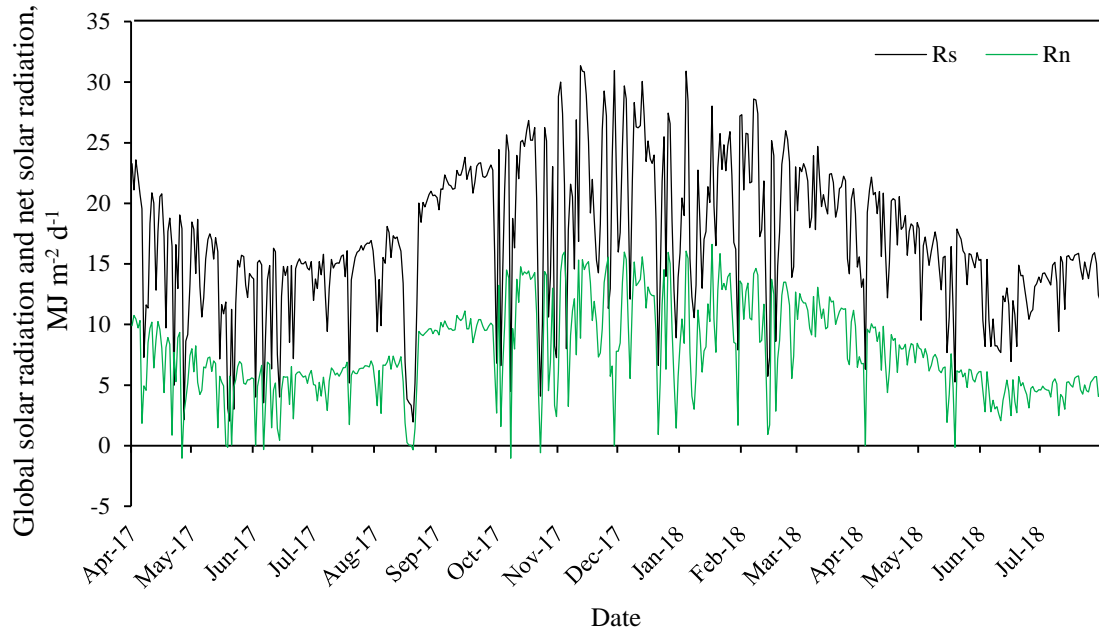


Figure 2.6 Daily global solar radiation (R_s) and net solar radiation (R_n) between April 2017 and July 2018 at Piracicaba, Brazil

2.3.2 Reference ET, actual crop ET (ET_a), and crop transpiration (T)

Table 2.2 shows reference evapotranspiration (ET_o) and actual crop evapotranspiration (ET_a) recorded in the studied period. The average daily ET_o ranged from $1.85 \pm 0.38 \text{ mm d}^{-1}$ in June 2017 to $4.52 \pm 1.38 \text{ mm d}^{-1}$ in November 2017. The highest ET_o value (5.86 mm d^{-1}) was recorded in November 2017 (late spring) while the lowest rate was registered (1.02 mm d^{-1}) in June 2018 (winter). ET_o totaled 1440.3 mm along the experimental time. Daily ET_a was lower than ET_o for all 16 months. Overall, ET_o and ET_a peaks occurred in high demand periods, corresponding to the months of late spring and throughout the summer, while the depressions in those parameters were observed during the colder and drier months. ET_a ranged from a minimum of 0.08 mm d^{-1} in August 2017 to a maximum of 7.54 mm d^{-1} during January 2018, so that average daily ET_a varied from $0.68 \pm 0.60 \text{ mm d}^{-1}$ at late winter to $4.2 \pm 1.85 \text{ mm d}^{-1}$ at the mid-summer. The whole-period ET_a and ET_o rates were $2.50 \pm 1.39 \text{ mm d}^{-1}$ and $3.37 \pm 1.18 \text{ mm d}^{-1}$.

Table 2.2 Maximum, minimum, and average daily reference evapotranspiration (ET_o) and oil palm actual evapotranspiration (ET_a) from April 2017 to July 2018. SD is the standard deviation.

Plant age (months)	Month	ET_o (mm d ⁻¹)			ET_a (mm d ⁻¹)		
		Max	Min	Ave ± SD	Max	Min	Ave ± SD
2017							
18	April	3.86	1.91	3.03 ± 0.77	3.64	0.69	1.75 ± 0.85
19	May	2.78	1.56	2.16 ± 0.38	2.90	0.60	2.07 ± 0.72
20	June	2.21	1.22	1.85 ± 0.38	1.90	0.33	1.05 ± 0.58
21	July	2.97	1.20	2.21 ± 0.40	2.10	0.53	1.28 ± 0.60
22	August	3.08	2.94	3.01 ± 0.10	1.27	0.08	0.68 ± 0.60
23	September	5.56	3.71	4.40 ± 0.48	4.27	1.43	2.65 ± 1.04
24	October	5.65	1.07	4.39 ± 1.64	6.33	1.71	3.51 ± 1.48
25	November	5.86	2.12	4.52 ± 1.38	6.72	1.61	3.42 ± 1.60
26	December	4.10	3.69	3.90 ± 0.29	5.00	1.97	3.48 ± 1.52
2018							
27	January	5.47	3.31	4.38 ± 0.86	7.54	1.78	4.20 ± 1.85
28	February	5.16	1.87	4.06 ± 0.96	5.94	1.57	3.27 ± 1.11
29	March	4.45	3.42	3.87 ± 0.35	4.92	1.92	3.66 ± 0.91
30	April	3.49	2.29	2.99 ± 0.47	4.36	1.01	2.83 ± 1.12
31	May	2.94	1.14	2.28 ± 0.43	4.17	0.65	1.71 ± 0.93
32	June	3.73	1.02	2.03 ± 1.18	1.61	0.30	1.00 ± 0.47
33	July	5.15	1.29	3.49 ± 1.09	3.58	0.69	1.98 ± 0.93

Average daily T (Table 2.3) ranged from 0.31 ± 0.05 mm d⁻¹ in August 2017 to 2.25 ± 1.40 mm d⁻¹ in January 2018 as observed for ET_a . Likewise, the highest T rate (5.71 mm d⁻¹) was registered in September 2017 during the transition between spring and summer. The seasonal variations in the observed transpiration rates (SD up to 1.09 mm d⁻¹) evidenced the dynamic characteristic of the transpiration process. Oil palm transpiration was very low (≈ 0.08 mm d⁻¹) in the winter months compared to other periods of the year. The average daily oil palm transpiration for all experimental period was 8.22 L tree⁻¹ d⁻¹ (1.43 ± 1.09 mm d⁻¹), oscillating between 1.58 to 13.30 L tree⁻¹ d⁻¹. In 2017, the seasonal transpiration for young oil palm trees was 3.58 L tree⁻¹ d⁻¹ in autumn, 6.94 L tree⁻¹ d⁻¹ during winter, and 9.78 L tree⁻¹ d⁻¹ in spring. In the following year, the transpiration rate was about 12.10 L tree⁻¹ d⁻¹ in the summer, decreasing to 8.18 L tree⁻¹ d⁻¹ in autumn, and reaching 11.78 L tree⁻¹ d⁻¹ in the winter.

Table 2.3 Canopy projection area, maximum, minimum, and average oil palm transpiration from April 2017 to July 2018. SD is the standard deviation.

from April 2017 to July 2018. SD is the standard deviation.						
Plant age (months)	Month	Canopy projection Area (m ²)	T (mm d ⁻¹)			T (L tree ⁻¹ d ⁻¹)
			Max	Min	Ave ± SD	
2017						
18	April	3.47	1.69	0.08	0.78 ± 0.56	2.70
19	May	3.82	2.12	0.08	1.10 ± 0.74	4.18
20	June	4.61	1.51	0.06	0.75 ± 0.57	3.38
21	July	4.98	2.29	1.60	1.93 ± 0.27	9.59
22	August	5.09	0.34	0.28	0.31 ± 0.05	1.58
23	September	5.29	5.71	0.17	1.78 ± 1.54	9.43
24	October	5.49	4.36	0.36	1.84 ± 1.35	10.07
25	November	5.61	4.25	0.02	1.34 ± 1.51	7.52
26	December	5.70	2.81	1.34	2.07 ± 1.04	11.82
2018						
27	January	5.91	4.51	0.23	2.25 ± 1.40	13.30
28	February	6.27	3.73	0.60	1.90 ± 0.92	11.92
29	March	6.80	3.82	0.17	1.72 ± 1.31	11.58
30	April	7.34	2.42	0.27	1.24 ± 0.80	9.05
31	May	7.97	3.60	0.09	1.05 ± 1.01	8.29
32	June	8.63	1.10	0.16	0.53 ± 0.41	4.61
33	July	9.15	2.74	0.01	1.37 ± 0.93	12.56

2.3.3 Single and dual crop coefficient

Table 2.4 presents the average ET_o , K_c and its components, and calculated water volumes to be applied via irrigation during the 16 months of study. The K_c values fluctuated from month to month, demonstrating difficulty in using a specific crop coefficient on a monthly scale for young palm oil plants. In addition, the values of K_c in months studied in both 2017 and 2018 (April, May, June, and July) were often not consistent from year to year.

The K_c values calculated as the ratio of the lysimeter measured ET_c and the ET_o ranged from 0.20 (July 2017) to 0.95 (May 2017), and the period average was 0.71. K_{cadj} ranged from a low of 0.02 in August 2017 to a high of 0.11 in April 2018. In general, average K_{cadj} was 0.08, accounting for 11.2% of the average K_c . Moreover, K_{cadj} values were lower at the first five months of the experiment due to a smaller canopy coverage. Average K_{cb} was 0.41, ranging from a minimum of 0.10 in the mid-winter 2017 (August) to a maximum of 0.75 in March 2018 (summer to autumn transition). In general, K_{cb} and K_e showed an opposite behavior over time, as that K_e decreased when K_{cb} increased. The highest K_e values occurred mainly after rainfall or in periods with frequent use of the drip irrigation system.

Water amounts to be applied by drip irrigation are shown in Table 2.4. Water volume calculated by $K_{cb}+K_e$ was higher than volumes calculated by K_{cadj} , K_c , and K_{cb} . Average

irrigation volumes for K_c , K_{cadj} , K_{cb} , and $K_{cb}+K_e$ during the 16 months of this experiment was 13.85 ± 6.57 , 16.29 ± 7.73 , 7.85 ± 3.68 , and 26.40 ± 12.30 L tree⁻¹ d⁻¹. Evidently, the highest water amounts were observed during the spring and summer, coinciding with the period of greater atmospheric demand.

Table 2.4 Reference evapotranspiration (ET_o), crop coefficient (K_c), adjusted crop coefficient (K_{cadj}) crop transpiration coefficient (K_{cb}), evaporation coefficients (K_{e1} and K_{e2}), and irrigation volume estimated for K_c , K_{cadj} , K_{cb} , and $K_{cb} + K_e$

Month/Year	ET_o	K_c	K_{cadj}	K_{cb}	K_{e1} ^a	K_{e2} ^b	Volumes to be applied (L tree ⁻¹ d ⁻¹)			
							K_c ^{c*}	K_{cadj} ^{d*}	K_{cb} ^{e*}	$K_{cb}+K_e$ ^{f, **}
Apr/2017	3.03	0.58	0.03	0.25	0.37	0.47	6.09	7.16	2.70	18.46
May/2017	2.16	0.95	0.06	0.49	0.40	0.49	7.87	9.25	4.18	16.58
Jun/2017	1.85	0.57	0.04	0.38	0.24	0.48	4.74	5.58	3.38	13.28
Jul/2017	2.21	0.20	0.04	0.39	0.40	0.14	6.39	7.52	4.95	11.18
Aug/2017	3.01	0.22	0.02	0.10	0.73	0.10	3.46	4.07	1.58	9.67
Sep/2017	4.40	0.60	0.05	0.41	0.73	0.17	13.99	16.46	9.43	24.46
Oct/2017	4.39	0.90	0.08	0.53	0.17	0.59	19.26	22.65	10.07	39.99
Nov/2017	4.52	0.77	0.07	0.27	0.10	0.85	19.18	22.57	7.52	46.19
Dec/2017	3.90	0.88	0.08	0.52	0.08	0.41	19.85	23.36	11.82	29.54
Jan/2018	4.38	0.93	0.09	0.53	0.07	0.73	24.75	29.12	13.30	47.15
Feb/2018	4.06	0.81	0.09	0.47	0.06	0.59	20.51	24.12	11.92	36.91
Mar/2018	3.87	0.52	0.06	0.42	0.50	0.70	14.69	17.28	18.49	42.57
Apr/2018	2.99	0.91	0.11	0.40	0.50	0.54	20.56	24.19	9.05	29.94
May/2018	2.28	0.74	0.10	0.45	0.70	0.31	13.51	15.89	8.29	18.87
Jun/2018	2.03	0.65	0.09	0.24	1.05	0.46	8.57	10.08	4.61	17.37
Jul/2018	3.49	0.61	0.09	0.43	0.42	0.13	18.17	21.37	12.56	20.30
Average	3.61	0.71	0.08	0.43	0.43	0.46	13.85	16.29	7.85	26.40

^a evaporation coefficient for the wetter area by the irrigation system ($A_w=2.2$ m²)

^b evaporation coefficient for dry area ($A_d=10.36$ m²)

^c $V = K_c \cdot ET_o \cdot A_c$;

^d $V = K_{cadj} \cdot ET_o \cdot A_i$;

^e $V = K_{cb} \cdot ET_o \cdot A_c$;

^f $V = (K_{cb} \cdot ET_o \cdot A_c) + (K_{e1} \cdot ET_o \cdot A_w) + (K_{e2} \cdot ET_o \cdot A_d)$;

* Alves Junior *et al.* (2007)

** Barboza Júnior (2007)

At is the total allocated area for each plant (70.2 m²); A_c is the canopy coverage area (m²); ET_o is the reference evapotranspiration; K_c is the crop coefficient; K_{cb} is the basal coefficient; K_{cadj} is the K_c adjusted by the ground coverage of the plant.

2.3.4 K_{cb} -LAI relationship

LAI measurements ranged from 1.19 to 2.98 from April 2017 to July 2018, displaying a constant increase over time. Likewise, the K_{cb} values determined presented a similar trend to the LAI increases. For these reasons, a good relationship between K_{cb} and LAI was found (Fig. 2.4), which was described by a linear function with R^2 of 0.9856. The K_{cb} - LAI relationship obtained for oil palm is $K_{cb} = 0.5895 LAI - 0.6674$.

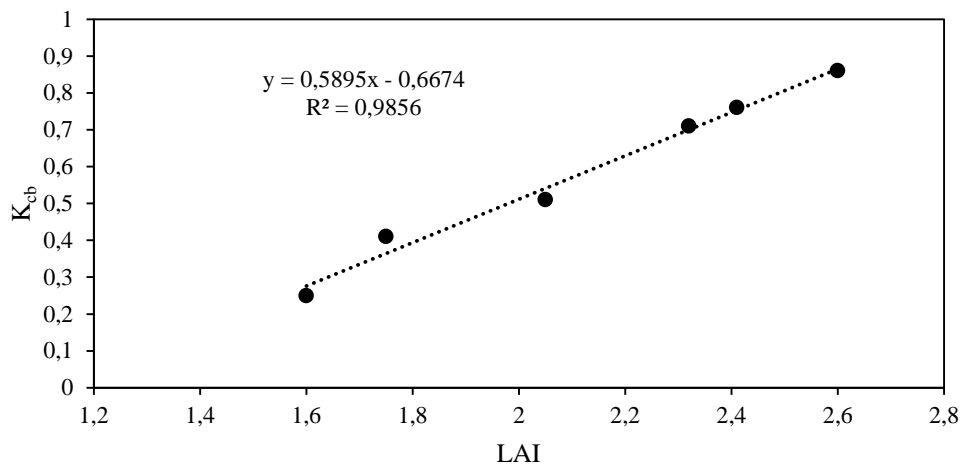


Figure 2.7 Relationship between lysimeter K_{cb} and the leaf area index (LAI) for oil palm.

2.4 Discussion

In South America, there are hardly any studies of oil palm water demands. Studies on the need and use of water by oil palm were carried out mostly in traditional areas of cultivation of this oilseed as Southeast Asia and West Africa. From their results, it was concluded that oil palm requires large amounts of water (average 6 mm d^{-1}) for satisfactory yields (Paramananthan, 2003; Carr, 2011). This value is greater than the average ET_a in all experimental period in this study (2.5 mm d^{-1}). Their value includes plants with various ages and cultivated under diverse weather and soil conditions. Given the scarcity of information about water requirements of oil palm trees by the third year (likewise to the present study), a direct and fair comparison between our findings and those results is hardly possible and not recommended. In order to discuss our findings properly with crops in comparable age conditions, an in-depth analysis of literature was done.

Similar to our results, Meijide *et al.* (2017) found an average ET_a of 2.5 mm d^{-1} ($K_c = 0.80$) for young oil palms (1-year-old) in Indonesia from eddy covariance measurements. Also, in Indonesia, evapotranspiration rates of 2.8 mm d^{-1} were derived from the eddy covariance technique for the 2-year old oil palms (Röll *et al.*, 2015). Henson and Harun (2005) reported average ET_a in 3-year-old oil palm trees of 1.3 mm d^{-1} ($K_c = 0.47$) and 3.6 mm d^{-1} ($K_c = 0.80$) in the Malaysian dry and wet seasons, respectively, which, in a seasonal basis, are close to those found herein.

On the other hand, Yusop *et al.* (2008) reported an average ET of 3.73 mm d^{-1} in a study carried out in Malaysia on a large-scale catchment water balance. Additionally, in an experiment using a drainage lysimeter to determine oil palm ET in Peninsular Malaysia,

Foong (1993) and Lee and Arifin (2013), determined daily ET values of 4.5 to 5.0 mm for immature oil palms. In particular, Lee and Arifin (2013) estimated values of 4.7 mm d⁻¹ in the first two years of measurements when plants were 4-5-years-old. Additionally, Antonini *et al.* (2015) reported ET_a values of 4.1 and 5.7 mm d⁻¹ in 7-year-old oil palm trees growing in the Brazilian Tropical Savanna. However, their values are different from those found in our study.

In this study, transpiration rates were much lower in the dry season. According to Kallarackal *et al.* (2004), one of the reasons for that is the atmospheric dryness which stimulates stomatal closure even with water available in the soil (see Fig. 2.1, 2.2, and 2.3). In India, these authors assessed the water use of irrigated oil palms 4-5-years-old and described transpiration rates ranging from 2.0 mm d⁻¹ (K_{cb} = 0.70) to 5.0 mm d⁻¹ (K_{cb} = 0.90). Bayona-Rodríguez and Romero (2016) estimated T rate of 1.15 mm d⁻¹ by the means of sap flow sensors on leaf petioles of 5-year-old oil palms in Colombia. Very low T rates (0.17 and 0.2 mm d⁻¹) have been described in Indonesia for 1- and 2-year-old oil palms (Röll *et al.*, 2015; Meijide *et al.*, 2017). Dufrêne *et al.* (1992) found transpiration rates ranging from 1.25 to 2.31 mm d⁻¹ for unirrigated plants in Ivory Coast. According to these authors, those little values were a consequence of the reduced size of the oil palms and corresponding leaf area and number.

Kallarackal *et al.* (2004) reported the water use from an oil palm tree to be between 140 and 385 L tree⁻¹ d⁻¹ in India, while Bayona-Rodríguez and Romero (2016) and Niu *et al.* (2015) estimated a water consumption of 80.5 and 77 L tree⁻¹ d⁻¹ in Colombia and Indonesia, respectively. When comparing their findings with the values found in the present study, we observed a clear difference in the amount of water required. This can be explained by the plant age which is directly related to the soil coverage of the soil by the canopy. In our study the oil palms were 2-3-years-old while in the abovementioned studies plant was between 4 and 12-years-old. Generally, the canopy cover is relatively small in the early years of cultivation, mainly with relatively large spaces such as the oil palm. Niu *et al.* (2015) point out that such differences may also be associated with the differences between transpiration and evapotranspiration since the latter encompasses effects of water flows from the palms and other vegetation such as epiphytes and weeds, as well as soil after events of rain and irrigation. For example, Röhl *et al.* (2015) reported that transpiration accounted for 8% of the evapotranspiration so that the majority of the water losses to atmosphere come from the evaporation of soil and water intercepted by the canopy of plants as well as the transpiration

of other plants. According to Schlesinger and Jasechko (2014), evaporative losses may also occur from the surface understory vegetation.

The K_c values of this study (Table 2.4) were about 10-fold higher than K_{cadj} due to the large spacing of the crop (70.2 m^2) compared to the canopy cover. K_{cadj} values will only be valid to be used in localized irrigation since in the determination of the K_{cadj} the ground cover (GC) was considered for the correction of K_c values (Campeche, 2002; Silva, 2005). The adjustment of K_c is an important aspect to be taken into account regarding the rational use of water resources. The use of this adjustment can provide a water savings because of additional consideration of the flow of water to the atmosphere from soil outside the crop-shaded area and wetting area of the irrigation system. Amount of water calculated by $K_{cb} + K_e$ was about 90% higher compared to the traditional crop coefficient (K_c) as a result of the high soil evaporation after irrigation and rainfall. Alves Junior *et al.* (2007) found irrigation volumes from $K_{cb} + K_e$ about 60% higher than K_c in young citrus trees in the same site and also attributed this discrepancy to the high soil evaporation rates in the wetted area by the irrigation system below the canopy (Alves Junior *et al.*, 2007). The results suggest that the individual contribution of soil evaporation and transpiration should be considered in determining the drip irrigation rates of trees. A lower water use found in this study by using K_{cb} indicates that soil has a great contribution on total water requirements of sparse crops once this amount includes transpiration of the palm and low evaporation rate under the canopy.

In addition to the reasons presented here for divergences between the values of water use and crop coefficient reported by several authors in literature, other differences arise due to different terminologies and abbreviations along with the absence of clear information about which version of Penman equation is used to determine ET_o (Carr, 2011). So, the use of crop coefficient-LAI (or crop coefficient-GC) relationships can provide additional information on the crop water consumption in a given climate (Lena, 2016). Besides, using only the crop coefficient (K_c or K_{cb}) to manage irrigation is questionable (Cerekovic *et al.* 2010; Majnooni-Heris *et al.* 2012). The strong relation between K_{cb} and LAI found in this work ($R^2=0.9856$) was superior to other studies. Lena (2016) determined a K_c -LAI relationship for *Jatropha* irrigated by a center pivot ($R^2=0.79$) and drip ($R^2=0.87$) in the same site of our study. Cerekovic *et al.* (2010) observed a K_c -LAI relationship for tomato in Italy described by a logarithmic equation ($R^2=0.83$). Likewise, a logarithmic equation defined a good K_c -LAI relationship ($R^2=0.88$) for canola irrigated in Iran (Majnooni-Heris *et al.*, 2012).

Despite of extensive existing research on the retrieval of crop coefficient-*LAI* relationships, we did not find any study that provides that information for oil palm. Thus, by comparing our results with those available in the literature for other crops, the K_{cb} -*LAI* relationship developed herein can be useful to estimate oil palm water requirement from *LAI* measurements.

2.5 Conclusions

In this study, we aimed to determine the water requirement of young oil palms under the Brazilian Humid Subtropical conditions. The main results indicated that the highest ET_a rates occurred in the months of late spring and throughout the summer, coinciding with the period of higher atmospheric demand. The analysis of lysimetric measurements showed that oil palm ET_a and T were $2.50 \pm 1.39 \text{ mm d}^{-1}$ and $1.43 \pm 1.09 \text{ mm d}^{-1}$, respectively. The corresponding K_c and K_{cb} were 0.71 and 0.41, respectively. Average K_{cadj} for all period was 0.08 and it is recommended only to be used for drip irrigation once it is a result of an adjustment that depends on GC and spacing of the crop. Furthermore, the results obtained herein indicate that the individual contribution of soil evaporation and transpiration should be considered in determining the drip irrigation rates in sparse crops in order to use water resources rationally in the agricultural production systems.

The K_{cb} values obtained from the lysimeter and its relationship with *LAI* was studied, providing a good fit represented by a linear function which facilitates the determination of water requirements of the oil palm under different environmental conditions from the present study.

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3 SATELLITE-BASED EVAPOTRANSPIRATION ESTIMATE FOR OIL PALM IN THE EASTERN BRAZILIAN AMAZON

Abstract

Oil palm is a perennial crop that presents great productive potential and lower production costs compared to other oilseeds. The increase in world demand for vegetable oils has contributed to the rapid expansion of this crop into equatorial regions. But there is a relatively few and contrasting information on actual water use of oil palm plantations, as well as the minimal amounts that guarantee good yields. In the present study, a remote-sensing-based ET and water balance model was performed over an 8-year consecutive period in a commercial oil palm plantation near Moju, Pará, Brazil. The use of the water balance model aimed to determine the spatiotemporal variation of oil palm evapotranspiration from adjusted satellite images, as well as the adjusted crop coefficient (K_{cadj}) and its components under Amazon climate conditions. We additionally estimated oil palm productivity based on the normalization of water productivity. As model input, we used Landsat 5, 7, and 8 imagery along with crop cover data and local soil and meteorological information. The multi-year average of daily and total ET_a was about $3.4 \pm 0.4 \text{ mm d}^{-1}$ and $1229 \pm 127.2 \text{ mm yr}^{-1}$. Seasonally, the oil palm water uses were $4.08 \pm 1.03 \text{ mm d}^{-1}$ ($864.4 \pm 80.91 \text{ mm}$) and $2.38 \pm 1.66 \text{ mm d}^{-1}$ ($364.7 \pm 88.94 \text{ mm}$) in the wet season and dry season, respectively. The seasonal difference can be explained by factors like the current soil water content, distribution of the root system, dynamics of rainfall in the region, soil hydraulic properties, and weather conditions, which contribute to the frequency of water stress. Irrigation can be vital to overcome the seasonal water deficit, as long as its use is economically feasible. In an annual average basis, K_{cadj} was 0.87 ± 0.42 , K_{cb} for the two first growing years was 0.78 ± 0.29 , reaching an average of 1.16 ± 0.04 from the third cropping year. Additionally, we found a good agreement ($d = 0.9801$) between *in situ* measured and modeled oil palm yields. The correlation was described by a linear function [$Yield_{mod} = 0.7626(Yield_{meas}) + 538.64$; $R^2 = 0.9913$], pointing to the possibility of using remote sensing data in a functional way for estimating oil palm productivity. The results presented here are the first insights into oil palm water requirements in the Amazon region using remote sensing data and paves the way to future research in order to increase our understanding of water flows in palm oil plantations in equatorial regions.

Keywords: *Elaeis guineensis* Jacq.; Remote sensing; Crop coefficient; Soil water balance

3.1 Introduction

The oil palm (*Elaeis guineensis* Jacq.) is a perennial monocotyledon belonging to the family *Arecaceae* that presents great productive potential and lower production costs compared to other oilseeds (Pádua, 2012; Zimmer, 2010). Originally from the west coast of Africa, the oil palm begins to produce fruits from the third year after planting and can last up to 30 years (Kuss *et al.*, 2015). However, in order to reach its productive potential, some edaphoclimatic conditions, such as sunshine and precipitation requirements, are necessary.

Two types of oils with different properties are extracted from the fruits: palm oil (extracted from the fruit) and palm kernel oil (extracted from the almond) (Corley and Tinker, 2003). Because of that, oil palm can play a fundamental role in supplying the world demand for vegetable oil in the future, since, among the oilseeds, it has the highest oil production per unit area (Corley, 2009; Lody, 2009). Moreover, the increased demand for vegetable oils has supported the expansion of oil palm plantations, making this crop also one of the fastest growing equatorial crops in the world (FAO, 2012; Fudholi *et al.*, 2015). Due to the increasing global demand and the insufficiency of land available for cultivation in traditional regions, governments in emerging countries such as Brazil point to the cultivation of oil palm as one of the main factors in reducing poverty and food and energy independence (Kongsager and Reenberg, 2012; Villela *et al.*, 2014).

In Brazil, the producing regions are concentrated in the North Region and the South Coast of Bahia State (Carioca *et al.*, 2009; Teles *et al.*, 2016). The Northern Region encompasses the Legal Amazon, which presents climatic and soil conditions that promote the cultivation of the oil palm obtaining high yields (La Rovere *et al.*, 2011; César *et al.*, 2013). In the Amazon Region, more than 90% of the 32 million hectares of deforested areas are located, capable of expanding the oil palm culture according to the Agro-Ecological Zoning of Oil Palm in Deforested Areas of the Amazon (ZAE-Palma) (Ramalho *et al.*, 2010). Moreover, over 90% of the national production occurs in the state of Pará, the second largest Brazilian state, which has 160000 hectares cultivated and perspectives expansion of 330000 hectares until the year 2020 (USDA, 2011; Glass, 2013). In addition to that, participation of Brazil in the world production of palm oil is about 0.6% (MAPA, 2013), which can increase in the next years with the expansion of the planted areas as well as the application of techniques that contribute to the increase of productivity. The increase in the production of palm oil crops in the Brazilian Amazon could contribute to the reduction of prices of palm oil, increasing competition with producing regions in southeastern Asia and consequently reducing pressure for increased deforestation in native forests that are targeted in the process of crop expansion.

Irrigation could be an important tool within this process of expansion and intensification of palm cultivation due to the prospects generated from the results of experiments with irrigated palm in the world and in non-traditional palm cultivation centers in Brazil. However, the information in the literature on the water requirement by the oil palm in the climate and soil conditions of the Amazon region are scarce. Moreover, little is known about the actual water use of oil palm and field conditions, as well as the minimal amounts

that guarantee good yields (Carr, 2011) and economic viability. Oil palm is claimed to require an average of 6 mm d^{-1} (Corley and Tinker, 2003; Paramanathan, 2003) from measurements done under variability of conditions, poor experimental design and lack of complete monitoring of soil and atmospheric conditions (Henson, 2006).

For adequate irrigation management and savings of water, precise crop evapotranspiration (ET_c) must be determined accurately, once it is the main component in the calculation of crop irrigation needs. The methodology proposed by Allen *et al.* (1998) for ET_c estimation by using reference evapotranspiration (ET_o) and a crop coefficient (K_c) is widely accepted ($ET_c = K_c \cdot ET_o$). In addition, the estimation of a dual crop coefficient, that includes a transpiration or basal crop coefficient (K_{cb}) (Wright, 1982) and soil evaporation coefficient (K_e), and a stress coefficient for soil water limiting conditions in the root zone (K_s) instead of a single K_c may be considered to achieve superior accuracy. K_s ranges from 0 to 1, where the highest value means no water stress in the root zone. In this sense, actual evapotranspiration (ET_a) is obtained by considering variations in transpiration due to the K_s or increases in soil evaporation caused by irrigation or rain. Thereby ET_a is calculated as: $ET_a = (K_s \cdot K_{cb} + K_e) \cdot ET_o$. Hereafter, any mention of evapotranspiration modeled by remote sensing methods refers to actual evapotranspiration (ET_a), which integrates transpiration of the crop, soil evaporation and the possible effects of water stress.

Conversely, the use of fixed K_c values is not recommended for tree crops like oil palm since K_c can vary seasonally as well as by factors such as the age of cultivation, phenological stage, agronomic practices, and variety. So, the use of relationships between crop coefficient and the vegetation indices (VI) based on surface reflectance are possible alternatives for empirical determination of K_c considering all the above-mentioned factors. Several reflectance-based crop coefficients for many crops are available in the literature (Bausch and Neale, 1987; Choudhury *et al.*, 1994; Duchemin *et al.*, 2006; Mateos *et al.*, 2013; Johnson *et al.*, 2014; Campos *et al.*, 2016; Campos *et al.*, 2017), most of them using normalized difference vegetation index (NDVI) (Rouse *et al.*, 1973) and the soil adjusted vegetation index (SAVI) (Huete, 1988). Reflectance-based crop coefficient approach ($K_{cb_{rf}}$) uses remote sensing data (shortwave reflectance imagery) to obtain NDVI or SAVI, which are related to the K_{cb} by means a linear transformation. In the $K_{cb_{rf}}$ approach, satellite images are used as inputs to track crop growth throughout the crop cycle through vegetation indices used to obtain the $K_{cb_{rf}}$ in real time, which in turn are used to adjust the K_{cb} corresponding to the actual growth conditions (Neale *et al.* 1989; Bausch, 1993; Neale *et al.*, 2012).

Remotely sensed data have been applied to estimate ET_a spatiotemporally to annual (Hunsaker *et al.*, 2005; Jayanthi *et al.*, 2007; González-Dugo and Mateos, 2008; Barker *et al.*, 2018a) and perennial crops (Samani *et al.*, 2009; Campos *et al.*, 2010; Odi-Lara *et al.*, 2016). In the last few years, satellite remote sensing has been used to observe land cover and estimate ET of the crops with an appropriate spatial and temporal resolution by monitoring biophysical parameters of the crops. The use of remote sensing data into soil water balance models has become common currently (Neale *et al.*, 2012; Campos *et al.*, 2016; Barker *et al.*, 2018a; Barker *et al.*, 2018b) and some results indicate that this method has the potential to estimate crop water requirements and water management over large agricultural areas (Consoli and Vanella, 2014).

Finally, given oil palms are usually cultivated in large monocultural systems with homogeneous stands of varying ages and likely heterogenous water requirements, the use of remote sensing-based ET models, specifically K_{cbf} -based water balance method, is an important tool to improve our understanding of the oil palm water use in Eastern Brazilian Amazon. Therefore, the objective of this work is to: (i) determine the spatiotemporal variation of oil palm evapotranspiration from adjusted satellite images; (ii) determine the adjusted crop coefficient (K_{cadj}) and its components; (iii) estimate oil palm productivity based on the normalization of water productivity.

3.2 Material and Methods

3.2.1 Study site

The study was carried out from January 2010 to July 2018 in a 19.05 ha plot of oil palm trees in a commercial orchard belonging to Biopalma/Vale company located near Moju, Pará (2.2°S, 48.8°W). Oil palm trees (*Elaeis guineensis* Jacq.) variety Compact x Ghana were planted in December 2009 at a 170 trees/ha density planting in a Grey Oxisoil with flat topography (< 0.5%). The soil texture is sandy loam at the first 10 cm (12% clay, 6% silt, 82% sand), sandy clay loam from 10 to 28 cm (30.5% clay, 8% silt, 61.5 sand), and sandy clay at depths greater than 30 cm (40.7% clay, 6% silt, 53.2% sand). According to Köppen's climate classification, the climate in the area is Tropical rainforest (Af) characterized by rains well distributed throughout the year. Precipitation ranges 2500–3000 mm yr⁻¹ with the driest period occurring between July and December, which has rainfall above 60 mm (SUDAM, 1984; Martorano *et al.*, 2017). Mean temperature is 26 °C ± 3 °C (Benami *et al.*, 2018) and

relative air humidity is between 80-85% yearly, associated to the rainfall regime (Martorano *et al.*, 1993).



Figure 3.1 Study site in Moju, Pará.

Fonte: Google Earth Pro

3.2.2 Water Balance Model and Evapotranspiration Estimate

The K_{cbrf} -based water calculations were computed using a version of the “*Spatial EvapoTranspiration Modelling Interface*” (SETMI) (Geli and Neale, 2012), which operates as a tool within ESRI ArcGIS 10.4 (Esri, Redlands, CA). Crop coefficients were obtained from reflectance data using a linear SAVI-to- K_{cbrf} relationship ($K_{cbrf} = 1.97SAVI - 0.1$) developed for corn and provided by I. Zution Gonçalves (personal communication, October 22, 2018) for short reference evapotranspiration. This relationship was used because we could not obtain evapotranspiration data of oil palm measured in the field. The interpolation method (Campos *et al.*, 2017) was used to determine daily K_{cb} values between existing points, although this interpolation might underestimate and overestimates the actual values for convex and concave tendencies respectively (Campos *et al.*, 2017).

A daily step time scale was applied by the model to determine ET_a computing effective rainfall and non-irrigation method. Thus, the model was performed to estimate gross irrigation requirements by the crop. As the model is based on the FAO-56 manual (Allen *et al.*, 1998), the water depletion in the root zone was used as a threshold to initiate counting the need for irrigation, which is completed by the end of the calculation day, based on achieving the input target depth above management allowable depletion (MAD).

A summary of all model parameterizations used in *SETMI* is presented in Table 3.1. These data were used to calculate the fraction of cover (f_c) following the FAO-56 manual, using the basal crop coefficient as well as to compute stress temperature that compromises the crop growth rates and biomass production. Calculation for f_c followed the steps and values described by Barker *et al.* (2018a).

Table 3.1 Parametrization used in the cover tab of the *SETMI*.

Input	Symbol	Value and unit
Maximum crop height	$h_{c \max}$	5.6 m ^a
Minimum crop height	$h_{c \min}$	0.9 m ^a
Curve Number	CN	80 ^b
Growing Degree Days Base Temperature	GDD _{base}	15 °C ^c
Base temperature stress	$T_{\text{base st}}$	18 °C ^d
Upper limit temperature stress	$T_{\text{upper st}}$	33 °C ^c
Weight for depletion	D_f	1.0 ^f
Weight for evaporated depth	D_e	1.0 ^f
Weight for lower soil layer volumetric water content	θ_{vL}	1.0 ^f
Weight for skin evaporated depth	D_{REW}	1.0 ^g
Maximum crop coefficient	$K_{c \max}$	1.2 ^h
Management allowable depletion	MAD	40% ⁱ

^a provided by Biopalma/Vale company from *in situ* measurements

^b USDA-NRCS (2004)

^c Corley and Tinker (2016)

^d Ramalho Filho *et al.* (2010)

^f Default value in *SETMI*

^g Jensen and Allen (2016)

^h Allen *et al.* (1998)

ⁱ User choice

3.2.3 Satellite Imagery

Imagery from Landsat 5 Thematic Mapper (L5-TM), Landsat 7 Enhanced Thematic Mapper Plus (L7-ETM+), and Landsat 8 Operational Land Imager (L8-OLI) was obtained from the U.S. Geological Survey for a total of 53 cloud-free images over the study area from January 2010 to December 2017 (Fig. 3.2). Specifically, we used 6 images from L5-TM, 12 L7-ETM+ images, and 35 images from L8-OLI. Northeastern Pará has relatively few cloud-free images for most of the dates throughout the year (especially from December to June) due to coincidence with the region's wet season when days with cloud coverage are much more frequent. However, the study field was in an overlap zone for Landsat images (Path-Row 223-61, 223-62, 224-61, and 224-62) which increased the frequency of satellite overpasses. Although Landsat Images 7 typically fail to cover all plots of interest in a single image, the 2012 and early 2013 images provided by this satellite were used in order to avoid a soil cover information gap once that Landsat 7 was the only satellite operating by that time.

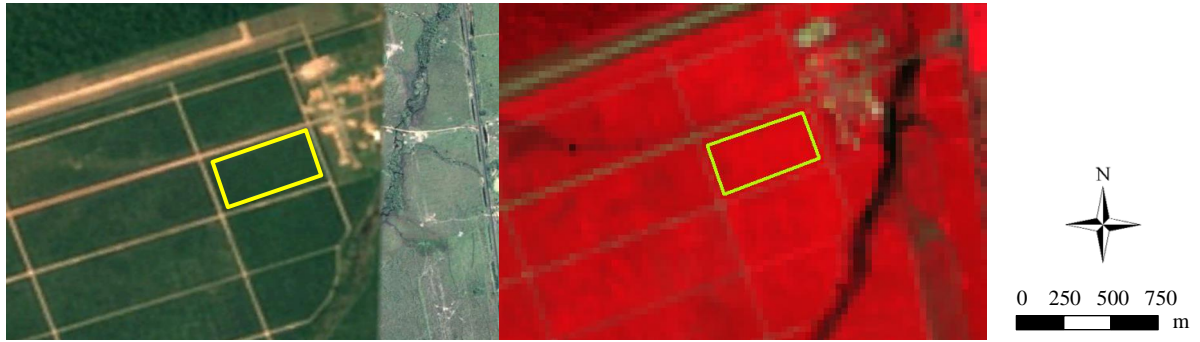


Figure 3.2 Study area real map and Landsat 8 false color surface reflectance image background.

3.2.4 Soil Water Balance Parameters and Coverage Properties

Some soil properties are required by *SETMI* in order to complete the water balance. The parameters and values used in the soil water balance to the root soil layer and soil moisture were field capacity (θ_{FC}), permanent wilting point (θ_{WP}), saturated hydraulic conductivity (K_{sat}), initial profile average volumetric water content (θ_{vini}), and saturated volumetric water content (θ_{vsat}) images as model inputs. The soil properties were estimated from the relative proportions of sand, silt, and clay in the soil by means HYDRUS-1D (Šimůnek *et al.*, 2005) and the values are presented in Table 3.2. As the field soil has a physically heterogeneous profile, we used three soil layers as an input into *SETMI*. θ_{vini} value inputs can be limited to be between θ_{FC} and θ_{WP} , but in this study, we have considered θ_{vini} as the same θ_{FC} values.

Other parameters required in the soil water balance based on FAO-56 methodology were used. Regarding surface soil parameters, evaporation layer (Z_e) was considered 0.05 m, total evaporable water (TEW) is 20.4 mm, and readily evaporable water is 3.8 mm. In the root zone level, we have taken into account a soil depletion fraction without stress (p) of 0.55, maximum effective root depth at 1.0 m, and an effective root depth during the initial growth stage of 0.1 m. The average water availability for this soil is about 175.65 mm m^{-1} .

Table 3.2 Parameters used in the soil water balance based on the FAO-56 methodology.

Soil Depth (m)	θ_{FC}	θ_{WP}	θ_{vini}	θ_{vsat}	K_{sat} (mm d ⁻¹)
	----- (mm m ⁻¹) -----				
0-0.1	202.22	60.65	202.22	416.3	1275
0.1-0.28	327.85	129.24	327.85	430.7	284.5
0.28-1.0+	353.40	166.64	353.40	441.8	206.2

3.2.5 Meteorological Data

SETMI requires daily weather data to run the water balance. As there was no weather station located at the study site, we have used meteorological information from the five closest weather stations to the oil palm plot. So, data from weather stations of the Belém/PA (1.41°S, 48.44°W), Castanhal/PA (1.31°S, 47.92°W), Tomé Açu/PA (2.4°, 48.15°W), Cametá/PA (2.23°S, 49.49°W) municipalities were provided by the National Institute of Meteorology (INMET). Moreover, data collected from a weather station that operates at an Agropalma Company's facility in Tailândia/PA were used. Meteorological variables included maximum and minimum air temperatures (T_{max} and T_{min}), dew point temperature (T_{dew}), solar radiation (R_s), wind speed (U_2) and relative humidity (RH). The average values were obtained by means the inverse distance methodology. Precipitation data were collected from a rain gauge installed near the perimeter of the study site.

Reference evapotranspiration (ET_o) was calculated using the Penman-Monteith equation (Allen *et al.*, 1998). Daily ET_o , precipitation, and T_{max} and T_{min} were used in the *SETMI*'s weather input tab for the water balance calculation.

3.2.6 Crop water productivity

The terms “Crop Water Productivity” and “Water Use Efficiency” are usually used to express production per unit of water used. Herein, we calculated those indices by using two different approaches. The first one, defined in this paper as crop water productivity (CWP), was determined according to Perry *et al.* (2009) and basically is the ratio of the output of crops per ET (m³). For this study, CWP was calculated at a fresh fruit bunch (FFB) basis from yield data provided by Biopalma/Vale Company.

The second methodology is the normalized water use efficiency (WUE_B^* , in t ha⁻¹), an innovative concept that considers the dependence of the water use efficiency on atmospheric conditions and necessity to standardize it for atmospheric demand and CO₂ concentration (Tanner and Sinclair, 1983). WUE_B^* is an improvement described in FAO-66 manual (Steduto

et al, 2012) and included in the AQUACROP model that takes into account the basal crop coefficient adjusted ($K_{cb, adj}$) for both water (K_{sw}) and temperature stresses (K_{st}), which is resultant of normalization of ET_{adj} by ET_o . WUE_B^* is calculated by Eq. 1, which is a linear relationship between biomass produced on a ground area basis and the sum of the ratio between crop transpiration considering the occurrence of water stress (T_{adj} , mm) and ET_o (mm). Further details about the use of remote sensing to estimate crop water productivity and crop yield can be found in Campos *et al.* (2018a)

$$WUE_B^* = \frac{Biomass}{\sum_{l=n}^n \frac{T_{adj}}{ET_o}} = \frac{Biomass}{\sum_{l=n}^n K_{cb,adj}} = \frac{Biomass}{\sum_{l=n}^n K_{cb} \cdot K_{sw} \cdot K_{st}} \quad (1)$$

$\sum K_{cb} \cdot K_{sw} \cdot K_{st}$ is an output provided by *SETMI* on daily basis, which is the best time step to generate factors affecting the biomass production according to FAO-66. However, we performed an annual scale analysis since oil palm is a perennial crop and the accurate computation of some biomass component (leaves, trunks, and roots) is difficult. In commercial plantations like this study, only *FFB* (and sometimes leaves) are computed, which makes it difficult to determine a reliable harvest index (*HI*) once there is no information about overall biomass production per individual. *HI* is the proportion of biomass that makes up the parts of plant interest over total biomass. Thus, in this paper, we used the information of leaves and *FFB* biomass production collected in the study site and means trunk and root biomass production available in Corley *et al.* (1971) for oil palm trees cultivated under similar conditions. Crop yield on a ground basis was estimated from Eq. 2. We considered an *HI* of 0.46 (Wahid *et al.*, 2005).

$$Yield = HI \cdot WUE_B^* \cdot \sum_{i=n}^n K_{cb} \cdot K_{sw} \cdot K_{st} \quad (2)$$

3.3 Results

3.3.1 Meteorological summary

Table 3.3 summarizes the meteorological conditions in the study site between 2010 and 2017. Records from the five-weather stations used in this study show that all meteorological conditions were close to the typical long-term average weather of the

Northeastern Pará. Annual average temperature, T_{ave} , (27.8 ± 0.8 °C) was about 1.8 °C more than the historical mean temperature (26 °C), ranging from 27.6 to 28.1 °C, which is within the temperature range recommended for oil palm (Ramalho Filho *et al.*, 2010). Average relative humidity (RH), solar radiation (R_s) and wind speed (U_2) were $74.2 \pm 5.1\%$, 17.4 ± 2.8 MJ m⁻² d⁻¹, and 1.2 ± 0.3 m s⁻¹. As shown in Table 3.3, the recorded precipitations (P_p) was greater than 1500 mm yr⁻¹, so that 2015 registered the lowest accumulated P_p (1644.1 mm), which is 34.2% lower than the annual average (2448 mm). 2011 had the highest annual P_p , which accounted for 3561 mm, representing over 42% of the annual precipitation mean.

Table 3.3 Summary of average meteorological variables during the period 2010-2017 in Moju, Pará, Brazil.

Year	$T_{max} \pm SD$ (°C)	$T_{min} \pm SD$ (°C)	$T_{ave} \pm SD$ (°C)	$T_{dew} \pm SD$ (°C)	$RH \pm SD$ (%)	$R_s \pm SD$ (MJ m ⁻² d ⁻¹)	$U_2 \pm SD$ (m s ⁻¹)	P_p (mm)
2010	32.6 ± 1.2	23.4 ± 0.7	28.0 ± 0.7	22.9 ± 0.7	78.9 ± 5.0	18.0 ± 2.9	1.2 ± 0.3	2313.5
2011	31.9 ± 1.4	23.3 ± 0.7	27.6 ± 0.8	22.7 ± 0.5	74.9 ± 3.6	18.0 ± 3.0	1.3 ± 0.4	3561.0
2012	32.1 ± 1.3	23.0 ± 0.6	27.6 ± 0.8	22.3 ± 0.6	73.0 ± 4.0	17.5 ± 2.5	1.3 ± 0.3	2897.8
2013	32.0 ± 1.1	23.4 ± 0.6	27.7 ± 0.6	22.7 ± 0.5	76.0 ± 3.8	17.5 ± 2.7	1.2 ± 0.3	2059.4
2014	32.1 ± 1.4	23.3 ± 0.6	27.7 ± 0.7	22.5 ± 0.6	74.6 ± 4.9	17.2 ± 2.7	1.3 ± 0.3	1972.7
2015	32.5 ± 1.5	23.5 ± 0.7	28.0 ± 0.9	22.5 ± 0.7	73.3 ± 5.0	16.3 ± 2.8	1.3 ± 0.5	1644.1
2016	32.5 ± 1.2	23.7 ± 0.7	28.1 ± 0.7	22.2 ± 1.0	70.7 ± 4.5	17.1 ± 2.5	1.2 ± 0.3	2497.9
2017	32.5 ± 1.7	23.4 ± 0.6	28.0 ± 0.9	21.9 ± 1.1	72.5 ± 5.1	17.6 ± 3.1	1.1 ± 0.4	2643.3

T_{max} : maximum temperature; T_{min} : minimum temperature; T_{dew} : dew point temperature; RH : relative humidity; R_s : global solar radiation; U_2 : 2-m wind speed; P_p : precipitation; SD: standard deviation.

3.3.2 Reference ET and spatiotemporal distribution of actual crop ET

Daily reference evapotranspiration (ET_o) and actual crop evapotranspiration (ET_a) are presented in Fig. 3.1A. ET_o had a well-defined pattern through the time reaching maximum values (≈ 6 mm d⁻¹) in the less rainy periods of the years, and it gradually decrease to minimum values (≈ 1.5 mm d⁻¹) toward the rainy months, when there were days with higher cloud cover and consequent lower radiation rates, respectively. A clear ET_a fluctuation over the years is apparent in Fig. 3.1A, with values close to zero in some days during the dry season as well as ET_a rates greater than 6 mm d⁻¹ in the wet season. Both ET_o and ET_a presented a tendency that is repeated over the years; however, we observe divergent progress between them, starting from the less rainy period to the beginning of the wet season. Notably, ET_a values varied markedly depending on the current water regime. This means that some stress factor may be influencing plant water consumption. Thus, out of 2922 days analyzed, about 56% of them were under water stress ($K_s < 1$). K_s values lower than 0.1 were reached especially after a period greater than ten days without rain. However, those values increased right after a minimum rainfall of 20 mm, reducing the effect of water stress on ET_a .

Soil water content (*SWC*) modeling has been plotted over time and can be seen in Fig. 3.1B. Water content average in the soil profile ranged from 0.158 to 0.313 m³ m⁻³ in the juvenile stage of the plants (2010, 2011, and 2012). From the fourth year until the end of the analyzed period, *SWC* in the soil profile was between 0.136 and 0.332 m³ m⁻³. *SWC* changed according to the plant water requirements, as observed in days after rainfall. In general, *ET_a* and *SWC* had similar patterns throughout the time, where the highest and lowest *ET_a* rates were registered each year when *SWC* reached maximum and minimum values, respectively (Fig. 3.1A). Conversely, we observed that *ET_o* curve followed the same trends as the *VPD* curve (Fig. 3.2B), although the highest values were registered in less rainy periods which coincided with peaks of *Rs* and *Rn* (data not shown) (Christoffersen *et al.*, 2014). Fig. 3.2B shows that in this region, which is categorized in the tropical rainforest zone, *VPD* values did not vary significantly over time, with an average of 0.99 ± 0.21 kPa.

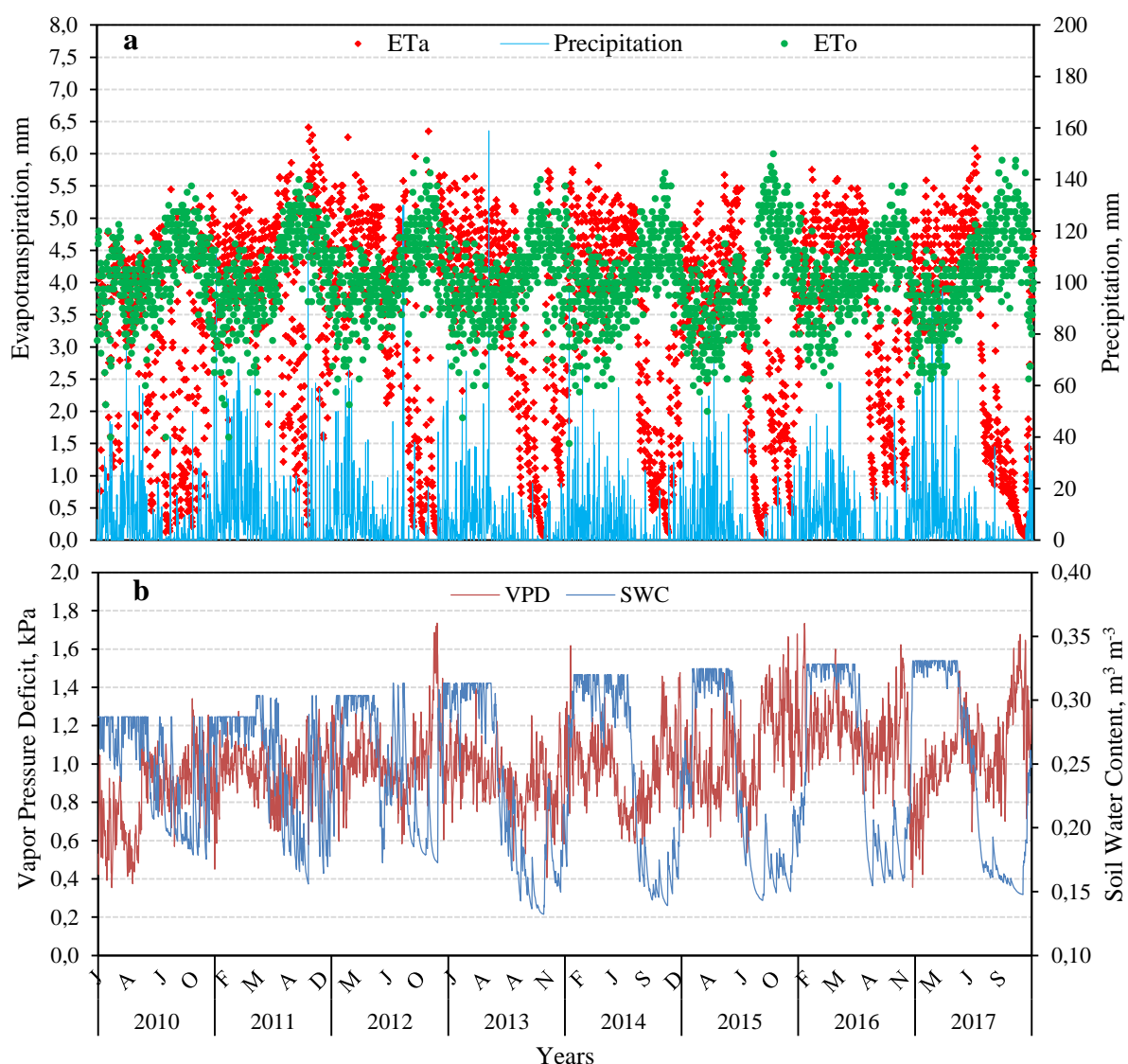


Figure 3.3 Time series fluctuation of a) daily actual evapotranspiration (ET_a), reference evapotranspiration (ET_o), and precipitation and b) diurnal vapor pressure deficit (VPD) and soil water content (SWC) from 2010 to 2017 in Moju, Pará, Brazil.

Table 3.4 summarizes ET_a , ET_o , crop transpiration (T) and soil evaporation rates (E) during the years studied. In all years, average ET_a was greater than 3.32 mm d^{-1} in the wet season, the value obtained in the first crop year. In the dry season, the maximum average ET_a value ($2.60 \pm 1.19 \text{ mm d}^{-1}$) was registered in 2016 (7th crop year), whereas the lowest mean ($1.61 \pm 1.41 \text{ mm d}^{-1}$) was found in the following year. Total crop evapotranspiration water consumed yearly from 2010 to 2017 was 1040, 1434, 1329, 1223, 1237, 1098, 1348, and 1125 mm yr^{-1} (Table 3.4). The corresponding daily average ET_a rates were 2.89, 3.93, 3.63, 3.35, 3.39, 3.01, 3.68, and 3.08 mm d^{-1} . Seasonally, the total average ET_a was $864.4 \pm 80.91 \text{ mm}$ ($4.08 \pm 1.03 \text{ mm d}^{-1}$) in the wet season and $364.7 \pm 88.94 \text{ mm}$ ($2.38 \pm 1.66 \text{ mm d}^{-1}$) in the dry

season. On the contrary, the average ET_o values were higher in the dry season comparing to the wet season. ET_o rates were kept around $4.50 \pm 0.11 \text{ mm d}^{-1}$ and $3.8 \pm 0.08 \text{ mm d}^{-1}$ in the dry and wet season, respectively. The multi-year average of total ET_o and ET_a were $1483 \pm 23.0 \text{ mm yr}^{-1}$ and $1229 \pm 127.2 \text{ mm yr}^{-1}$, respectively.

Table 3.4 Seasonal averages \pm standard deviation of actual evapotranspiration (ET_a), reference evapotranspiration (ET_o), crop transpiration (T), and evaporation (E) in oil palm cultivation in Moju, Pará, Brazil.

Year	Season	ET_a (mm)		ET_o (mm)		T (mm d ⁻¹)	E (mm d ⁻¹)
		Daily	Period	Daily	Period		
2010	Wet	3.32 ± 1.17	684	3.88 ± 0.53	821.7	1.50 ± 0.73	1.81 ± 1.07
	Dry	2.33 ± 1.60	356	4.49 ± 0.49	687.7	1.64 ± 1.16	0.68 ± 0.85
2011	Wet	4.10 ± 0.79	869	3.78 ± 0.53	800.5	3.41 ± 0.70	0.68 ± 0.38
	Dry	3.69 ± 1.68	565	4.63 ± 0.49	708.5	3.50 ± 1.62	0.19 ± 0.21
2012	Wet	4.53 ± 0.72	966	3.84 ± 0.49	818.6	4.38 ± 0.73	0.16 ± 0.09
	Dry	2.37 ± 1.85	363	4.44 ± 0.56	679.9	2.27 ± 1.80	0.10 ± 0.15
2013	Wet	4.10 ± 1.10	869	3.77 ± 0.54	800.1	3.98 ± 1.12	0.12 ± 0.11
	Dry	2.31 ± 1.59	354	4.30 ± 0.51	657.5	2.20 ± 1.54	0.11 ± 0.19
2014	Wet	4.13 ± 1.07	876	3.78 ± 0.59	801.0	3.97 ± 1.04	0.16 ± 0.13
	Dry	2.36 ± 1.70	361	4.37 ± 0.48	669.3	2.24 ± 1.65	0.12 ± 0.18
2015	Wet	3.88 ± 1.05	822	3.59 ± 0.59	760.7	3.79 ± 1.05	0.09 ± 0.06
	Dry	1.81 ± 1.24	276	4.46 ± 0.82	682.1	1.76 ± 1.22	0.05 ± 0.12
2016	Wet	4.46 ± 0.63	951	3.80 ± 0.49	809.4	4.23 ± 0.61	0.23 ± 0.11
	Dry	2.60 ± 1.39	397	4.41 ± 0.43	674.3	2.49 ± 1.37	0.10 ± 0.17
2017	Wet	4.15 ± 1.17	879	3.70 ± 0.60	785.0	3.86 ± 1.17	0.28 ± 0.15
	Dry	1.61 ± 1.41	246	4.66 ± 0.49	713.1	1.48 ± 1.37	0.13 ± 0.21

Fig. 3.1 and Table 3.4 show that a high value of the evaporative fraction existed throughout the first two studied years, accounting about 46% and 12% of total crop ET in 2010 and 2011, respectively. In the following years, E component ranged from 2.4 to 7.1% of the yearly ET_a . T was the main component of the ET_a over the whole study period, accounting for 54.1% in 2010, 87.9% in 2011 and it remained above 90% of the ET_a in the subsequent years. Except for 2010 and 2011, T was significantly higher in the wet season comparing to dry season.

Fig. 3.2 displays 30-meter resolution output images with the overall characteristics of the spatial-temporal distribution of ET_a in March 1st and September 1st of each year. These days were chosen because they are right in the middle of both wet and dry seasons, respectively. Clearly, we can observe that ET_a was well distributed in the study area, even though there were gaps caused by the stripes in Landsat 7 images, which are characterized for

having only 78% of their pixels. For this reason, no data pixels were obtained in output images of 2010, 2011, 2012, and up to March 2013, once Landsat 7 was the only satellite in operation. In general, we observed a season. As mentioned before, the ET_a behavior in the study area shows similar patterns year after year, mainly due to the higher evapotranspiration rates in the period with higher rainfall indices in relation to the driest season of the year.

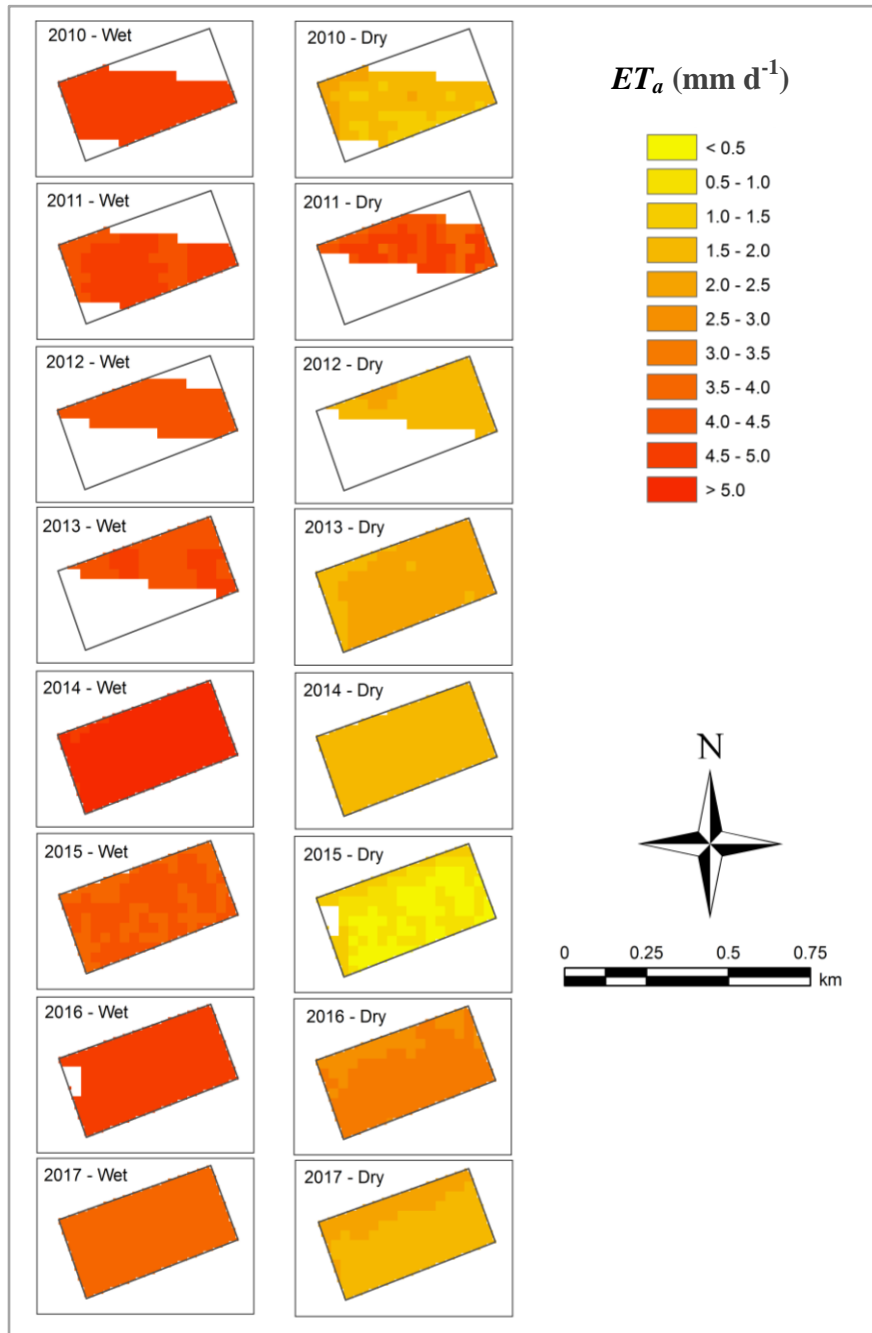


Figure 3.4 Spatial distribution of the seasonal ET_a in Moju, Pará, Brazil from 2010 to 2017.

3.3.3 Adjusted crop coefficient and its components

Fig. 3.3 shows graphs of the evolution of calculated K_{cadj} and K_{cb} curves and individuals K_{cbrf} values for each year. Each chart is represented by a 10-pixel average near to the center of the studied field. The first three plots display a progression of the crop coefficients during the initial development stage of oil palm, previously to the bunches production. When analyzing the plots in Fig. 3.3 it is possible to notice a temporal similarity of K_{cadj} in most of the studied years.

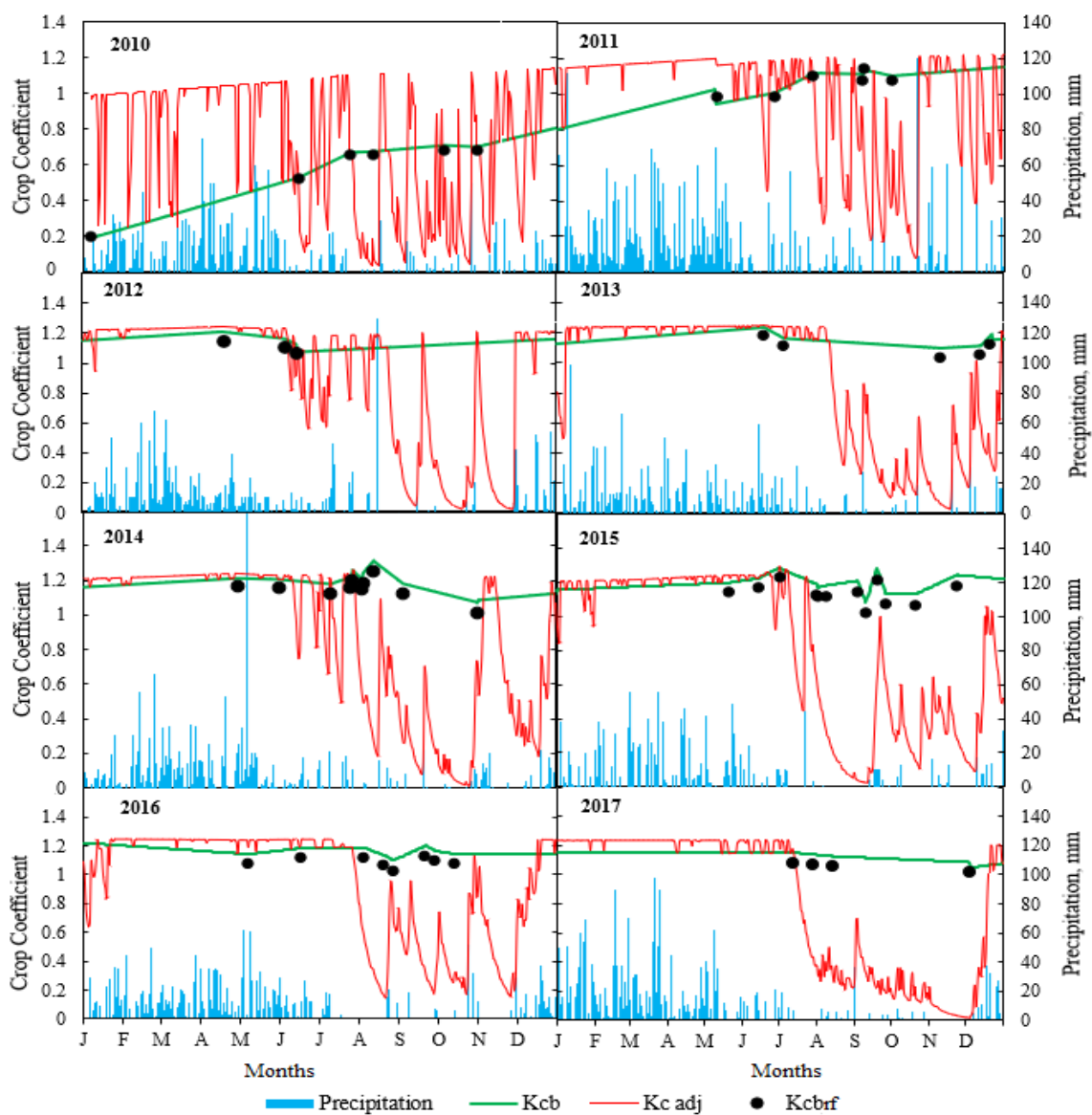


Figure 3.5 Temporal evolution of the precipitation, basal crop coefficient (K_{cb}), adjusted crop coefficient (K_{cadj}), and basal crop coefficient based on reflectance (K_{cbrf}) during the period 2010-2017 in an oil palm cultivation in Moju, Pará, Brazil.

In Table 3.5 a summary of the seasonal results of crop coefficients is given. On an annual average basis, K_{cadj} was 0.87 ± 0.42 . Most of K_{cadj} variations occurred during periods with lower rainfall for all years, with mean values of 0.56 ± 0.40 while in the wet season, the average K_{cadj} was 1.09 ± 0.25 . Particularly, we also observed noticeable K_{cadj} oscillations in the first semester (wet season) of 2010, with daily values ranging from 0.1 to 1.1 (Fig. 3.3). In this same year, average K_{cadj} accounted for 0.72 ± 0.36 (Table 3.5).

Table 3.5 Seasonal averages \pm standard deviation of adjusted crop coefficient (K_{cadj}), basal crop coefficient (K_{cb}), and evaporation coefficient (K_e) in oil palm cultivation in Moju, Pará, Brazil.

Year	Season	K_{cadj}	K_{cb}	K_e
2010	Annual	0.72 ± 0.36	0.54 ± 0.18	0.35 ± 0.30
	Wet	0.86 ± 0.29	0.43 ± 0.17	0.49 ± 0.28
	Dry	0.53 ± 0.37	0.68 ± 0.03	0.16 ± 0.20
2011	Annual	0.97 ± 0.31	1.02 ± 0.10	0.12 ± 0.11
	Wet	1.09 ± 0.18	0.96 ± 0.09	0.19 ± 0.10
	Dry	0.81 ± 0.37	1.10 ± 0.02	0.04 ± 0.05
2012	Annual	0.92 ± 0.43	1.14 ± 0.04	0.03 ± 0.03
	Wet	1.18 ± 0.12	1.13 ± 0.02	0.04 ± 0.02
	Dry	0.56 ± 0.44	1.16 ± 0.03	0.02 ± 0.04
2013	Annual	0.88 ± 0.43	1.17 ± 0.05	0.03 ± 0.04
	Wet	1.10 ± 0.28	1.18 ± 0.03	0.03 ± 0.03
	Dry	0.56 ± 0.39	1.16 ± 0.07	0.03 ± 0.05
2014	Annual	0.88 ± 0.44	1.15 ± 0.05	0.04 ± 0.04
	Wet	1.11 ± 0.27	1.18 ± 0.04	0.04 ± 0.03
	Dry	0.57 ± 0.44	1.12 ± 0.02	0.03 ± 0.04
2015	Annual	0.82 ± 0.45	1.19 ± 0.04	0.02 ± 0.02
	Wet	1.10 ± 0.28	1.20 ± 0.03	0.03 ± 0.02
	Dry	0.43 ± 0.34	1.19 ± 0.04	0.01 ± 0.02
2016	Annual	0.94 ± 0.38	1.17 ± 0.02	0.05 ± 0.04
	Wet	1.14 ± 0.28	1.17 ± 0.02	0.06 ± 0.03
	Dry	0.61 ± 0.36	1.16 ± 0.02	0.03 ± 0.04
2017	Annual	0.81 ± 0.49	1.13 ± 0.03	0.06 ± 0.05
	Wet	1.18 ± 0.14	1.14 ± 0.03	0.08 ± 0.03
	Dry	0.36 ± 0.33	1.12 ± 0.02	0.03 ± 0.04

Regarding K_{cb} , this component had an initial steep increase at the very young stand age, starting from a minimum value of 0.19 to a maximum value of 1.14 (Fig. 3.4) averaging 0.78 ± 0.29 . From January 2012, K_{cb} did not vary considerably over the years, displaying a flat curve, with an annual average of 1.16 ± 0.04 between 2012 and 2017. With respect to evaporation coefficient (K_e), maximum average values were reached in 2010 (0.35 ± 0.30) and 2011 (0.12 ± 0.11), during the crop establishment stage. For the remaining years, K_e was kept between 0.02 and 0.06 (Table 3.5).

3.3.4 Crop irrigation requirements

The gross irrigation water requirement simulated by the water balance model is shown in Fig. 3.4 in terms of annual and seasonal volumes. The annual values ranged from 272 to 444 mm, with 2015 being the year with higher demand. The highest required amounts of irrigation water were found in the dry season in all years, as well as the average differences between the seasons reached 125%. On a seasonal scale, the average water demand for the dry period was 241 mm while in the humid season was 114 mm, evidencing a well-defined demand of water between the seasons. Particularly, the main difference within a year was observed in 2017 (244%), when seasonally irrigation water required accounted for 205 and 60 mm for the dry and wet seasons, respectively. Alternatively, in 2015 the water requirement for both dry and wet seasons were 252 and 192 mm, with a difference of 31.23% between them. This lower difference, in addition to the fact 2015 was a year of El Niño, indicates that this period presented several stages of water shortage.

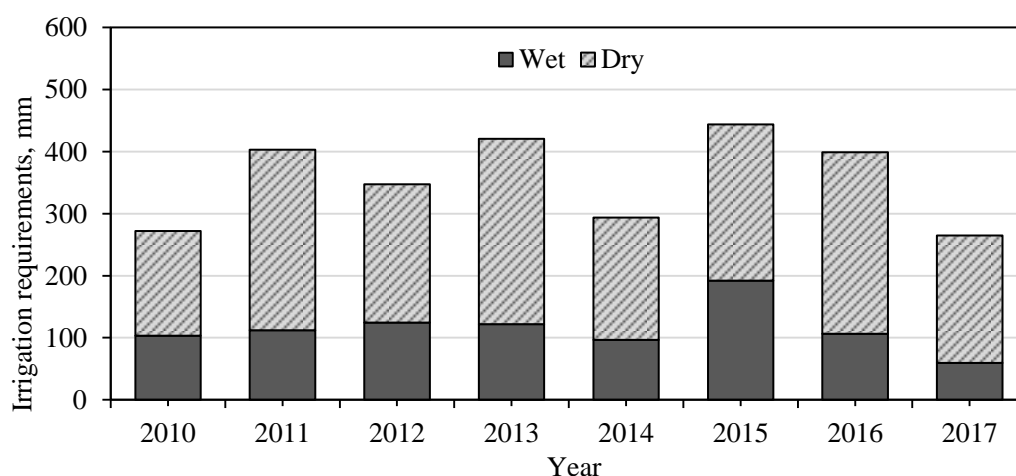


Figure 3.6 Irrigation requirement of an oil palm cultivation in Moju, Pará, Brazil during the period 2010-2017.

3.3.5 Water use efficiency

Oil palm biomass production, CWP , WUE_B^* , and observed and estimated crop productivity are summarized in Table 3.6. Overall, there was a linear increase in all oil palm biomass components. Likewise, total biomass production increased linearly ($R^2 = 0.9237$), although a small decay in that value was found in 2016 when the annual biomass production reached 64.65 t ha^{-1} , 6.45% lower than the previous year. CWP was not calculated for the first

two cropping because the bunches production started from the third year (March 2012), which was a modest production accounting for an annual *FFB* yield of 4.36 t ha⁻¹. *CWP* was higher in 2015 (3.32 kg m⁻³). In 2016 *CWP* decreased by 28.9%, followed by an increase of 33.5% in 2017. With regard to WUE_B^* , the highest value (320 g m⁻²) was found in 2017.

Table 3.6 Oil palm biomass components, crop water productivity (*CWP*), normalized water use efficiency (WUE_B^*), in situ measured productivity (Y_{meas}) and modeled productivity (Y_{mod}) for eight years in Moju, Pará, Brazil.

Year	Biomass (g m ⁻²)					<i>CWP</i> (g m ⁻²)	WUE_B^* (g m ⁻²)	Y_{meas} (g m ⁻²)	Y_{mod} (g m ⁻²)
	Roots ¹	Trunk ¹	Leaves	Bunches	Total				
2010	130.0	110.0	196.5	-	436.5	-	3.6	-	-
2011	225.6	174.0	365.6	-	765.1	-	2.9	-	-
2012	275.5	369.2	774.1	436.4	1855.2	0.3	7.0	436.4	853.4
2013	325.3	564.5	1163.2	1332.7	3385.7	1.1	13.0	1332.7	1557.4
2014	375.1	759.8	1440.2	2066.4	4641.5	1.7	18.0	2066.4	2135.1
2015	425.0	955.1	1854.3	3648.3	6882.7	3.3	27.8	3648.3	3166.0
2016	474.8	1150.4	1662.6	3177.4	6465.2	2.4	22.5	3177.4	2974.0
2017	524.7	1345.7	1932.9	3547.9	7351.2	3.2	31.7	3547.9	3381.6

¹Corley *et al.* (1971)

A comparison between the total yield modeled based on Eq. 2 and yield measured on site over time are plotted in Fig. 3.5. The resulting linear equation was $Yield_{mod} = 0.7626 (Yield_{meas}) + 538.64$ and $R^2 = 0.9913$. Fig. 3.5 shows a fair good agreement with the measured and modeled values for oil palm trees under conditions of cultivation in the Northeast of Pará. The *RMSE* comparing experimental and simulated values was 297.4 g m⁻² with a higher index of agreement ($d = 0.9801$).

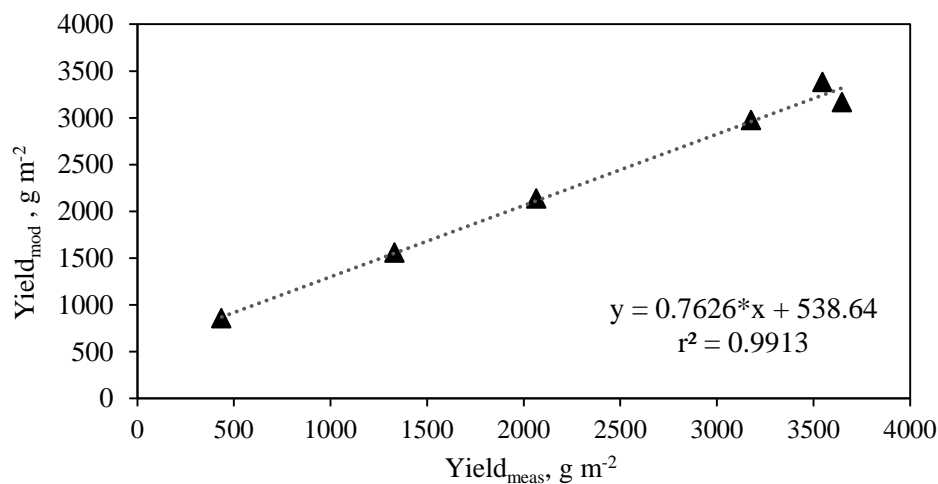


Figure 3.7 Comparison of measured and modeled oil palm yield based on a theoretical harvest index (*HI*) (Wahid *et al.*, 2005).

3.4 Discussion

ET_o is the main factor used to determine the ET_c based on the rate of transpiration in the area and it is an important variable in the hydrologic cycle (Xu *et al.* 2006, Safitri *et al.* 2019). The multi-year average ET_o calculated by using Penman-Monteith equation in this study was the same daily ET_o rate (4.0 mm d^{-1}) registered by Safitri *et al.* (2019) in the tropical rainforest zone in Indonesia and in accordance to the average value of ET_o for tropical humid zones, which ranges between 3.0 and 5.0 mm d^{-1} (Allen *et al.*, 1998).

In this study, we observed that ET_a was lower during the dry season comparing to the rainy period (Table 3.2). This same trend was also found by Henson and Harun (2005) in Malaysia, where ET_a averaged 1.3 mm d^{-1} ($K_c = 0.30$) and 3.6 mm d^{-1} ($K_c = 0.84$) in dry and wet seasons, respectively. Radersma and Ridder (1996) reported annual ET of 1118 mm (3.0 mm d^{-1}) in Ivory Coast. The authors also registered seasonal ET_a values accounting for 623 and 395 mm for both wet and dry seasons, respectively. Those values are close to the seasonal and annual ET_a totals found in our study.

In Johor, Malaysia, Yusop *et al.* (2008) using a large-scale catchment water balance approach estimated annual oil palm ET rates of 1365 , 1201 , and 1098 mm for a 2-, 5-, and 8-year-old oil palm stand, respectively. In the same site, ET_a of mature palms was calculated to be 2.6 mm d^{-1} ($K_c = 0.81$) during the wet season and 1.96 mm d^{-1} ($K_c = 0.56$) in the dry season, while T component was 2.27 ($K_{cb} = 0.70$) and 1.23 mm d^{-1} ($K_{cb} = 0.35$) (Dufrêne *et al.*, 1992). Foong (1993) reports ET_c rate average of 4.5 - 5.0 mm d^{-1} for the first seven years of cultivation of the oil palm in Malaysia. On an annual basis, our ET_a results (3.37 mm d^{-1}) are different from those presented in their study. This difference can be explained by the likely absence of water stress overtime once irrigation was used in their experiment. Similar values could be reached if we do not compute days under water stress ($K_s < 1$), obtaining values of 4.64 mm d^{-1} .

Still in Malaysia, Henson and Harun (2007) found ET_a rates of 3.9 and 2.7 mm d^{-1} in plants between 7- and 8-year-old. Those values are close to the ones found in our study in the years 2016 (3.68 mm d^{-1}) and 2017 (3.08 mm d^{-1}) (see section 3.3.2), when the plants were 7- and 8-year-old. Nelson *et al.* (2006) carried out a study with oil palm in Papua New Guinea and reported an ET_a value of 4.1 mm d^{-1} in an 8-year oil palm plantation. Safitri *et al.* (2019) registered average daily ET_a rates of 3.07 mm d^{-1} ($K_c = 0.68$) and 3.51 mm d^{-1} ($K_c = 0.7$) by a seven and 8-year-old oil palm stand in spodosol, respectively. Antonini *et al.* (2015) reported

ET_a between 4.1 and 5.7 mm d⁻¹ ($K_c = 1.1$) in irrigated 7-year-old oil palm trees under the Brazilian Tropical Savanna during the driest period of the year.

Differences between our results and some of those reported by the literature may be associated to different soil types, depth of the root systems and soil hydraulic properties (Campos *et al.*, 2017; Safitri *et al.*, 2019). In addition to that, some errors may occur in K_{cbrf} -based water balance due to the difficulty in obtaining cloud-free images in regions where oil palm is cultivated (Ng *et al.*, 2012), as exhibited in Fig. 3.3. In Northeastern Pará there is a problem regarding the low availability of imagery during the rainy season, which is characterized by the high cloud cover. Consequently, the use of additional data sources such as unmanned aerial vehicles (UAVs or drones) and more frequent satellite imagery (Ng *et al.*, 2012; Barker, 2018) is good option to improve the frequency of remote sensing inputs.

The seasonal oscillation of ET_a exhibited in Fig. 3.1 can be explained by the water content in the soil. The highest ET_a values were reached when soil moisture was high, which indicates that SWC was sufficient for the normal functioning of the physiological processes in the plant (Laio *et al.*, 2001). According to Campos *et al.* (2013), water stress is capable of reducing potential evapotranspiration up to 20%, especially during the dry season. In addition, oil palm trees are known for their ability to absorb relatively large amounts of soil from the water (Safitri *et al.*, 2019), and the distribution of the root system, as well as the dynamics of rainfall in the region, can contribute to the frequency of water stress. In this study, we observed that ET_a rates declined mainly during the less rainy period of the years. As the evaporation and transpiration are determined respectively by the soil moisture in the surface and root soil layer, the ET_a might have been influenced by the characteristics of the plant and the climatic conditions in the region (Campos *et al.*, 2016). In this investigation, T rates were lower in the dry season than those registered during the wet season, as also observed by Kallarackal *et al.* (2004) in Peninsular India. By means of a comparison between Fig. 3.1B and Fig. 3.6 it is possible to observe that even with a relatively high atmospheric demand ET_a and T (Fig. 3.6) values fell in the drier period due to the low SWC , evidencing the influence of water stress. As the soil dries, the increase in the production of abscisic acid in the roots causes the closure of the stomata (Incoll and Jewer, 1987; Davies and Zhang, 1991), in the same way, that higher SWC may promote the production of cytokinin, inhibiting stomatal closure. Moreover, ET in equatorial regions is substantially linked to R_n , which is higher during the dry season in Amazon region (Hasler and Avissar, 2007), when the cloudiness is lower than in the wet season. In addition to that, the typical small VPD in humid regions make the differences in aerodynamics resistance between the agricultural crop and the reference

crop equally small (Allen *et al.* 1998), if there is sufficient water available on the soil to supply the plants.

The highest evaporative demand (E) was observed at the first two cropping years (Fig. 3.6A), especially after rainfall and when the vegetation fraction cover was in a minimum (López-Urrea *et al.*, 2009). Nevertheless, E rates remained below 1 mm d^{-1} from the second year of cultivation, comprising about 10% of the ET_a over the entire study period. Conversely, T rates tended to be between 80 and 90% of the ET . According to Schlesinger and Jasechko (2014), the ratio T/ET_a is $70 \pm 14\%$ in a humid climate, which is close to the ratio found in our study. The small difference may stem from different considerations about evaporative loss that occurs from the surface of understory vegetation and soils, as well as different ratios of precipitation interception (Schlesinger and Jasechko, 2014).

High T rates registered from the third cropping year matched with the moment that plant cover (f_c) surpassed 80%, leaf area index (LAI) was greater than 2 and $SAVI$ reached values over 0.6 (Fig. 3.6A and 3.6B). Campos *et al.* (2017) related that K_{cb} - VI relationships are usually established in terms of a $K_{cb \text{ min}}$ for bare soil and a $K_{cb \text{ max}}$ for a $SAVI$ or a limit LAI in the effective cover from which an increase in vegetation density (LAI , $SAVI$ or $NDVI$) does not lead to an increase in the transpiration rate. According to Campos *et al.* (2018), depending on the canopy architecture, multispectral VI 's are generally saturated for LAI values from 3 to 5. In the present study, $SAVI$ saturates for LAI values close to 2 (Fig. 3.6B), contrasting with the values described by Neale *et al.* (1989) and Bausch (1993), who indicate LAI values greater than 3.2 for $NDVI > 0.8$ and an LAI equals 3, respectively. Bausch (1993) recommended the K_{cb} should be limited at effective cover once the $SAVI$ index continues to increase even with LAI values greater than 3. In Fig. 3.6B, $SAVI$ does not vary even when LAI values exceed 3.

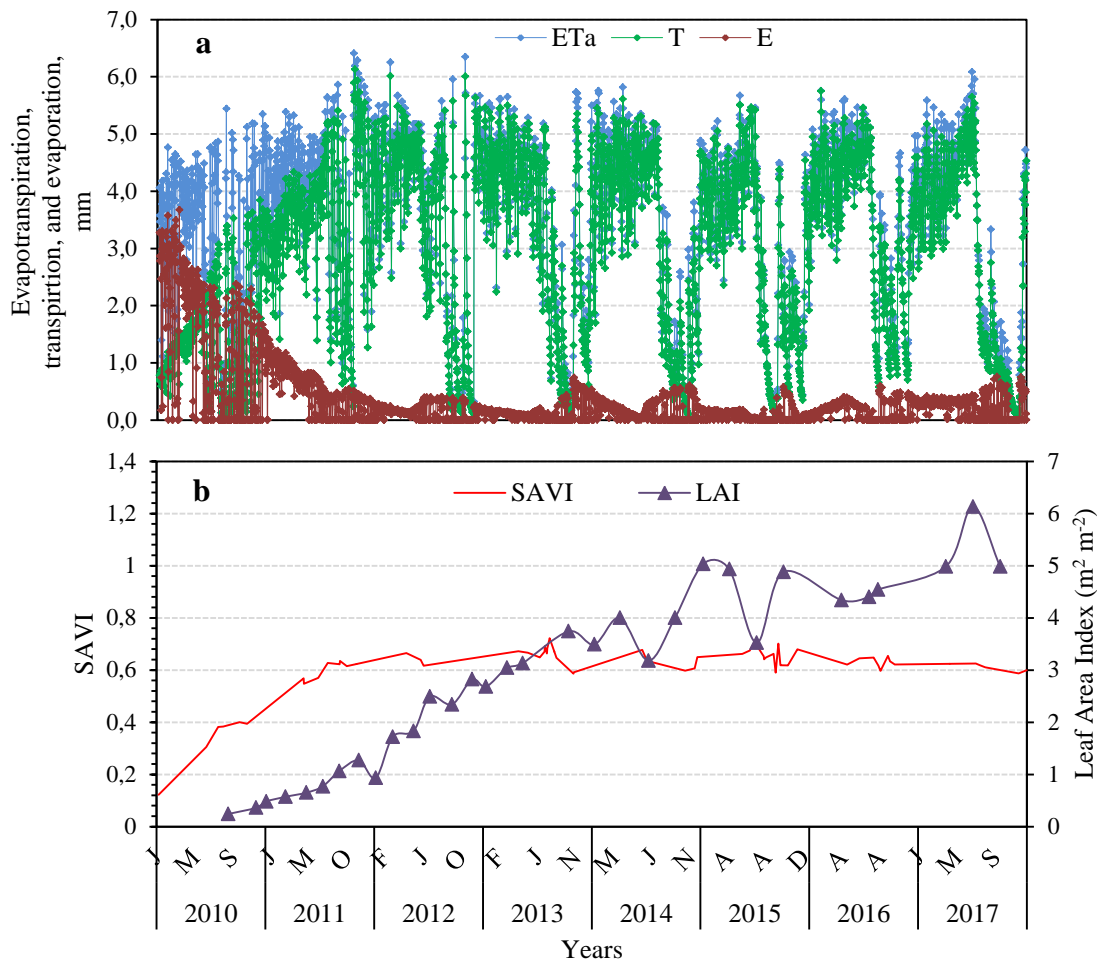


Figure 3.8 Temporal evolution of a) actual evapotranspiration (ET_a), crop transpiration (T), and soil water evaporation (E), and b) SAVI derived from Landsat images and in situ measured LAI during the period 2010-2017 in an oil palm cultivation in Moju, Pará, Brazil

Some authors reported that the most of root water uptake is near to the soil surface, where soil moisture is provided by the rainfall, while in the deeper layers it can be from the rainwater with deep percolation or the capillary from groundwater (Nelson *et al.* 2006; Safitri *et al.* 2019). Despite the average high rainfall in state of Pará, the seasonality of precipitation may promotes water stress during the dry season, causing the ET_a rates to be higher in dry or humid seasons depending on the intensity of dry period, vegetation type, and depth of water table (Costa *et al.*, 2010; Vourlitis *et al.*, 2011; Lathuilliere *et al.*, 2012; Harper *et al.*, 2014). According to Carr (2011), the generally accepted way of comparing different conditions and their effects on oil palm productivity is to use the concept of soil water deficit. Irrigation can be a valuable tool to minimize the water deficit stress and its potential negative effects on oil palm yields. Information in the literature has shown that irrigation promotes higher oil palm yields, especially due to changes in bunch number (Mite *et al.*, 2000; Palat *et al.*, 2000; Lee *et al.*, 2005; Palat *et al.*, 2009; Lee and Arifin, 2013). In Fig. 3.7 is shown the mean *FFB* yields

collected during the seven productive years in this study and it is clear a sharp increase in productivity of *FFB* by 2015, followed by a reduction of 12% in 2016. This decrease might be associated with the occurrence of El Niño phenomenon, which causes droughts in the Amazon region and contributes for intensification of water stress (Chen *et al.*, 2011). Under severe water stress conditions ($>300 \text{ mm yr}^{-1}$), the sex determination and inflorescence abortion are affected, causing latency period of 22 to 23 and nine to 11 months prior to harvest, respectively (Keong and Keng, 2012). Moreover, according to Lubis *et al.* (1993), these phenomena are most likely to occur in plants between 3 and 5 years. Thus, the water stress recorded in 2015 added to the effect of stress occurred in 2014 may have affected production in 2016 (ABRAPALMA, 2016). As exhibited in Fig. 3.4, the required higher gross irrigation amounts in the dry season indicate an opportunity for irrigation use. However, irrigation can be expensive and difficult to operate, and its economic feasibility must be considered.

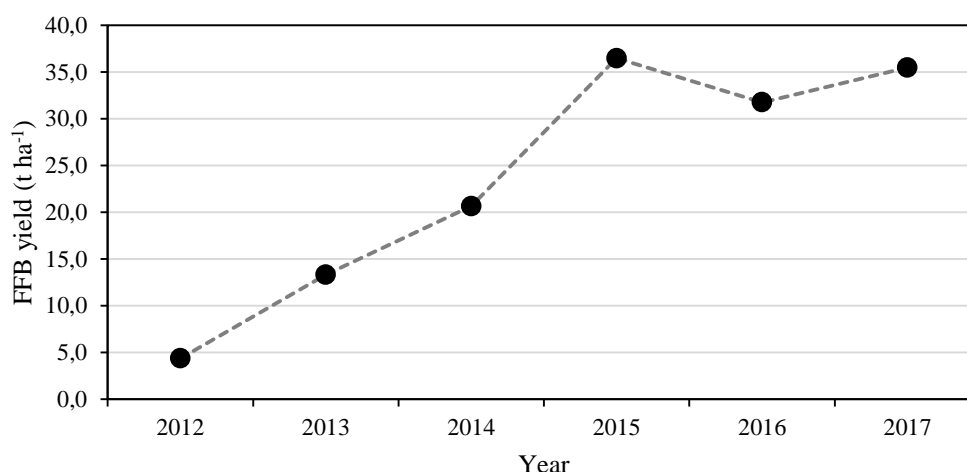


Figure 3.9 Oil palm fresh fruit bunches (*FFB*, t ha⁻¹) yield from 2012 to 2017 in an oil palm cultivation in Moju, Pará, Brazil.

The analysis of the results revealed a satisfactory performance of AQUACROP and FAO-66 approach for estimation of productivity in terms of oil palm biomass once *RMSE* comparing measured and modeled yield was within the range found by other approaches. Oil palm fruit production starts between 2.5 and 3 years after planting (Carr, 2011; Balasundram *et al.*, 2013), and the computation of initial yields is difficult due to irregular and inexpressive production of bunches, especially in the first three years of production. Despite this, the methodology was relatively accurate to detect the yield even during the juvenile stage. Moreover, the distribution of the oil palm yield during the year depends on water stress,

which may promote losses of about 10% for each 100 mm increase in water deficit (Carr, 2011). Differences in oil palm productivity along the year observed in this study were also reported by other authors (Claret de Souza *et al.*, 2012; Teles *et al.*, 2016), evidencing the seasonal effects on bunch production (Mhanhmad *et al.*, 2011).

Because of the scarcity of references available in the literature using remote sensing methods to understand oil palm productivity, further discussion about the performance of the approach for this crop is difficult. Alternatively, studies with wheat (*Triticum aestivum*) have found *RMSE* of 580 g m⁻² (Iqbal *et al.*, 2014), 810 g m⁻² (Jin *et al.*, 2017), 520 g m⁻² (Jin *et al.*, 2014), and 450 g m⁻² (Campos *et al.*, 2018b) using the AQUACROP model calibrated for their respective areas. Campos *et al.* (2018a) reported *RMSE* of 81.1 and 106.2 g m⁻² for maize and 26.7 and 35.1 g m⁻² for soybeans using different harvest indices in Nebraska, USA. These values are different from the *RMSE* found in the present study (297.4 g m⁻²) and this difference might be due to the use of irrigation. In this sense, Zeleke *et al.* (2011) observed a good agreement ($d=0.969$ and $d=0.953$) between measured and modeled aboveground biomass of two varieties of canola (*Brassica napus* L.) in Australia. The *RMSE* in their study were 210 and 258 g m⁻² in an experiment conducted during a season with enough rainfall, similarly to the present study. According to some authors, low concordance indices are associated with unsatisfactory model performance in simulating conditions under water stress (Heng *et al.*, 2009; Zeleke *et al.*, 2011; Campos *et al.*, 2018b).

3.5 Conclusions and final remarks

The present work was designed to estimate the oil palm water requirement over Northeastern Pará, in the Eastern Brazilian Amazon during 2010-2017. In order to achieve the proposed objectives, we used remote sensing data into a soil water balance model to obtain the first information on oil palm actual evapotranspiration (ET_a) on a daily basis in Brazilian Amazon. The 8-year-average of daily and total ET_a was estimated to be 3.4 ± 0.4 mm d⁻¹ and 1229 ± 127.2 mm yr⁻¹. Seasonally, the oil palm water uses were 4.08 ± 1.03 mm d⁻¹ (864.4 ± 80.91 mm) and 2.38 ± 1.66 mm d⁻¹ (364.7 ± 88.94 mm) in the wet season and dry season, respectively. Transpiration was the main component of the ET_a over the whole study period, accounting for 54.1% in 2010, 87.9% in 2011 and it remained above 90% of the ET_a in the subsequent years due to the increase of the fraction of ground cover over time. On an annual average basis, K_{cadj} was 0.87 ± 0.42 while the average K_{cb} for the first two crop years was 0.78 ± 0.29 and reached an average of 1.16 ± 0.04 during the productive stage (from 2012 to

2017). Variations on ET_a and K_{cadj} observed in this study can be a consequence of eventual water stress (especially during the less rainy periods) as result of the seasonality of precipitation in Northeaster Pará as well as the hydraulic soil properties. As discussed herein, irrigation can be an important tool to overcome the seasonal water deficit, but its use must be well evaluated from an economic point of view since the implantation of an irrigation system can be expensive and difficult to operate.

Additionally, the results provided by the water balance model, point the satisfactory performance of AQUACROP and FAO-66 approach for estimation of productivity in terms of oil palm biomass. The relationship between *in situ* measured and modeled oil palm yields showed a good agreement ($d = 0.9801$) and it was described by a linear function ($Yield_{mod} = 0.7626(Yield_{meas}) + 538.64$; $R^2 = 0.9913$). These findings highlight the functionality of using remote sensing data for the determination of oil palm productivity as well as other crops.

Lastly, our study brings the first insights into oil palm water use in the Amazon region by using remote sensing data. We highlight that further research must be done to better understand the water fluxes in oil palm plantations in equatorial regions, especially by using oil palm K_{cb} - VI relationship determined from VI and K_{cb} measured on the field as well as site-specific soil hydraulic properties.

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