University of São Paulo
"Luiz de Queiroz" College of Agriculture

Crop evapotranspiration and crop coefficient of jatropha from first to fourth year

Bruno Patias Lena

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

Piracicaba
2016

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versão revisada de acordo com a resolução CoPGr 6018 de 2011

Advisor:
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To my parents Marcos and Rozania;

To my sister Clarissa;

To all my relatives and friend.

Offer

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RESUMO

Evapotranspiração e coeficiente de cultivo do pinhão-manso do primeiro ao quarto ano

A determinação de coeficiente de cultivo (K_c) com metodologia adequada é essencial para quantificar o consumo hídrico de cultivos em diferentes regiões. Valores de K_c do pinhão-manso (*Jatropha curcas* L.) ainda não foram determinados e essa informação é muito importante para auxiliar o manejo de irrigação de maneira adequada. O objetivo desse estudo foi determinar a evapotranspiração (ET_c) e K_c do 1º ao 4º ano de cultivo do pinhão-manso, e correlacionar K_c com o índice de área foliar (IAF) e a soma da unidade térmica (SUT). O experimento foi realizado de março de 2012 à agosto de 2015 na Escola Superior de Agricultura "Luiz de Queiroz" (ESALQ)/Universidade de São Paulo (USP), na cidade de Piracicaba, SP, Brasil. O experimento foi divido nos tratamentos irrigados por pivô central, gotejamento e sem irrigação. Foram utilizados dois lisímetros de pesagem (12 m^2 de superfície em cada lisímetro) por tratamento para realizar a determinação de ET_c (uma planta por lisímetros). A evapotranspiração de referência (ET_0) foi determinado pelo método de Penman-Monteith a partir de dados meteorológicos coletados na estação meteorológica localizada ao lado do experimento. Valores diários de K_c foram determinados nos tratamentos irrigados pela razão entre ET_c e ET_0 (K_c=ET_c/ET_0). IAF foi determinado utilizando o equipamento LAI-2200 Plant Canopy Analyzer, que foi previamente calibrado para adequar as características do dossel do pinhão-manso. Em todos os anos avaliados, o IAF foi quase zero durante o início do período vegetativo, aumentando os valores conforme a planta começou a se desenvolver até atingir valores máximos durante o período produtivo, decrescendo os valores até zero no estádio de desenvolvimento de senescência foliar. A variação anual de ET_c no 2º, 3º e 4º ano foi muito similar, explicado pelos diferentes períodos de desenvolvimento da cultura e a variação de IAF no ano. No 1º ano, K_c foi 0,47 para os dois tratamentos irrigados. No 2º, 3º e 4º ano, K_c variou de 0,15 a 1,38 no tratamento irrigado por pivô central e de 0,15 a 1,15 no tratamento irrigado por gotejamento. A média dos valores de K_c no 2º, 3º e 4º ano durante os períodos vegetativos e produtivos foi de 0,77, 0,93 e 0,82 no tratamento irrigado por pivô central, respectivamente, e 0,69, 0,79 e 0,74 no tratamento irrigado por gotejamento, respectivamente. A relação entre K_c e IAF mostrou, para o tratamento irrigado por pivô central, um ajuste logaritmo com coeficiente de determinação (R^2) e somatória do erro médio ao quadrado (SEMQ) de 0,7643 e 0,334, respectivamente, e 0,8443 e 0,2079 para o tratamento irrigado por gotejamento, respectivamente. Nos três anos analisados, K_c correlacionado com SUT mostrou o melhor ajuste à equação polinomial de 2ª ordem para os dois tratamentos.

Palavras-chave: Lisímetros; Irrigação; Consumo hídrico do pinhão-manso

ABSTRACT

Crop evapotranspiration and crop coefficient of jatropha from first to fourth year

The determination of crop coefficient (K_c) with adequate methodology is important to quantify regional water requirement. Jatropha (*Jatropha curcas* L.) K_c is still unknown and this information will be essential to provide reliable irrigation parameters, as well as for crop zoning. The objective of this study was to determine jatropha actual crop evapotranspiration (ET_c) and K_c from 1st to 4th growing year, and correlate K_c with leaf area index (LAI) and cumulative thermal unit (CTU). The experiment was performed from March 2012 to August 2015 at "Luiz de Queiroz" College of Agriculture (ESALQ)/University of São Paulo (USP), at Piracicaba city, SP, Brazil. The experiment was divided into center pivot, drip, and rainfed treatments. Two large weighing lysimeters (12 m^2 each lysimeter) per treatment were used to determine jatropha ET_c (one plant per lysimeter). Reference evapotranspiration (ET_0) was determined by Penman-Monteith method from a weather station data situated close to the treatments. Daily K_c was determined for the two irrigated treatments by the ration between ET_c and ET_0 (K_c=ET_c/ET_0). LAI was determined using the LAI-2200 plant canopy analyzer, which was previously calibrated for jatropha canopy type. In all growing years, LAI was almost zero at the beginning of vegetative stage, increasing until a maximum during productive stage, and decreasing to zero in the leaf senescence stage. Annual ET_c trend during the three growing was very similar, which was explained by the different growing periods and the LAI variation. In the 1st year K_c was 0.47 for both treatments. In the 2nd, 3rd, and 4th years K_c ranged from 0.15 to 1.38 for center pivot treatment and from 0.15 to 1.25 for drip treatment. K_c average in 2nd, 3rd, and 4th years during vegetative and productive growing periods was 0.77, 0.93, and 0.82 for center pivot treatment, respectively, and 0.69, 0.79, and 0.74 for drip treatment, respectively. The relationship between K_c and LAI for the center pivot treatment was adjusted to a logarithmical equation with coefficient of determination (R^2) and root mean square error (RMSE) of 0.7643 and 0.334, respectively. For the drip treatment R^2 was 0.8443 and 0.2079, respectively. In all three years analyzed, K_c related to CTU by a 3rd degree polynomial equation for both treatments.

Keywords: Lysimeter; Irrigation; Jatropha water balance

FIGURE LIST

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ABREVIATION LIST

ΔS	Soil water storage variation
CTU	Cumulative thermal unit
D	Drainage
DNS	Days of new season
ET_0	Reference evapotranspiration
ET_c	Crop evapotranspiration
$ET_{estimated}$	Estimated crop evapotranspiration
ET_{real}	Real crop evapotranspiration
FC	Field capacity
I	Irrigation
K_c	Crop coefficient
LAI	Leaf area index
LAI_{E_P}	pattern estimated leaf area index
LAI_{E_R}	recomputed estimated leaf area index
LAI_R	real leaf area index
LS	Leaf senescence stage
P	Productive stage
Pr	Precipitation
PWP	Permanent wilting point
R	Surface runoff
S	South
SWHC	Soil water holding capacity
T_b	basal temperature
T_{max}	maximum temperature
T_{min}	minimum temperature
V	Vegetative stage
W	West

INITIALS LIST

EMBRABA	Brazilian Agricultural Research Corporation
ESALQ	“Luiz de Queiroz” College of Agriculture
CEPAGRI	Centro de Pesquisa Meteorológica e Climática Aplicadas a Agricultura
FAO	Food and Agriculture Organization of the United Nations
USP	University of São Paulo

SIMBLES LIST

p	significance level
%	percentage
°	degree
°C	degree Celsius
c	Index of confidence
cm	centimeter
cm d^{-1}	centimeter per day
d	Willmott index of agreement
g dm^{-3}	grams per decimeter cubed
ha	hectare
L h^{-1}	liters per hour
m	meter
m^2	meter square
mm	millimeter
mm d^{-1}	millimeter per day
NSE	Nash-Sutcliffe efficiency
r	Person correlation coefficient
R^2	coefficient of determination
RMSE	root mean square error
s	seconds

1 INTRODUCTION

The high energy demand for human activities is increasing the daily feedstock consumption. Most part of it is from non-renewable feedstock such as oil and natural gas. Even it has a well stablish energy chain, there are many consequences by the oil exploration and usage (KHARAKA; DORSEY, 2005). According to the International Energy Agency (IEA, 2012), in 2040 there will be an increase in energy demand up to 56% in comparison to 2011 world energy consumption. In addition, 84% of total energy production will be from non-renewable sources (charcoal, natural gas, and petroleum).

As the environmental impacts increased due the high fossil fuel usage, in the past years it was observed an increase of researches related to renewable feedstock for energy production with characteristics of reducing environmental damage (EMBRAPA, 2010; KOHLHEPP, 2010). With the need to replace the fossil fuel for biofuels (alcohol and oilseed), many studies with crops that produce renewable feedstock started to be studied. Therefore, it was observed a substantially increase in research with oilseeds for biodiesel production. According to Atabani et al. (2012), the biodiesel is extremely promising due the high amount of different feedstocks presented. Besides considering the inedible crops as those with more importance for high scale production, the authors also describe that it is still necessary to invest in researches and in government incentive so that it can become economically feasible.

Jatropha (*Jatropha curcas* L.) is an oilseed currently used for biodiesel production, highlighted especially by some specifics characteristics that increased the interest of studying this culture, such as drought tolerant and requires low soil fertility (OPENSHAW, 2000; ARRUDA et al., 2004), also presenting fast development and easy propagation (ACHTEN et al., 2008). Brittaine and Lutaladio (2010) mention that jatropha can be cultivated from 30° N to 35° S, showing the high development ability under different soil and climates conditions. Although jatropha is able to survive in regions with low annual precipitation (from 250 to 300 mm), some authors describe a better plant development under regions with annual precipitation varying from 1,000 to 1,500 mm (FACT, 2010).

The main reason that jatropha started to be studied was the high seed oil content, presenting values varying from 27 to 40%, depending on the crop management (HELLER, 1996; ACHTEN et al., 2008), as well as the high yield when cultivated under adequate water and nutrient availability (HEIFFIG, 2006; TEWARI, 2007; CARNELLI, 2008). According to Fact (2010), jatropha can reach up to 5,000 kg ha^{-1} depending on the crop management. Studies with seedling (MAES et al., 2009) and plant resistance to drought stress (LUÍS, 2009), as well as the seed yield improvement when cultivated with irrigation (EVANGELISTA et al., 2011; OLIVEIRA et al., 2012; SANTOS, 2015; ANDRADE, 2016) were essential to understand the plant characteristics. In addition, the literature shows several studies with the jatropha oil characteristics, especially for the oil usage on partial and total diesel replacement. The oil characteristics such as low toxicity after burning, increase the engine performance, and the low carbon dioxide emission (PARAWIRA, 2010; KOH; GHAZI, 2011) are considered the main reason that jatropha oil can be used for diesel replacement.

Although jatropha oil has good quality characteristics for biodiesel production, as already mention by many authors (OLIVEIRA et al., 2009; ONG et al., 2011; MAZUMDAR et al., 2012), the real potential production and economic feasibility is still questionable. Achten et al. (2007) and Ferreira et al. (2013) describe that, in Brazil and India, several difficulties about jatropha production management are the main reason that jatropha is not produced in large scale. The authors also mention that the jatropha economic feasibility is associated mainly by the crop characterization, by the technology implementation on the production system and by the improvement of genetics characteristics.

There are many speculations about jatropha water consumption during the season, however, there is not long-term and continuously reliable information about the real water consumption. Authors mention that jatropha is drought tolerant and can produce under extreme conditions, but it is possible to observe yield improvement in regions with high annual precipitation, as well as for regions with high chances of water deficit (EVANGELISTA et al., 2011; SINGH et al., 2013).

Characterizing the water consumption from crops is required to identify the real water consumption, allowing to use this information in water demand studies, irrigation management, agricultural zooning, yield prediction, and other hydrologic studies. The water consumption from crops, also known as actual crop evapotranspiration (ET_c), is defined as the amount of water consumed by a crop over time (ALLEN et al., 1998). For jatropha, there are few studies with ET_c determination, especially those that has information from the beginning of development to the adult stages (maximum production). In this context, characterizing jatropha continuously and long-term ET_c values is necessary to identify the water usage dynamic during the season, as well as to stablish irrigation manage strategies.

Determining ET_c is quite complex and requires technical and scientifically personnel support. ET_c can be determined by many different methods, such as Bowen ratio energy balance system (BOWEN, 1926; TANNER, 1960; FRITSCHEN, 1962) and Eddy Covarience (RAYNOLDS, 1895), however, the standard method internationally recommended is the weighing lysimeters (HOWELL; MCCORMICK; PHENE, 1985; FARIA CAMPECHE; CHIBANA, 2006; JIA et al., 2006; CARVALHO et al., 2007; ALLEN et al., 2011; MARIANO et al., 2015). Lysimeters are known by the high precision on the ET_c determination.

Besides determining ET_c, it is also important to determine crop coefficient (K_c), which is calculated by the ratio between ET_c and reference evapotranspiration (ET_0) ($K_c=ET_c/ET_0$) (ALLEN, 1986; SMITH, 1991; ALLEN et al., 1998). K_c is mainly used to stablish the relationship between water demand from a specific crop and the local climate characteristics. In others terms, ET_c is calculated by the multiplying K_c and local atmospheric demand ($ET_c=K_c\ ET_0$). According to Lascano and Sojka (2007), K_c values is necessary for irrigation design and irrigation scheduling during the season. The long-term and continuously jatropha ET_c and K_c determination is essential and necessary, which will allow to characterize the jatropha water consumption.

1.1 Jatropha plant

Jatropha is from Euphorbiaceous family, called scientifically as *Jatropha curcas* L.. Heller (1996) mentions that jatropha family has many species with economy importance, highlighting jatropha by its medicinal characteristics and by the high oil content within seed that can be used for biodiesel production. The real jatropha origin center is still unknown. Some studies describe Mexico and North of Center America as the possible origin center (DEHGAN; WEBSTER, 1979; HELLER, 1996). Some authors mention that jatropha was scattered by Portuguese to Africa and Asia (BRITTAINE; LUTALADIO, 2010) and it can be found in tropical and subtropical climates (OPENSHAW, 2010).

By definition, jatropha is a small tree or a tall shrub, and it can reach up to 5 m height depending on the water and nutrient availability (HELLER, 1996; ACHTEN et al., 2008; BRITAINE; LUTALADIO, 2010; FACT, 2010), but with lower development when cultivated under low water and nutrient availability (CORTESÃO, 1956). According to Arruda et al. (2004), the main stem is divided in multiples branches from the base, with long braches and several scars produced by the leaves fall during leaf senescence phase. The branches have high latex content that can be easily dripped with any injury (ARRUDA et al., 2004; HENNING, 2009; YE et al., 2009). The fruits are composed by three seeds, with ovoid shape and diameter ranging from 1.5 to 3 cm. When plant is producing fruits, they are green and, after initiating the maturation process, the fruits are yellow until starts to become brown, period considered the best harvest point (DRANSKI et al., 2010). In within each fruit, there are three seeds, which has the dark shell and white endosperm. Seeds usually have length and width of 1.8 and 1 cm, respectively.

The jatropha annual season phenology includes three phenological phases: vegetative, productive, and leaf senescence (Figure 1). Plant height and leaf area index (LAI) vary during the year, which will directly influence on jatropha water consumption. From the beginning of vegetative (spring) to mid productive (summer) phase, plant height and LAI sharply increase until a maximum value. By the end of productive phase jatropha plant initiate the leaf senescence, which is characterized by the fast leaves fallowing.

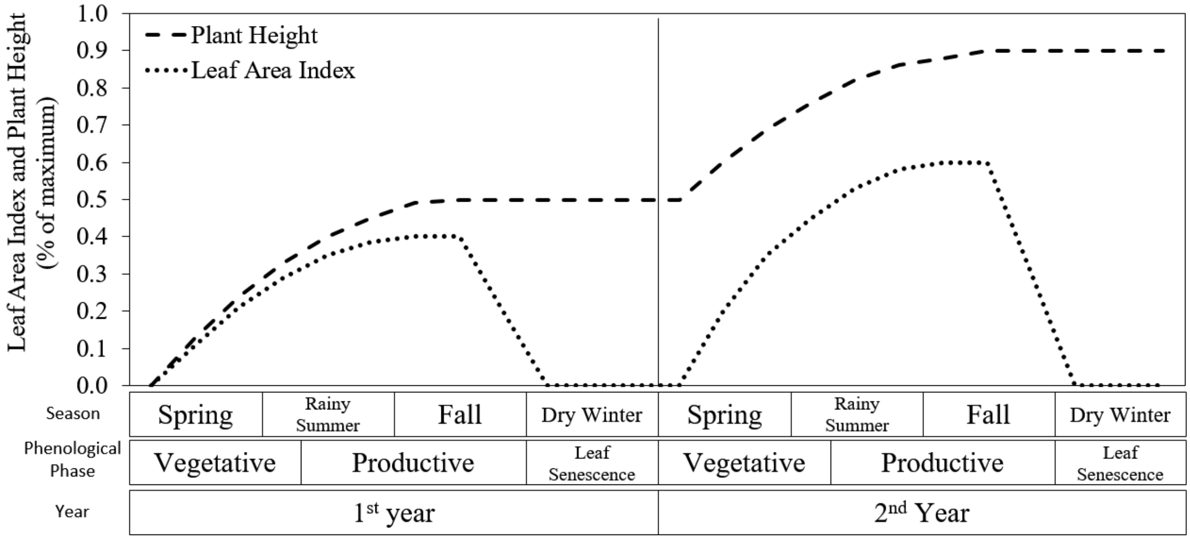

Figure 1.1 - Theoretical leaf area index and plant height fluctuation of jatropha during 1st and 2nd year (LENA, 2013)

Jatropha can be cultivated in between 30° N to 35° S and until 1,000 m altitude, with best air temperature varying from 20 to 28 °C (SATURNINO et al., 2005; BRITAINE; LUTADADIO, 2010; FACT, 2010). Information about water requirement from jatropha plant is still scarce and controversial, especially for those that evaluated the irrigation effect on yield (FOIDL et al., 1996; HELLER, 1996; TEWARI, 2007; FRANCIS; EDINGER; BECJER, 2005; ARIZA-MONTOBBIO; LELE, 2010; EVANGELISTA et al., 2011; FARIA et al., 2011; OLIVEIRA; BETRÃO, 2010). Despite jatropha can growth with annual precipitation of 300 mm (KHEIRA; ATTA, 2009; BRITAINE; LUTADADIO, 2010), many authors state that jatropha has better growth in regions with annual precipitation above 1,000 mm (OPHENSHAW, 2000; SATURNINO et al., 2005; BRITTAINE; LUTADADIO, 2010; FACT, 2010).

In the literature, there are few information about the jatropha yield, and most of the information is controversial. Climate condition and crop management may lead to the different yield values, which can be explain the non-standard results found in the literature. In a review, Arruda et al. (2004) presented yield ranging from 500 to 2,000 kg ha^{-1} of seeds, but with values reaching up to 6,373 kg ha^{-1}, also the yield information under great crop management conditions can be used as jatropha potential production indicative. Carnielli (2008) stated that jatropha produce at least 2,000 kg ha^{-1} of seed and, according to Heiffig (2006), it can reach up to 3,500 kg ha^{-1} of seed even under rainfed condition. If jatropha is cultivated under adequate irrigation management, soil fertility, and crop management, it is possible to produce at least 5,000 kg ha^{-1} (TEWARI, 2007).

According to Achten et al. (2008), jatropha seed can present from 27 to 40% of oil and, depending on the extraction methodology, it can reach up to 50% (KALANNAVAR; 2008; ANDRADE, 2016). Recent studies indicate that jatropha oil is an excellent feedstock, presenting high quality that can well substitute the diesel (SARIN et al., 2007; ACHTEN et al., 2008; WANG et al., 2012; KAUSHIK; BHARDWAJ, 2013; ARAÚJO et al., 2014; ANDRADE, 2016).

Many questions about plant development under different nutrient and water management have been studied, showing good results about yield improvement. Guimarães and Beltrão (2008), Albuquerque, Severino and Beltrão (2013), and Andrade (2016) presented positive effect on yield when plants are irrigated and have high nitrogen soil levels, showing that jatropha is considered drought tolerant and can develop under low soil fertility.

1.2 Crop evapotranspiration and crop coefficient

ET_c is known as the total water consumed by a determined plant. By definition, ET_c is the sum of soil evaporation (E) (and/or by the free water deposited after an irrigation or precipitation event) and the leaf transpiration (T). According to Allen et al. (1998), ET_c may vary depending on the plant development stage, as well due the climate and soil conditions. During the initial development, the plants have low LAI, so E is the main component of total ET_c. However, as the plants starts to produce new branches and leaves, the soil surface is covered by the plant, reducing E rates and, consequently, T becomes the main ET_c component.

Determining plant water consumption (ET_c) is an important information for crop irrigation management. In addition, the ET_c annual variation is also required to identify plant water requirement in each plant development phase, allowing stablish strategies to increase water use efficiency and maximizing yield. ET_c is also essential for crop zooning studies, for yield prediction and for general hydrologic studies.

During the crop season, the amount of water required by a plant may vary substantially. Period of the year and local climate conditions (radiation, wind speed, air temperature, and relative humidity), as well as the crop development characteristics (growing phases) and water management are the main reasons that ET_c is variable. To comprehend the ET_c dynamic over the year, it is necessary to identify the relationship between all these factors together.

ET_c determination is quite complex and requires high technical and scientifically support, and it can be performed by many different indirect (by estimations) and direct (by direct measurements) methodologies. The indirect methods to determine ET_c are those that use either meteorological data or the evaporation tank methodology to estimate ET_c (ALLEN et al., 1998). However, in studies that intend to determine high precision ET_c values, the direct methods are the most recommended, highlighting the Bowen Ratio Energy Balance System (BOWEN, 1926; TANNER, 1960; FRITSCHEN, 1962), Eddy Covarience (REYNOLDS, 1895) and weighing lysimeters (HOWELL; MCCORMICK; PHENE, 1985; FARIA; CAMPECHE; CHIBANA, 2006; JIA et al., 2006; CARVALHO et al., 2007; ALLEN et al., 2011; MARIANO et al., 2015). Lysimeter are internationally known as the most reliable methodology for ET_c determination for a specific crop due its high precision, accuracy, and the ability of performing ET_c measurement in 10 min basis or less. According to Aboukhaled, Alfaro and Smith (1982), weighing lysimeters are big tanks with soil, installed in the field, presenting only soil or with vegetation where it is possible to determined ET_c or soil E rates.

In addition to the water consumption determination from a specific crop, it is still defined the ET_0. According to Allen et al. (1998), this meteorological variable is related to the water consumption from a hypothetic standardized culture (similar to grass) that has the characteristics of fast vegetative growth, aerodynamic resistance of 70 s m^{-1}, albedo of 0.23 and that is cultivated under adequate water and nutrient availability, free from insects and disease, with 12 cm height, and it is not under advective effect. Using the grass reference standardized FAO-56 method (ALLEN et al., 1998), ET_0 can be estimated using only air temperature, relative humidity, solar radiation, and wind speed data.

In addition to ET_c, there is K_c, which is calculated by the ratio between ET_c and ET_0 (K_c=ET_c/ET_0). This coefficient was created to stablish the relationship between ET_c and ET_0, adding the local climate effect on the ET_c determined from a specific crop (JENSEN; BURMAN; ALLEN, 1990; ALLEN et al., 1998). Therefore, it is possible to use K_c values for any region that intends to determine the water consumption from any crop. This is possible by multiplying K_c and ET_0, resulting in the ET_c values (ET_c=K_c ET_0). In this way, ET_c can be determined in any region, allowing to stablish crop management strategies, especially those related to the dimensioning projects and irrigation management (LASCANO; SOJKA, 2007).

1.3 Leaf area index and cumulative thermal unit

LAI is a plant variable expressed as foliage density (or area) by the surface area available to the plants (m^2 m^{-2}). It can be used to understand different plant development phases, to comprehend the within and bellow canopy microclimate change, an indicative of plants water consumption, sunlight interception, and crop yield prediction (BREDA, 2003). LAI is variable during plant development, in which has low values in the beginning of plant development, increasing until maximum values during productive phase and it becomes low again during senescence period. Cumulative thermal unit (CTU) concept, also expressed as heat unit growing degree days, is an information that is usually correlated to predict some plant development phases (MILLS, 1964). It also con be associated to the speed in which plant develop, by associating the thermal effect to the plant growth. CTU is expressed by Equation 1:

$$CTU = \sum_{i=1}^{n}\left(\frac{T_{max}+T_{min}}{2} - T_b\right) \quad (2)$$

where

CTU - cumulative thermal unit (°C),

T_{max} - maximum air temperature of the day (°C),

T_{min} - minimum air temperature of the day (°C),

T_b - basal temperature threshold for each crop (°C).

The Allen et al. (1998) standardizing was essential for guarantee that ET_c and K_c studies were performed adequately, providing a batter comprehension about the climate effect on crop water consumption in different regions. Even the authors describe multiple K_c values for most of the commercial crops, it was observed a substantially increase of researches with K_c determination due the need to find values even more precise (FARAHANI; OWEIS; IZZI, 2008; HUNSAKER et al., 2011; PAYERO; IRMAK, 2013; LÓPEZ-URREA et al., 2016).

Utilizing K_c as the main variable to manage irrigation is essential, however, due this value is usually determined to a specific local, utilizing it for a different climate region that was originally determined is questionable. Using only K_c does not consider the extreme climate change neither the plant crop development in the local where intends to manage irrigation adequately. For these reasons, many studies were performed with the objective of correlating others variables with K_c values, such as days after emergence (STEGMAN et al., 1977), growing stage (DOOREMBOS; KASSAM, 1979), and fraction of thermal unit (AMOS; STONE; BARK, 1989; NIELSEN; HINKLE, 1996; STEELE; SAJID; PRUNTY, 1996; HUNSAKER, 1999; SEPASKHAH; ANDAM, 2001), allowing to better comprehend the specific water consumption dynamic from a crop in a different region were K_c was originally determined. However, the correlation between K_c and LAI index, as well as the correlation between K_c and CTU, have been widely used by many authors, showing that both approaches can be used to adjust K_c values for any region (CEREKOVIC; TODOROVIC; SNYDER, 2010; HUNSAKER et al., 2011; LENA FLUMIGNAN, FARIA, 2011; DJAMAN; IRMAK, 2013; BORGES, et al., 2015; HOWELL et al., 2015; SALAMA; YOUSEF; MOSTAFA, 2015). In addition, when CTU is used to correlate the K_c values, it has the advantage of considering the air temperature on the plant development, providing even better adjustment (RITCHIE; NESMITH, 1991; MARTINEZ-COB, 2008).

The objective of this study was to determine actual crop evapotranspiration and crop coefficient of jatropha from first to fourth year under center pivot and drip irrigation system, as well as for rainfed condition. In addition, it was also objective to stablish the relationship between crop coefficient with both leaf area index and cumulative thermal unit for the irrigated water managements, as well as to calibrate and test the LAI-2200 Plant Canopy Analyzer for jatropha leaf area index estimation.

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2 CROP EVAPOTRANSPIRATION AND CROP COEFFICIENT OF JATROPHA FROM FIRST TO FOURTH YEAR

Abstract

Water requirements from crops in an important information to manage irrigation. Jatropha (*Jatropha curcas* L.) actual crop evapotranspiration (ET_c) and crop coefficient (K_c) is still unknown, which is necessary to understand the plant water demand dynamic, as well as to stablish strategies to improve irrigation efficiency. The objective of this study was to determine jatropha ET_c and K_c from 1st to 4th growing year. The experiment was performed from March 2012 to August 2015 at "Luiz de Queiroz" College of Agriculture (ESALQ)/University of São Paulo (USP), Brazil. The experiment was divided into center pivot, drip, and rainfed treatments. Two large weighing lysimeters (12 m^2 surface area) were used per treatment to perform jatropha ET_c determination (one plant per lysimeter). Reference evapotranspiration (ET_0) was determined by grass based Penman-Monteith method using data from a weather station located close to the experiment. K_c was determined for the irrigated treatments by the ration between ET_c and ET_0 ($K_c=ET_c/ET_0$). For all years analyzed, ET_c values ranged from 0.7 to 8 mm d^{-1} for center pivot treatment, from 0.6 to 7.4 mm d^{-1} for drip treatment, and from 0.4 to 5.4 mm d^{-1} for rainfed treatment. It was observed higher values for irrigated treatments in comparison to rainfed treatment, which was explained by the higher soil water availability provided by irrigation. In the 1st year, K_c was 0.47 for both treatments, varying from 0.4 to 0.9. In the 2nd, 3rd, and 4th year, K_c ranged from 0.15 to 1.38 for center pivot treatment and from 0.15 to 1.25 for drip treatment. K_c average for 2nd, 3rd, and 4th during vegetative and productive growing stages together was 0.77, 0.93, and 0.82 for center pivot treatment, respectively, and 0.69, 0.79, and 0.74 for drip treatment, respectively. The reason K_c for center pivot treatment was slightly higher than drip treatment was due the high soil moisture after irrigation event, increasing soil evaporation rates. Annual ET_c and K_c fluctuation in 2nd, 3rd, and 4th years was very similar, which was explained by the growing stage and the leaf area index dynamic during the year, presenting values varying from 0 to 0.5 in the 1st year, from 0 to 1.4 in the 3rd year, and from 0 to 2 in the 3rd year. The comparison between K_c and leaf area index showed, for center pivot treatment, a logarithmical equation with coefficient of determination (R^2) and root mean square error (RMSE) of 0.7877 and 0.3831, respectively, and 0.8655 and 0.1419 for drip treatment, respectively. For all three years analyzed, K_c related to cumulative thermal unit showed a 3rd degree polynomial equation for both treatments, with R^2 ranging from 0.3373 to 0.6297 in the center pivot treatment and from 0.5445 to 0.6386 in the drip treatment.

Keywords: Irrigation; Water balance; Leaf area index; Cumulative thermal unit

2.1 Introduction

High quantities of feedstock are daily consumed to produce energy for human activities. Most of these feedstock comes from non-renewable source such as oil. Although petroleum has a well-defined energy chain, several consequences occur with its exploration and usage (KHARAKA; DORSEY, 2005). According to the International Energy Agency (IEA, 2012), in 2040 it will be necessary 54% more energy in comparison to 2011. Moreover, 84% of total energy produced will be from non-renewable sources such as natural gas, petroleum, and charcoal. With environmental impacts increase due the high fossil fuel consumption, governments started to look for renewable energy sources. In this context, it was observed in substantially increase of new researches with crops that produce renewable feedstock for biodiesel production (BASHA; GOPAL; JEBARAJ, 2009; BORUGADDA; GOUD, 2012; TABATABAEI et al., 2015). According to Atabani et al. (2012), biodiesel is very promising due the amount of feedstock available.

Jatropha (*Jatropha curcas* L.) is an oilseed currently used for biodiesel production, highlighted especially by some specifics characteristics such as drought tolerant, it requires low soil fertility, it presents fast development and easy propagation (OPENSHAW, 2000; ARRUDA et al., 2004; ACHTEN et al., 2008). In addition, its seeds have high oil content, varying from 27 to 40% depending on the plant management (HELLER, 1996; ACHTEN et al., 2008). Brittaine and Lutaladio (2010) mention that jatropha can be cultivated from 30°N to 35°S, showing the high ability to develop under different soil and climates. Even jatropha is able to survive in regions with low annual precipitation (from 250 to 300 mm), some authors describe better plant development under regions with annual precipitation varying from 1,000 to 1,500 mm (FACT, 2010). However, the jatropha water consumption is still unknown and this is the main reason that jatropha is not explored commercially yet (JONGSCHAAP et al., 2007; ACHTEN et al., 2008; MAES et al., 2009). Few studies can be found in the literature about jatropha water requirement (RAO et al., 2012; RAJAONA; SUTTERER; ASCH, 2012; GARG; WANI; RAO, 2014), however, there is not reliable information that can be used to manage irrigation adequately. Determining reliable actual crop evapotranspiration (ET_c) is necessary to characterize the amount of water required according to the local weather conditions and seasonal plant growing development, as well as to create a relationship between plant water consumption and local climate condition. There are many speculations about jatropha water consumption in the literature, but there is not continuous and long-term ET_c values.

According to Allen et al. (1998), ET_c is defined the sum of soil evaporation (and/or by the free water deposited after an irrigation or precipitation event) and the leaf transpiration over time. During the crop season, ET_c rates from a crop may vary substantially. Period of the year and local climate characteristic (radiation, wind speed, air temperature, and relative humidity), as well as the crop development characteristics (growing stages) and water management are the main reasons that ET_c rates is variable. To comprehend this ET_c dynamic, it is necessary to stablish the relationship between all this factor together.

There are many methodologies can be used to determine ET_c, highlighting the Bowen Ration Energy Balance System (BOWEN, 1926; TANNER, 1960; FRITSCHEN, 1962) and the weighing lysimeter (HOWELL; MCCORMICK; PHENE, 1985; ALLEN et al., 2011). Although weighing lysimeters are very expansive, it has the advance of good quality ET_c determination in short time period (HOWELL; MCCORMICK; PHENE, 1985; PAYERO; IRMAK, 2008; MARIANO et al., 2015). Once ET_c is determined, it can be used to comprehend the crop water consumption dynamic and to identify when crop water demand is higher or lower, improving the irrigation and water use efficiency.

In addition to ET_c, there is K_c, which is calculated by the ratio between ET_c and ET_0 ($K_c=ET_c/ET_0$). This coefficient was created to stablish the relationship between ET_c and ET_0, adding the local climate effect on the ET_c determined from a specific crop (JENSEN; BURMAN; ALLEN, 1990; ALLEN et al., 1998). When this relationship is created, it is possible to use K_c values for any region that intends to determine the water consumption from a crop. This is possible multiplying K_c and ET_0, resulting in the ET_c values ($ET_c=K_c\ ET_0$). In this way, ET_c can be determined in any region, allowing to stablish crop management strategies, especially those related to the dimensioning projects and irrigation management (LASCANO; SOJKA, 2007).

The Food Agriculture Organization of United States (FAO) Irrigation and Drainage Paper n° 56 (ALLEN et al., 1998) presents a range of K_c values for most commercially important crops, so it can be used to estimate ET_c for any region. However, studies indicate that K_c may change and may not be proportionally the same to different climates (GUERRA et al., 2014; GUERRA; VENTURA; SNYDER, 2015), and the use of K_c value as the only parameter to manage irrigation is questionable. Using both approaches of comparing K_c with leaf area index (LAI) and K_c with a cumulative thermal unit (CTU) can provide better comprehension about crop water consumption to any climate, and it can be used to improve irrigation efficiency as well. Studies with an interaction between K_c with LAI have showed that both components have a positive correlation (CEREKOVIK; TODOROVIC; SNYDER, 2010; LENA; FLUMIGNAN; FARIA, 2011; MANJNOONI-HERIS et al., 2012). According to this authors, it was observed that K_c and LAI may have linear or logarithmical correlation and it is directly associated to the crop growing stage. However, K_c in comparison with CTU has been showing that temperature has an important role in plant development (YAN; HUNT, 1999; RITCHIE; NESMITH, 1991), proving even more reliable understanding about the plant water consumption. The correlation with LAI and CTU is essential when K_c values are used to manage irrigation in regions with the different climate where K_c was originally determined. Determining the influence of LAI and temperature on plant development is essential to improve both irrigation and plant water use efficiency.

The objectives of this study were to determine continuous and long-term ET_c and K_c of jatropha from 1st to 4th year, as well as to stablish a relationship between K_c and LAI and K_c and CTU.

2.2 Material and Methods

This study was conducted in the experimental area of the 'Luiz de Queiroz' College of Agriculture, University of São Paulo, in Piracicaba city, São Paulo, Brazil (22º41'58''S and 47º38'42''W and 511 m altitude). The soil is a Nitisol (EMBRAPA, 2006) with a clay texture from 0 to 40 cm depth (53% clay) and a very clay texture from 40 to 120 cm depth (62% clay), with a density varying from 1.27 and 1.58 g cm^{-3} (FLUMIGNAN, 2011). The climate is subtropical humid with hot summer (Cwa), according to the Köppen-Geiger classification (KOTTEK et al., 2006). It is characterized by high precipitation amount in the hot summer and a mild dry winter, with mean annual temperature and total annual precipitation of 21.6 ºC and 1,328.1 mm, respectively (CEPAGRI, 2016).

The study was performed from 1st to 4th year crop, starting at March 2012 and ending at August 2015, with 42 months of experiment. This work is a sequence of Lena (2013), in which presented data during 1st and 2nd year for jatropha development. Seedlings were produced in greenhouse condition from September to November 2011, and transplanted to the experimental field in December 2011, with data collection started in March 2012, considering Jatropha annual season (or year) from September 1st to August 31st. Plants were cultivated in triangular spacing, with 3 x 4 m between plants and rows, respectively, totalizing 12 m^2 available area for each plant (834 plants ha^{-1}). In order to guarantee plant establishment after seedling, it was performed four irrigations of 10 mm each during the first month (until mid-January 2012). The experiment was divided into center pivot irrigation, drip irrigation, and rainfed treatments. In Figure 2.1, it can be observed the experiment layout with all treatments. The center pivot, drip, and rainfed treatments area were 1, 0.5, and 0.5 ha, respectively. For meteorological data collection, it was used an automatic weather station located close to the experimental area with 0.44 ha and cultivated with *Paspalum notatum* Flügge grass. The weather station measured data of air temperature and relative humidity, solar radiation, wind speed and direction, atmospheric pressure, net radiation, and precipitation every 3 s, providing averages in 15 minute, hourly, and daily intervals.

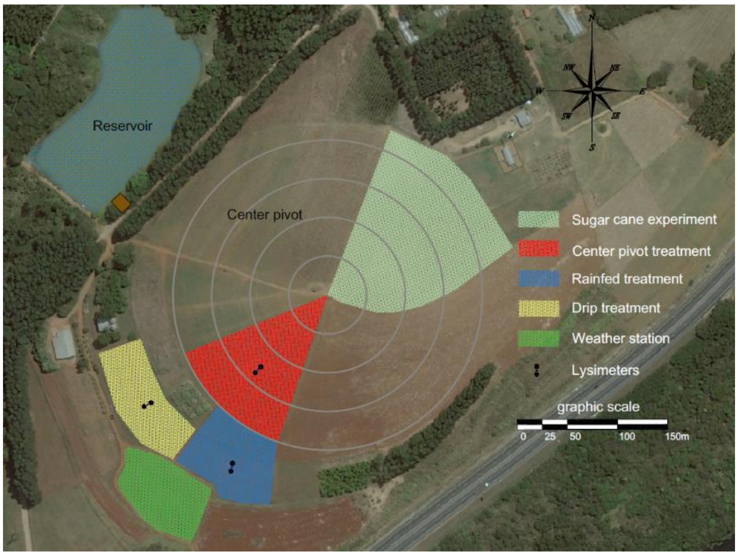


Figure 2.1 - Experimental area layout with the treatments and weather station

Plant height was measured using a tape by determining the distance between the soil surface and the highest plant leaf. Each assessment was performed with 5 plants per treatment randomly chosen, considering both plants in each lysimeter plus three plants outside the lysimeters, totalizing 15 plants for all treatments. LAI was performed using LAI-2200 Plant Canopy Analyzer (LI-COR, 2016), collecting data from 5 plants per treatments. According to the manufacturer suggestion, LAI was determined using the "isolated plant" methodology.

For jatropha ET_c determination, it was used two large weighing lysimeters per treatment, totalizing six lysimeters in the experiment. The lysimeters were constructed, calibrated, and tested by Flumignan (2011). The lysimeter tanks were made of carbon steel, circular with 12 m^2 (3.91 m diameter) and 1.3 m depth. The base of the tank was built in a cone format. The tank was supported by three concrete pillars, build with reinforced concrete. Load cells were positioned in between the tank and the concrete pillars. Two PVC cylindrical reservoirs were installed horizontally and below the lysimeters tanks to collect and storage the drainage water. These reservoirs were closed by a valve so the water inside was periodically manually drained.

The weighing system was composed by three load cells per lysimeter with 10 ton capacity each. One *datalogger* (model CR1000 from Campbell Scientific®) was used to collect the signal from the load cells for the two lysimeters in each treatment. Data were transformed to kilogram (kg) by using the calibration equations provided by Flumignan (2011) for each lysimeter. The mass of each lysimeter (kg) was converted to millimeters of water (mm) dividing by 12, which represents the lysimeter surface area in m^2.

The soil water storage from the lysimeters were used to calculate the plant water requirement to apply irrigation. To determined soil available water, it was used the difference between soil field capacity (FC) and permanent wilting point (PWP) by the soil retention curve provided by Flumignan (2011), where it was obtained 7% of soil available water in a volumetric basis. For 1.3 m depth from lysimeter soil, the different between FC and PMP was 90 mm (1,300 0.07). The soil water storage was graphically managed so the soil available water varied from 200 mm (at FC) to 110 mm (at PWP). The FC for lysimeters was determined according to Bernardo et al. (2005), considering accumulated precipitation during short period that guaranteed the soil saturation, in which the reservoir was kept open for four days so all the saturated water was percolated. In the end of the fourth day, it was considered the soil was at FC.

To determine water requirement for each irrigation event, it was used the lysimeters soil water storage data. In the center pivot treatment, the irrigation depth was applied according to plant requirement. In average, during vegetative and productive phases, irrigation was applied twice a week with 25 mm each. Since the drip irrigation system provides a fixed water application (2.5 L h^{-1} with 50 cm emitter flow interval), the water volume provided in each irrigation event was conditioned by the time that the system was kept on. The frequency of each application was, in average, three times per week with 5 hours each. For both treatments, irrigation was applied to maintain soil moisture above 50% of soil water holding capacity (SWHC).

ET_c was calculated from the water inputs, outputs, and variation soil water storage over time inside the lysimeter system using Equation 1:

$$ET_c = P + I \pm R - D \pm \Delta S \tag{1}$$

where

ET_c – Jatropha evapotranspiration, mm;

P – precipitation, mm;

I – irrigation depth, mm;

R – surface runoff, mm;

D – drainage, mm;

ΔS – variation in soil water storage inside the lysimeter, mm.

P was measured by the weather station, I was determined by the amount of irrigated water, D was determined by the amount of water drained by the drainage reservoirs (using the lysimeters data), and R was considered zero due the raised lysimeter edge (approximately 3 cm height). In addition to ET_c, daily ET_0 values were calculated using the REF-ET software (ALLEN, 2000). ET_0 was hourly estimated by using the grass based Penman-Monteith reference evapotranspiration method with the ASCE standardized equation (ASCE, 2005). The results of ET_c were statistically analyzed by Assistat v.7.7 software using t-test (Student, $p > 0.05$) for week average data to compare the results of annual ET_c average between treatments.

K_c was determined by the ratio between ET_c and ET_0 ($K_c = ET_c/ET_0$). The comparison between K_c and LAI was performed with LAI data from 1st, 3rd and 4th years. The reason of not using LAI data from the 2nd year was due the missing data of LAI during this year. For each LAI determination, a K_c average from 15 days before the LAI determination date was used to perform the comparison between both components. LAI and K_c was compared using Microsoft Office Excel software, presenting coefficient of determination (R^2) and root mean square error (RMSE).

The comparison between K_c and CTU was performed from 2nd to 4th year (each year separately), only during vegetative and productive growing stages. This period was between 1 and 273 days of new season (DNS), from September 1st to May 31st. CTU was determined according to the Equation 2:

$$CTU = \sum_{i=1}^{n} \left(\frac{T_{max} + T_{min}}{2} - T_b \right) \qquad (2)$$

Where

CTU - cumulative thermal unit (°C),

T_{max} - maximum air temperature of the day (°C),

T_{min} - minimum air temperature of the day (°C),

T_b - basal temperature threshold for jatropha (°C).

It was considered T_b for jatropha of 18 °C, according to Wassner (2007), however, those days in which T_b was below 18 °C, it was considered CTU equal to zero. The comparison was performed using daily values of K_c and CTU, presenting R^2 values provided by the Microsoft Office Excel software.

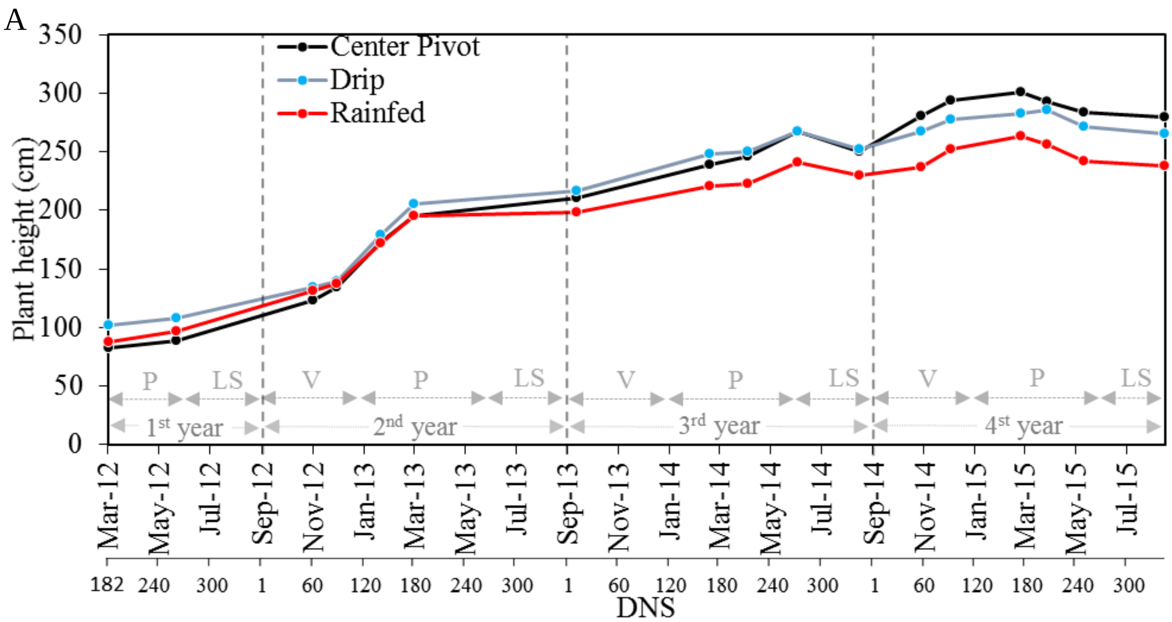
2.3 Results and Discussion

2.3.1 Plant growth and leaf area index

The jatropha growing season (or year) is composed by three growing phases, classified as vegetative, productive, and leaf senescence. From the beginning of vegetative (spring) to mid productive (summer) growing phases, plant height and LAI increased substantially until reaching maximum values. After the productive growing stage, it is observed a fast increase of leaves fall, moment that the plants are in the leaf senescence stage, characterized by the low LAI values.

Plant height within treatments was very similar during the experimental period (from 1st to 4th year) (Figure 2.2A). At the beginning of the experiment (March 2012) plants height were 82, 102, and 88 cm for the center pivot, drip and rainfed treatments, respectively, and 280, 265, and 238 cm at the end of the experiment for the same treatments, respectively (August 2015). Daily average growth was 0.15, 0.12, and 0.11 cm d^{-1} for the center pivot, drip and rainfed treatments, respectively. During vegetative and productive phases, plant height increased faster than leaf senescence phase (Figure 2.2A). While height increment from vegetative to productive phases was 0.40, 0.19, and 0.17 cm d^{-1} for the 2nd, 3rd, and 4th year, respectively, during leaf senescence phase was 0.05, -0.15, and -0.12 cm d^{-1} for the same years, respectively. The reason of negative values for the 3rd and 4th years was due the plant prune performed in the last month of both years (August), decreasing plant height when compared with the previously measurement.

From the 1st year (March 2012) to the beginning of 4th year (September 2014), plant height from drip treatment was slightly higher in comparison with others treatments (Figure 2.2A). For center pivot treatment, plant height was lower than others from the 1st year to mid-productive stage of the 2nd year, moment where rainfed treatment presented lower values until the end of 4th year crop. For center pivot treatment, plant height was higher than the others treatments only after September 2014, remaining with higher values until the end of the experiment (August 2015). Both irrigated treatments presented higher values in comparison with rainfed treatment during all experiment, with exception only during March 2012 and March 2013. During this period, it was observed high precipitation amount, so it was not necessary to provide irrigation to the irrigated treatments and, consequently, the plant water demand for all treatments was very similar. The water demand for all treatments was very similar due high precipitation amount, consequently, irrigation in both irrigated treatments was not performed. It is clear how close the values between irrigated and rainfed treatments were during this period, with a subsequent higher difference after March 2013.



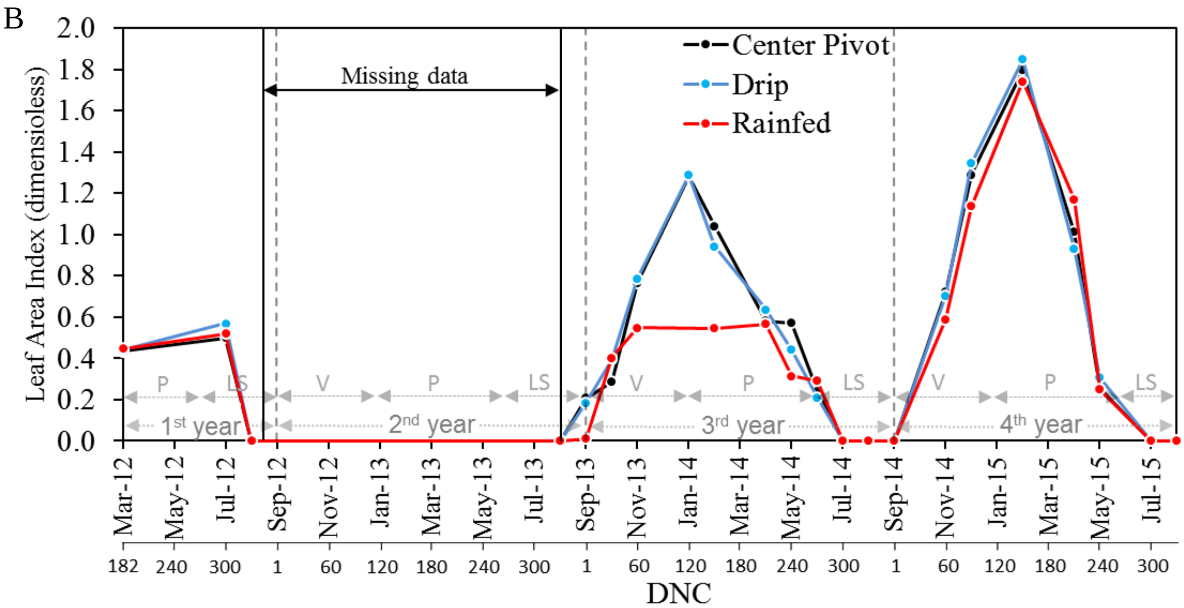


Figure 2.2 - Plant heights (A) and leaf area index (B) of center pivot, drip, and rainfed treatments from 1st to 4th year. “V” is vegetative phase, “P” is productive phase, “LS” is leaf senescence phase, and “DNS” is days of new season

For plant height, the statistical analysis showed that, in 7 out of 17 observations, there were difference between treatments (Table 2.1). It can be observed that, in March 1st 2012, the drip treatment was statistically different from other treatments at 5% level of probability by the Tukey test, however, in May 22nd 2012, drip treatment was different statistically from center pivot, but not from rainfed treatment. It can be explained by the fast development in the drip treatment during the beginning the experiment, also reflecting in higher LAI values (Figure 2.2B). Until April 4th 2014, it was not observed statistically difference for plant height between treatments. In this moment, plant height from rainfed treatment was different from drip treatment, but not different from center pivot and, in August 8th 2014, the values from rainfed treatment was different from others treatment, presenting values around 30 cm lower. From December 3rd 2014 to May 11th 2015, it was observed that drip treatment did not differ from others treatments, however, center pivot treatment was statistically different from rainfed treatments.

Table 1 – Statistic analysis results for plant height average by Tukey test for center pivot, drip, and rainfed treatments

Data	Plant height (cm)		
	Center Pivot	Drip	Rainfed
03/01/12	82^{b}	102^{a}	88^{b}
05/22/12	89^{b}	108^{a}	97^{ab}
11/01/12	123^{a}	134^{a}	131^{a}
11/29/12	134^{a}	139^{a}	137^{a}
01/20/13	173^{a}	179^{a}	172^{a}
03/01/13	195^{a}	205^{a}	195^{a}
09/11/13	211^{a}	217^{a}	198^{a}
02/17/14	239^{a}	248^{a}	220^{a}
04/04/14	246^{ab}	250^{a}	222^{b}
06/03/14	268^{a}	267^{a}	241^{a}
08/15/14	250^{a}	252^{a}	230^{b}
10/28/14	280^{a}	267^{a}	237^{a}
12/03/14	294^{a}	278^{ab}	252^{b}
02/24/15	301^{a}	282^{ab}	264^{b}
03/27/15	293^{a}	285^{ab}	256^{b}
05/11/15	284^{a}	271^{a}	242^{a}
15/08/15	280^{a}	265^{a}	238^{a}

* Averages followed by the same letter in the column differ each other by t-test (Student) at 0.05 significance level.

In Figure 2.2B is presented LAI data from 1st to 4th year of jatropha for all treatments. In the 1st year, LAI values was very similar between treatments and it is explained by the high precipitation occurred during this period. Irrigation was not necessary, so all treatments had similar soil water available during the 1st year period. In the second 2nd year, no data of LAI were recorded, so the LAI presentation and analysis was performed with the results of 3rd and 4th year. Considering the annual cycle, there was an increase of LAI from the beginning of vegetative phase until mid-productive phase (from September to February), which was observed a maximum value for both years analyzed in all treatments. As the plant initiated the leaf senescence phase, LAI had a gradual decrease until reaching zero, moment that the plants were completely without leaves (from March to August).

Comparing jatropha LAI between 3rd and 4th year, it was verified very similar values during spring and winter for both years, however, with a slightly superiority during summer and fall for the 4th year. While the maximum values of LAI in the 3rd year were 1.3 for both irrigated treatments and 0.6 for rainfed treatment, in the 4th year the maximum values were around 1.8 for all treatments. The higher maximum values in the 4th year in comparison with 3rd was due bigger plant height in the 4th year, which provided a higher leaf density.

It was observed that from November 2013 to April 2014 the LAI of rainfed treatment was lower than irrigated treatments, showing the influence of irrigation on jatropha plant development. While it was observed water drought stress in the plant for rainfed treatment, for the irrigated treatments the water was being replaced adequately until February 2014 by irrigation, contributing for the higher values observed. In the 4th year, it was observed that LAI for rainfed treatment was similar to both irrigated treatments, which was also explained by the water replacement. During 4th year, the water was not provided by irrigation for both irrigated treatments due the low reservoir water level used in the irrigation system, so the only water replacement for all treatments was due the precipitation. Consequently, LAI was similar between treatments (maximum difference of 0.2 in November 2014).

The LAI evaluation was considered a valuable tool to comprehend ET_c variation among years and treatments. It is possible to affirm that, according to the LAI values presented, this component influenced directly ET_c rates. Once LAI increased (during vegetative and productive phases), the jatropha plant water consumption also increased, observed by the higher ET_c rates. During leaf senescence LAI decreased and, consequently, a lower ET_c rates was observed. The moment that LAI values were maximum, ET_c data were also maximum, demonstrating that water consumption was directly related to the LAI.

2.3.2 Soil water storage

The soil water storage was evaluated from 1st to 4th year for all treatments and the daily values are presented in Figure 2.3. Soil water storage data is essential to determine ET_c, but it requires a very carefully analysis and interpretation in order to find and exclude possible errors. Allen et al. (1998) describes that ET_c is only valid if plants are not under any stress, i.e., when soil condition (water and nutrition availability) and plant sanity (disease and pasts) are not affecting on the adequate plant development. We observed disease, weeds, and pests, and we were not able to perform irrigation on the irrigated treatments during some period in the experiment. The data were consequently excluded so only reliable data were used. Within the 1279 days analyzed during the experiment, it was used 976, 945, and 694 days for the center pivot, drip, and rainfed treatments representing 76.3, 73.9, and 54.3% from total, respectively. The reason why rainfed was around 20% lower than others treatments was due the plant death in both lysimeter that occurred during the 3rd year, so it was determined ET_c during this year.

In Figure 2.3, it is possible to observe that during some moments, the soil water storage from irrigated treatments was below 50% from SWHC. These periods were between early August and early December 2012 for center pivot treatment, late December 2013 and late August 2014 for drip treatment, and most part of 4th year for both irrigated treatments. When it was observed soil water storage level below 50% of SWHC, ET_c data from both irrigated treatments were exclude because it was considered that jatropha plants were under water deficit stress. In 2014, the annual precipitation in Piracicaba city was 700 mm, and it represented only 53% from annual average. Consequently, the reservoir water level was below the pump velvet level for drip irrigation system, which as not possible to perform irrigation from January to late October 2014 in this treatment. With the return of regular precipitation, the reservoir water level started to increased, however, the reservoir water level was only adequate to perform the irrigation after March 2015, so we considered that irrigation was not influencing the plant water demand until the end of the experiment. It is important to emphasize the decision-making of not perform the irrigation during 4th year of evaluation because, according to the plant development, it is not necessary to provide water from irrigation from late reproductive to leaf senescence phases. Besides jatropha has the ability in tolerate water deficit stress, especially during leaf senescence phase, the plants will not use water even with high soil water availability. Therefore, ET_c during leaf senescence in the 4th year was considered adequate.

In the 1st year, the soil water storage was very similar in all treatments (Figure 2.3). Also, the irrigation was not performed due the high amount of precipitation, in which was essential to maintain soil water storage close to FC. In the 2nd year, it was also observed high quantities of precipitation and well distributed from mid-November 2012 to early April 2013 and from late May to mid-July 2013. Irrigation depths were generally lower during these periods than other, since precipitation was replacing water to the plants satisfactorily. Therefore, irrigation was essential in maintaining the soil moisture near the FC. In the 3rd year, due the low precipitation, it was not able to perform irrigation only for drip treatment after mid-January 2014. It is possible to observe that irrigation influenced the soil water storage in both treatments during the 3rd year. With exception during January, February, March, and August

2014, the soil water storage of center pivot treatment was above 50% of SWHC, showing the irrigation effect on the soil water level increasing. Since irrigation was not performed during 4th year for both irrigated treatment, the soil water storage fluctuation was very similar within treatments.

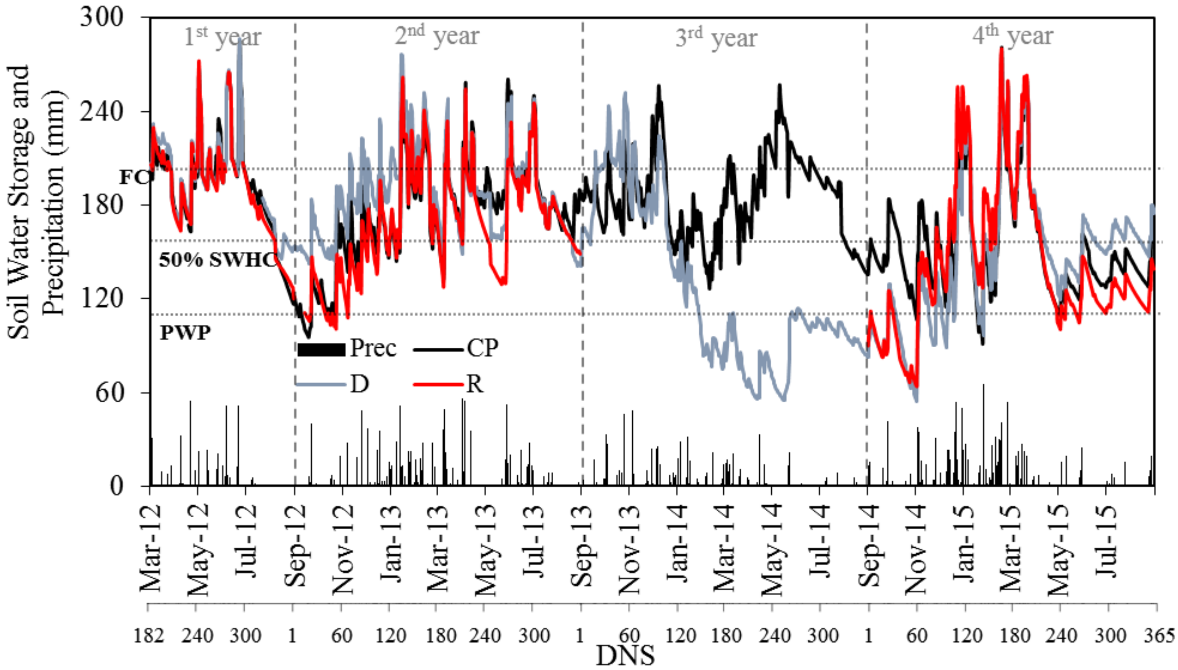
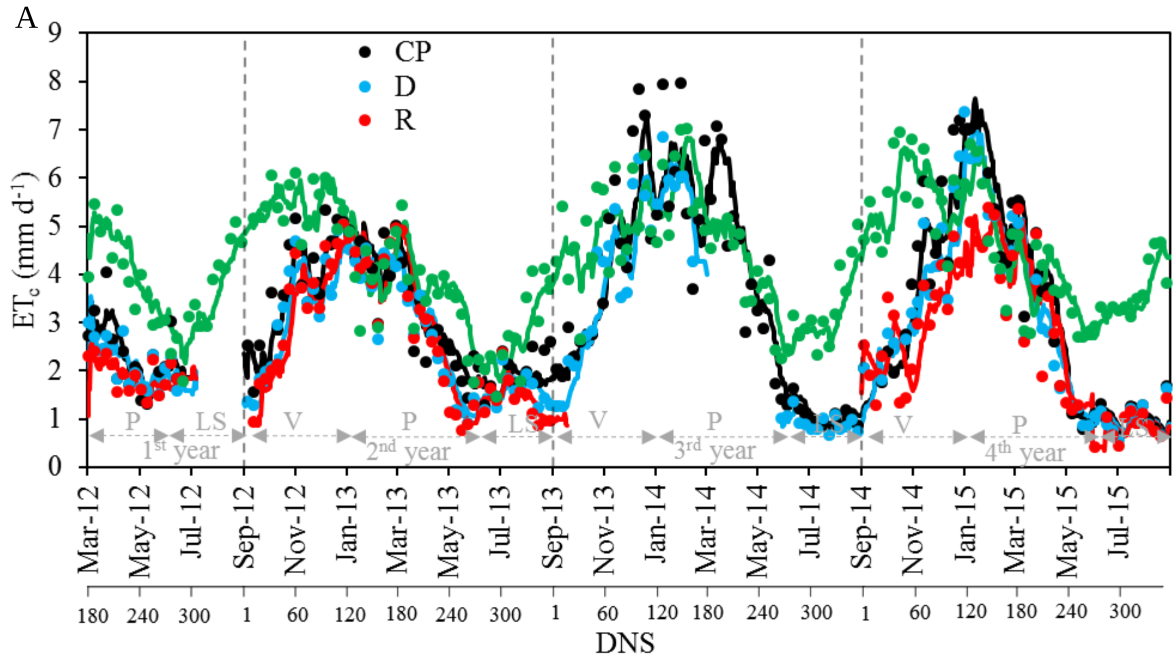


Figure 2.3 - Soil water storage of treatments irrigated by center pivot, drip, and rainfed and precipitation from 1st to 4th year of jatropha. FC is the field capacity; SWHC is the soil water holding capacity; PWP is the permanent wilting point

2.3.3 Actual crop evapotranspiration and crop coefficient

In Figure 2.4A, ET_c weekly average values for all the treatments varied from 1 to 8 mm d^{-1} during all experiment, and ET_0 values ranged from 2 to 6.5 mm d^{-1} during the same period. With exception of the 1st year, the highest ET_c values were observed from October to March, while the lowest values occurred between April and September (Figure 2.4A). The ET_c dynamic during the annual season is mainly explained by the jatropha growing phases. During vegetative and productive, the plants are producing new leaves, flowers and fruits, requiring high amount of water, increasing ET_c rates. After the productive phase, the plants start the leaf senescence, moment when all leaves fall and the plants reduce the water consumption. The irrigation frequency increased or decreased depending on the jatropha water demand during the growing periods.



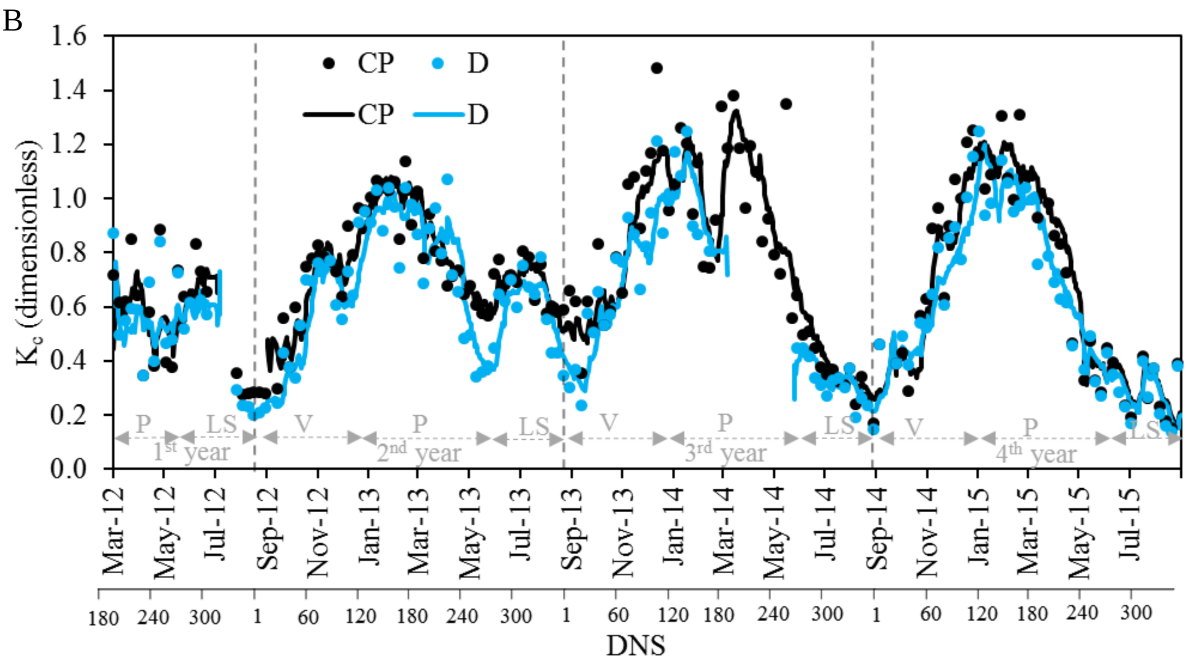


Figure 2.4 - Weekly average (dots) and 30 days moving average (lines) for reference evapotranspiration (ET_0) and crop evapotranspiration (ET_c) (A), and crop coefficient (K_c) (B) of jatropha for the treatments irrigated by center pivot, drip, and rainfed from 1st and 4th year. DSN is days of new season

From March to September 2012, ET_c values were generally less than 3 mm d^{-1} (Figure 2.4A), explained due the plants were at the beginning of development (low IAF and plant height), presenting only vegetative growth. However, in the 2nd year, ET_c rates increased after October 2012, with higher values during the vegetative and productive phases, when values ranged from 3.5 to 5 mm d^{-1}. After the productive phase, it was observed a substantially decrease of ET_c rates due the leaf senescence stage, with values ranging from 1 to 2 mm d^{-1}.

The 3rd and 4th year was very similar to 2nd, with increase of ET_c during vegetative, higher values during productive, and a decrease when plant started the leaf senescence phase. From December to April, ET_c ranged from 4 to 8 mm d^{-1} and from 3 to 7 mm d^{-1}, respectively, in the 3rd and 4th year.

Considering data only from 2nd to 4th year, ET_c rates for center pivot treatment presented higher values, followed by drip and rainfed treatments. The difference of ET_c rates between irrigated treatments was due the way the water was applied. In the center pivot irrigation system, the water was applied over the entire soil surface, increasing the soil surface moisture and, consequently, increasing the soil evaporation rates after irrigation. Moreover, it was also observed water drops on the top of leaves after irrigation, contributing to the increase of free water evaporation. In comparison to the drip irrigation system, the water was applied only close to the main stem of the plant, so only a small portion of the soil surface had the soil moisture increased, and there were not water drops on the top of the leaves as well. Consequently, the soil evaporation rates were lower in the drip treatment in comparison to center pivot treatment, considering the main reason to the difference on ET_c rates for both treatments. The irrigation system influence on ET_c rates was also observed for crops with high spacing cultivation such as coffee tree (FLUMIGNAN; FARIA; PRETE, 2011; LENA; FLUMIGNAN; FARIA, 2011) and blueberry (BRYLA; GARTUNG; STRIK, 2011). The statistical analysis for ET_c annual values showed that, in the 2nd year, there was difference between treatments ($p < 0.05$), however, for 3rd and 4th year there was not difference (Table 2.2).

Table 2.2 – Actual crop evapotranspiration (mm d^{-1}) as function of water management from 2nd to 4th year for jatropha

Treatment	2nd year	3rd year	4th year
Center Pivot	3.08^{a}	3.35^{a}	3.36^{a}
Drip	2.65^{ab}	3.00^{a}	2.98^{a}
Rainfed	2.54^{b}	*	2.70^{a}

*Missing data. Averages followed by the same letter in the column differ each other by t-test (Student) at 0.05 significance level

In Figure 2.4B is presented the weekly K_c average for the irrigated treatments from 1st to 4th year, with the vegetative (1-120 DNS), productive (121-270 DNS), and leaf senescence growing phases (271-365 DNS). Similarly to ET_c, K_c also varied during the annual cycle due the jatropha growing phase, with an increase of K_c values in the vegetative, a maximum during productive and a decrease in the leaf senescence (Figure 2.4B).

K_c values ranged from 0.14 to 1.38 for center pivot treatment and from 0.15 to 1.25 for drip treatment. During the 1st year, it was not necessary to provide water from irrigation due the high amount of precipitation (Figure 2.3) and because plants were with low height, with both treatments presenting very similar K_c values, ranging from 0.35 to 0.87 in both treatments. K_c average during 1st year was 0.6 and 0.55 for center pivot and drip treatments, respectively, showing a small difference due the similarity of water availability. From the 2nd year, it was observed difference of K_c values between treatments due the irrigation, as well as the K_c fluctuation pattern over the year. In the 2nd year, K_c ranged from 0.28 to 1.14 in the center pivot treatment and from 0.23 and 1.04 for the drip treatment. The 3rd and 4th K_c fluctuation was very similar, ranging from 0.15 to 1.38 for center pivot and 0.14 and 1.25 for drip treatment, respectively. For the 2nd, 3rd, and 4th year, it was also observed higher K_c values of jatropha during productive phase, followed by the vegetative and leaf senescence phase. In mid-December 2013, mid-January 2014, and early and mid-March 2014, it was observed K_c values above 1.3 for center pivot treatment, values considered slightly higher than those that are considered feasible for most of crops (ALLEN et al., 1998). It was explained by the increase of soil water availability from the irrigation, increasing ET_c values (above 7 mm d^{-1}), as well as by the low ET_0 rates during the week analyzed (below 5 mm d^{-1}), contributing for the increase of K_c values.

During some moments in all years analyzed, it was observed water drought stress, and pest and disease as well. Considering the Allen et al. (1998) recommendations for adequate K_c determination, it was necessary to exclude some values of K_c for both treatments (Figure 2.4B). However, during leaf senescence phase in the 3rd and 4th year, K_c values were considered adequate even under drought stress. The jatropha plant has a deciduous characteristic, i.e., it loses all leaves during the coldest period of the year (from 274-365 DNS). As jatropha was completely without leaves and the culture has the ability to survive in extreme drought condition, we decided that irrigation would not be necessary so we did not exclude the K_c values during this growing phase for 3rd and 4th year. Comparing only the leaf senescence phase between 2nd year and 3rd and 4th years, it was observed that irrigation increased K_c values, which is explained by the elevation of soil evaporation after irrigation event. Even if water is provided by irrigation during leaf senescence phase, the jatropha plants will not consume it. Irrigation is not necessary for this growing phase, so it is possible to save water and energy. The irrigation will only influence on the plant development from vegetative to productive stages, period that plants require water to produce new leaves, branches, and fruits.

2.3.4 ET_c and K_c values synthesis

All data observed was compiled and presented monthly and during each phenological phase averages in two separated tables. In Table 2.3 it is presented monthly ET_c and ET_0 averages, as well as the K_c values. The highest ET_c in the 1st year were observed in March 2012, with values of 3, 2.3, and 2 mm d^{-1} for center pivot, drip and rainfed treatments, respectively. In the 2nd year, the month in which ET_c was higher was in December 2012 for the center pivot treatment (4.8 mm d^{-1}) and in January 2013 for the drip and rainfed treatments (4.5 mm d^{-1}). The lowest ET_c values were observed in August 2012 for all three treatments (1.3, 1, and 0.8 mm d^{-1} for the center pivot, drip, and rainfed treatments, respectively). In the 3rd year, the highest ET_c values was observed in January 2014 (7.6 and 6.1 mm d^{-1} for center pivot and drip treatments, respectively) and the lowest ET_c in July 2014 for center pivot treatment (1.0 mm d^{-1}) and in August 2014 for drip treatment (0.9 mm d^{-1}). In the last year of experiment, jatropha ET_c was higher in February 2015 for center pivot (6.9 mm d^{-1}) and rainfed (4.9 mm d^{-1}) treatments, and January (6.3 mm d^{-1}) for drip treatment, and lower in June for all treatments (1, 0.9, and 0.8 mm d^{-1} for center pivot, drip, and rainfed treatments, respectively). K_c monthly values were not higher than 1.3 and 1.1 for center pivot and drip treatments, respectively, and not lower than 0.2 for both treatments. From December to February for 2nd, 3rd, and 4th years, K_c values were always close to 1, showing that during summer the jatropha plants require more water than other periods of the year.

Table 2.3 – Crop evapotranspiration (ET_c), reference evapotranspiration (ET_0), and crop coefficient (K_c) of jatropha in the center pivot (CP), drip (D), and rainfed (R) water management from 1st and 4th year

Year	Date	ET_c CP (mm d^{-1})	ET_c D (mm d^{-1})	ET_c R (mm d^{-1})	ET_0 (mm d^{-1})	K_c CP (dimensionless)	K_c D (dimensionless)	Year	Date	ET_c CP (mm d^{-1})	ET_c D (mm d^{-1})	ET_c R (mm d^{-1})	ET_0 (mm d^{-1})	K_c CP (dimensionless)	K_c D (dimensionless)
1st year	Sep/12	*	*	*	*	*	*	3rd year	Sep/13	2.3	1.5	*	4.9	0.5	0.3
	Oct/12	*	*	*	*	*	*		Oct/13	3.1	3.1	*	5.3	0.6	0.7
	Nov/12	*	*	*	*	*	*		Nov/13	5.1	4.1	*	5.2	1.0	0.8
	Dec/12	*	*	*	*	*	*		Dec/13	4.2	5.6	*	5.8	1.1	1.1
	Jan/13	*	*	*	*	*	*		Jan/14	7.6	6.1	*	6.4	1.2	1.0
	Feb/13	*	*	*	*	*	*		Feb/14	*	*	*	6.1	0.9	*
	Mar/12	3.0	2.3	2.0	5.0	0.6	0.5		Mar/14	3.3	*	*	5.1	1.3	*
	Apr/12	2.0	1.9	1.8	4.5	0.5	0.4		Apr/14	4.1	*	*	4.5	1.0	*
	May/12	1.6	1.7	1.4	3.6	0.5	0.5		May/14	2.6	*	*	3.2	0.8	*
	Jun/12	2.0	2.0	2.0	3.1	0.7	0.7		Jun/14	1.3	1.0	*	2.9	0.5	0.4
	Jul/12	*	*	*	3.6	*	*		Jul/14	1.0	1.0	*	3.1	0.3	0.3
	Aug/12	*	*	*	4.7	*	*		Aug/14	1.1	0.9	*	4.3	0.3	0.2
2nd year	Sep/12	1.7	1.4	1.1	5.2	0.4	0.3	4th year	Sep/14	2.1	2.1	2.2	4.9	0.4	0.4
	Oct/12	3.9	3.1	2.6	5.6	0.8	0.6		Oct/14	2.5	2.8	2.2	6.5	0.4	0.5
	Nov/12	3.6	3.4	3.3	5.8	0.7	0.7		Nov/14	4.7	4.0	3.3	5.7	0.8	0.7
	Dec/12	4.8	4.2	4.3	5.5	0.9	0.8		Dec/14	6.0	5.3	4.0	5.4	1.1	1.0
	Jan/13	4.7	4.5	4.5	4.2	1.1	1.0		Jan/15	5.1	6.3	4.5	4.4	1.1	1.0
	Feb/13	4.6	4.2	4.3	4.2	1.0	0.9		Feb/15	6.9	4.6	4.9	5.8	1.2	1.1
	Mar/13	*	*	*	4.3	*	*		Mar/15	4.4	3.7	4.1	3.7	1.0	0.8
	Apr/13	2.3	2.4	2.0	3.8	0.7	0.6		Apr/15	3.1	2.5	2.5	4.1	0.8	0.6
	May/13	1.9	1.2	1.0	3.3	0.6	0.4		May/15	1.0	1.1	1.2	2.9	0.4	0.4
	Jun/13	1.6	1.5	1.6	2.2	0.7	0.7		Jun/15	1.0	0.9	0.8	3.3	0.3	0.3
	Jul/13	2.1	1.8	1.6	2.7	0.8	0.7		Jul/15	1.0	1.0	0.9	3.3	0.3	0.3
	Aug/13	2.0	1.5	1.0	3.9	0.6	0.4		Aug/15	1.0	0.9	0.9	4.4	0.2	0.2

* Missing data

Although Table 2.3 data can be used for more refined applications, Table 2.4 shows more summarized data for ET_c, ET_0, and K_c values for each growing phase in the center pivot, drip, and rainfed treatments. Based on the small height and LAI of jatropha plants during the 1st crop year and the small differences of ET_c values between treatments, it was considered an average of 1.8 mm d^{-1}. In the 2nd, 3rd, and 4th year, ET_c values were higher during productive, intermediate during vegetative and lower during productive phase (Table 2.4), with exception for the 2nd year, in which during leaf senescence growing phase was similar than vegetative phase. Since K_c was calculated by the ratio between ET_c and ET_0, the difference between treatments followed the same proportion that was observed for ET_c rates. K_c values was higher during productive phase for the three years analyzed, varying from 0.9 to 1 for center pivot treatment and from 0.8 to 0.9 for drip treatment. In the 2nd year, K_c during leaf senescence phase was slightly higher than observed values for vegetative phase, which did not occur in the 3rd and 4th year. While in the 2nd year the plants were normally irrigated during leaf senescence phase, in the 3rd and 4th year there was not irrigation for the plants in the same phase, increasing K_c values during leaf senescence phase in the 2nd year. This comparison allows to observe that even there was available water in the soil, the plants did not use the water and most of the water was evaporating from the soil surface.

Table 2.4 – Crop evapotranspiration (ET_c), reference evapotranspiration (ET_0), and crop coefficient (K_c) values by growing stage for jatropha in the center pivot, drip, and rainfed water management from 1st to 4th year

Year	Phenological phase*	ET_c			ET_0	Kc	
		Center Pivot	Drip	Rainfed		Center Pivot	Drip
		mm d^{-1}				dimensionless	
1st year	All year (Mar to Aug)	1.8			3.9	0.5	
2nd year	Vegetative (Sep to Nov)	3.4	2.9	2.9	5.4	0.6	0.5
	Productive (Dec to May)	3.7	3.3	3.4	4.0	0.9	0.8
	Leaf senescence (Jun to Aug)	1.8	1.6	1.4	2.8	0.7	0.6
3rd year	Vegetative	3.3	3.1	-	4.7	0.7	0.6
	Productive	5.1	5.0	-	4.9	1.0	0.9
	Leaf senescence	1.1	0.9	-	3.3	0.4	0.3
4th year	Vegetative	3,4	3,2	2,6	5,7	0.6	0.6
	Productive	5.0	4.4	3.8	4.8	1.0	0.9
	Leaf senescence	1.0	1.0	0.9	3.7	0.3	0.3

* Months coincide with the phenological stages in the studied area. These months may vary in other regions

Although it is possible to observe an increase of researches with jatropha plant in many filed areas, especially those with the jatropha oil characteristics for biodiesel production (NAYAK; PASTEL, 2010), socioeconomic aspects of oil production in developing countries (CARELS, 2009), and the need to improve the productive chain from harvest to biodiesel production (LIM et al., 2015), information about lysimeter based ET_c determination for jatropha is still unknown. Some studies describe that irrigation can improve yield (EVANGELISTA et al., 2011; OLIVEIRA et al., 2012; ANDRADE, 2016), however, there is not good, continuous, and reliable information that can be used to manage irrigation. Our findings can be considered the first that used adequate methodology to determine ET_c and K_c continuously during 3 years and a half in three water management for jatropha. Some studies were performed to determine ET_c and K_c for jatropha (RAJAONA; SUTTERER; ASCH, 2012; GARG; WANI; RAO, 2014), but the results were based on estimation and for short periods. One example is the study presented by Suterer (2010), which had the objective of determining ET_c based on adjusted jatropha K_c. The author reported ET_c values between 1.9 mm d^{-1} during initial and final periods and 5.5 mm d^{-1} in the mid-period. To calculate the ET_c rates, the author used adjusted K_c values from data reported in the literature in combination with estimates recommended by Allen et al.

(1998). K_c values were 0.6, 1.2, and 0.4 for the initial (vegetative), mid (productive), and final stages (leaf senescence), respectively. Despite the efforts of the author to estimate ET_c and K_c values for jatropha, it is important to determine continuous and long-term data with appropriate methods such as weighing lysimeters methodology, as presented in our study.

2.3.5 Correlation between K_c and LAI and K_c and CTU

The proposal of comparing K_c with LAI can be used as an additional information to manage jatropha irrigation, adding better comprehension about jatropha water consumption. The relationship was performed during 1st, 3rd, and 4th year crop, using the K_c and LAI results presented for center pivot and drip treatment in Figure 2.2B and Figure 2.4B, respectively. It can be observed the best adjustment was the logarithmic equation for both treatments, with R^2 of 0.7643 and 0.8443 for center pivot and drip treatments, respectively, with RMSE of 0.3340 and 0.2079 for center pivot and drip treatments, respectively (Figure 2.5).

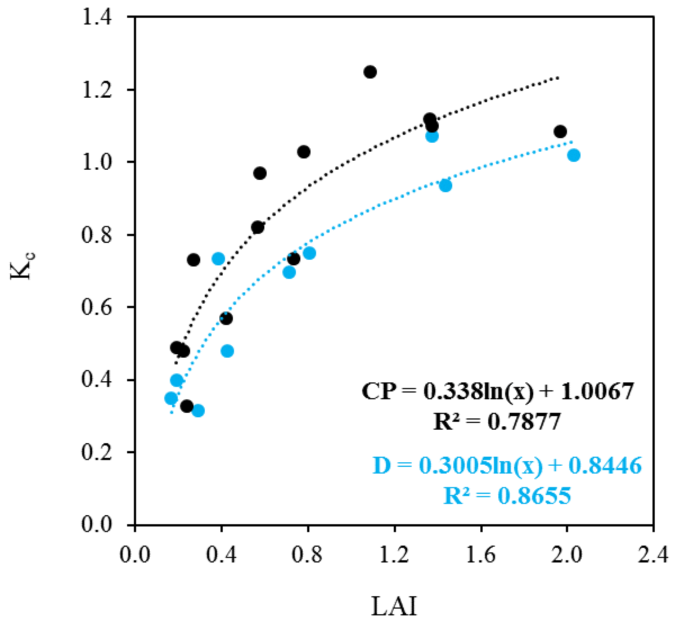


Figure 2.5 - Correlation between crop coefficient (K_c, dimensionless) and leaf area index (LAI, dimensionless) for center pivot (CP) and drip (D) treatments

Many studies can be found in the literature with the relationship between K_c and LAI of crops. The authors usually mention that using only K_c data to manage irrigation is questionable and, when K_c is related to LAI, it is possible to better understand the plant water requirement. Using tomato in South Italy, Cerekovic, Todorovic and Snyder (2010) observed that the best equation was the logarithmic, with R^2 of 0.8341. Majnooni-Heris et al. (2012) mention that, for canola irrigated in Iran, the logarithmic equation was considered the best to the observed data for the correlation between K_c and LAI, with R^2 of 0.88. There is not information in the literature about this relationship for jatropha, however, the results presented for others crops were very similar to those presented in this study, with logarithmic equation tendency with R^2 higher than 0.75.

For the comparison between K_c and CTU, it was calculated CTU only during vegetative and productive phases. CTU for the 2nd, 3rd, and 4th year was 1,724, 1,674 and 1,726 °C, respectively. From 60 to 200 DNS, it was observed that CTU increased faster in all years analyzed, coinciding with the hottest period of the year. However, from 1 to 60 and 201 to 273 DNS had low CTU increment, period with mild temperature rates. For all years analyzed (Figure 2.6), it was observed a 2nd order polynomial equation. The R^2 values varied from 0.33 to 0.61 for center pivot treatment and from 0.52 to 0.61 dor drip treatment. It was observed higher values of R^2 in the 4th year (Figure 2.6C) in both treatment, with very close values each other. It was observed that the K_c vs CTU fluctuation was very similar within the years. As CTU data increase, daily K_c also increased, reaching a maximum K_c when CTU was between 800 and 1000 °C, followed by a decrease of K_c until the end of the season. Center pivot treatment values were slightly superior in comparison with drip treatment, except for the 4th year between 1 and 70 DNS, which it was observed higher values for drip treatment.

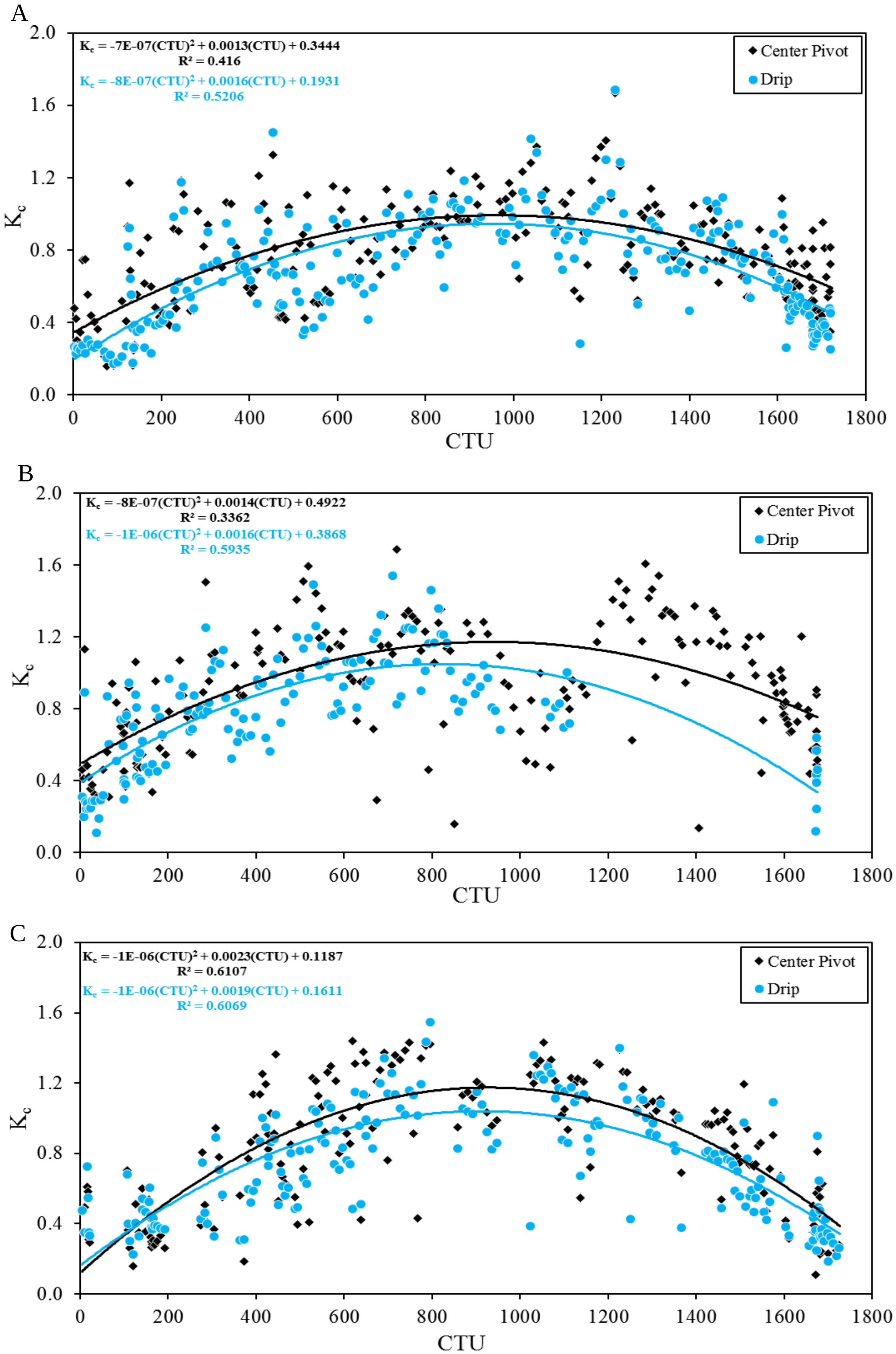


Figure 2.6 - Crop coefficient (K_c, dimensionless) and cumulative thermal unit (CTU, °C) for 2nd (A), 3rd (B), and 4th (C) year from 0 to 273 days of new season of jatropha cultivation

Studies with the comparison between maize K_c values and fraction of thermal unit (CTU/day after planting), Martínez-Cob (2008) presented a 3rd order polynomial equation with R^2 of 0.771 and 0.647 in the 1997 and 1998 growing season, respectively. Howell et al. (2015), comparing sunflower K_c during 2009 and 2011 seasons with CTU, mentioned values that was very similar with the data fluctuation presented in this study, especially when during the stages with higher water requirement. In order to identify the K_c fluctuation for winter wheat in Nebraska, EUA, Irmak, Djaman and Sharma (2015) found that K_c varied depending on year season and this component can be compared with CTU to improve the water usage in irrigation system. These authors found as the best equation a 6th order polynomial for both 2008/09 and 2009/10 seasons. Besides the shape of the equation line was different with the equation presented in this study, it is possible to affirm that the comparison between K_c and CTU in cultures tends to present higher values during the periods with high water demand by the plants (vegetative and productive) and lower values during establishment and end season period.

2.4 Conclusions

1. Jatropha ET_c and K_c varied as a function of plant development over year, during the year and according to the water management method.
2. Higher ET_c values were observed in the treatment irrigated by the center pivot system, followed by the drip and rainfed treatments.
3. ET_c varied from 1 to 8 mm d^{-1} in all treatments, with medium values during vegetative phase, higher during productive phase, and lower during leaf senescence phase.
4. K_c was slightly higher for center pivot than drip treatment, ranging from 0.14 to 1.38 for center pivot and from 0.15 to 1.25 for drip;
5. The correlation between K_c and LAI was adjusted by a logarithmical equation with R^2 higher than 0.75 for both treatments; and K_c and CTU showed a 3rd degree polynomial equation for both treatments

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3 PERFORMANCE OF LAI-2200 PLANT CANOPY ANALYZER ON LEAF AREA INDEX OF JATROPHA NUT ESTIMATION

Abstract

Leaf area index (LAI) of crops can be determined by many different methodologies with direct or indirect measurements. The use of sensors to estimate LAI has the advantage of fast and easy measurements, however, it is necessary to test and calibrate in order to verify its reliability. The objective of this study was to calibrate and test the LAI-2200 Plant Canopy Analyzer on the estimative of LAI of jatropha nut trees. The study was conducted in the experimental area of Biosystems Engineering Department of ESALQ/USP, in Piracicaba, Sao Paulo, Brazil. The test was performed with 9 jatropha nut plants, by comparing estimated LAI data with LAI-2200 equipment with real LAI by destructive sampling. The isolate plant measurement model overestimated around 30% of real LAI and the pattern measurement model underestimated around 10%. Both models were considered adequate according to the statistical parameters results and they can be used to correct estimated LAI in order to present better result of LAI for jatropha nut.

Keywords: Sensor calibration, gap fraction, canopy light interception.

3.1 Introduction

Leaf area index (LAI) of crops is a component used in many studies in different research area. LAI, also expressed as foliage density (or area) by the surface area available to the plant (m^2 m^{-2}), can be used to comprehend the within and bellow canopy microclimate change, an indicative of water consumption by the plants, sunlight interception, and crop yield prediction (BREDA, 2003).

LAI can be determined by many different methodologies with direct and indirect measurement and, depending on the method, it can be more or less complex with advantage or disadvantage (GOWER; KUCHARIK; NORMAN, 1999; JONCKHEERE et al., 2004). The direct measurement provides reliable data, but is timing consuming and may be impractical according to the amount of data required. Indirect methods that use sensors to estimate LAI of crop is becoming very common due the advantage of performing multiples measurements in short time and it can be applied by any crop. One sensor that is widely used is the LAI-2200 Plant Canopy Analyzer (LI-COR, 2016), which has the advantage of estimating LAI of crop in an easy, fast, and simplified way. LAI-2200 uses a fish-eye sensor that estimates LAI from the light interception at five zenith angles. It calculates LAI by the gap fraction from above and below canopy measurements. In the literature, it is possible to observe many studies that use LAI-2200 and the previous version (LAI-2000) in different crops (GUARRIGUES et al., 2008), eucalypt (RODY et al., 2014), pines (DEBLONDE; PENNER; ROYER, 1994) and forest (WOODGETEA et al., 2015).

Even though LAI-2200 is considered the world standard instrument to measure LAI for crop that has short homogeneous canopy such as soybean and wheat, the use of LAI-2200 for crop with high gap fraction or large plant row is questionable. Usually when intends to determine LAI of a single tree or crops with high gap fraction between plants or rows, the manufacturer of LAI-2200 recommends that reading must be adjusted and recalculate (LI-COR, 2016), presenting the methodology called “isolate plant”. Jatropha nut (*Jatropha curcas* L.), crop used in this study, is a small tree with main characteristic of high percentage of oil within the seed that is used to produce biodiesel (HELLER, 1996; ACHTEN et al., 2008; BRITTAINE; LUTALADIO, 2010; FACT, 2010). Jatropha nut is usually cultivated with large plant row (3 m or higher between plants), requiring high criteria when performing readings with LAI-2200. Comparing real LAI index with measured LAI (estimated) by the sensor is necessary to determine the influence of gap fraction and it is possible to establish a model that reduces the reading errors. Behera et al. (2010), evaluating the performance of LAI-2000 Plant Canopy Analyzer measurement for jatropha nut, performed several reading using all the sensors field view caps (11°, 45°, 90°, 180°, 270°, and 360°) at 15 and 30 cm intervals from the stem base. They found that 90° narrow azimuthal viewing presented the best results, with RMSE of 0.262 and 0.29 at 30 cm and 15 cm stem interval, respectively. However, the methodology used by the authors did not meet with manufacturer recommendation for jatropha canopy type. Finally, the authors performed only one above reading and, according to the manufacturer, for each below canopy reading, one above canopy reading must be performed at the same azimuthal direction so the sensor is able to compare the gap fraction for all four directions. Therefore, it is necessary to understand the sensor reliability, especially when performing readings that meets to the manufacturer suggestions. Testing and calibration using adequate methodology as well as creating a relationship between real and estimated LAI, are essential to establish the real reliability of LAI-2200 on LAI estimation for jatropha nut plant.

The objective of this study was to calibrate and test the LAI-2200 Plant Canopy Analyzer sensor on the estimative of leaf area index of jatropha nut using the manufacturer’s methodology recommendation.

3.2 Material and Methods

3.2.1 Field experiment

The study was conducted at experimental area of 'Luiz de Queiroz' College of Agriculture (ESALQ) of University of São Paulo (USP), in Piracicaba city, Brazil (22º41'58'' S and 47º38'42'' W and at approximately 530 m of altitude). The performance of LAI-2200 test was conducted in the same research area of japropha nut with evapotranspiration and crop coefficient under enter pivot, drip and rainfed water management. The experiment had 2 ha, divided in 1 ha for center pivot, 0.5 for drip and 0.5 for rainfed. Plants were cultivated with 3 m x 4 m plant and row spacing, respectively. Real and estimated LAI readings were performed with nine jatropha nut plants from February 2013 to April 2013 and from January 2014 to March 2014, ranging from 29 and 43 months old plants, using plants during vegetative and productive growing stage. All measurements were taken under overcasting sky condition, always until 9:00 AM or after 5:00 PM, avoiding direct sunlight that could compromise the adequate reading.

3.2.2 LAI-2200 test and calibration

Initially, LAI-2200 takes reading and calculates LAI for a hypothetical short homogenous canopy of 1 m height, and these readings are considered the pattern measurement. However, in order to adapt the reading for jatropha nut canopy characteristic, it is necessary to recalculate the data using the LAI-2200 software provided by the manufacturer. By adding the plant canopy shape information into the software, it recalculates the previous estimated LAI (pattern measurement) to the isolate plant measurement. The test was performed in both approaches, one that met the manufacturer recommendation by the isolate plant measurement methodology and other using the pattern measurement.

In Figure 3.1, it is presented the methodology of isolated plant measurement that was performed in each of the nine plants chosen to determine estimated LAI with LAI-2200. It was utilized a 90° sensor field cap at 10 cm intervals from the stem base, and at 10 cm of ground level. To avoid interference by the surrounded plants, the readings were taken crosswise to the crop row. It was taken four reading above and below plant canopy with the sensor aimed to the outside of the plant, forming a 90° angle between directions (Figure 3.1).

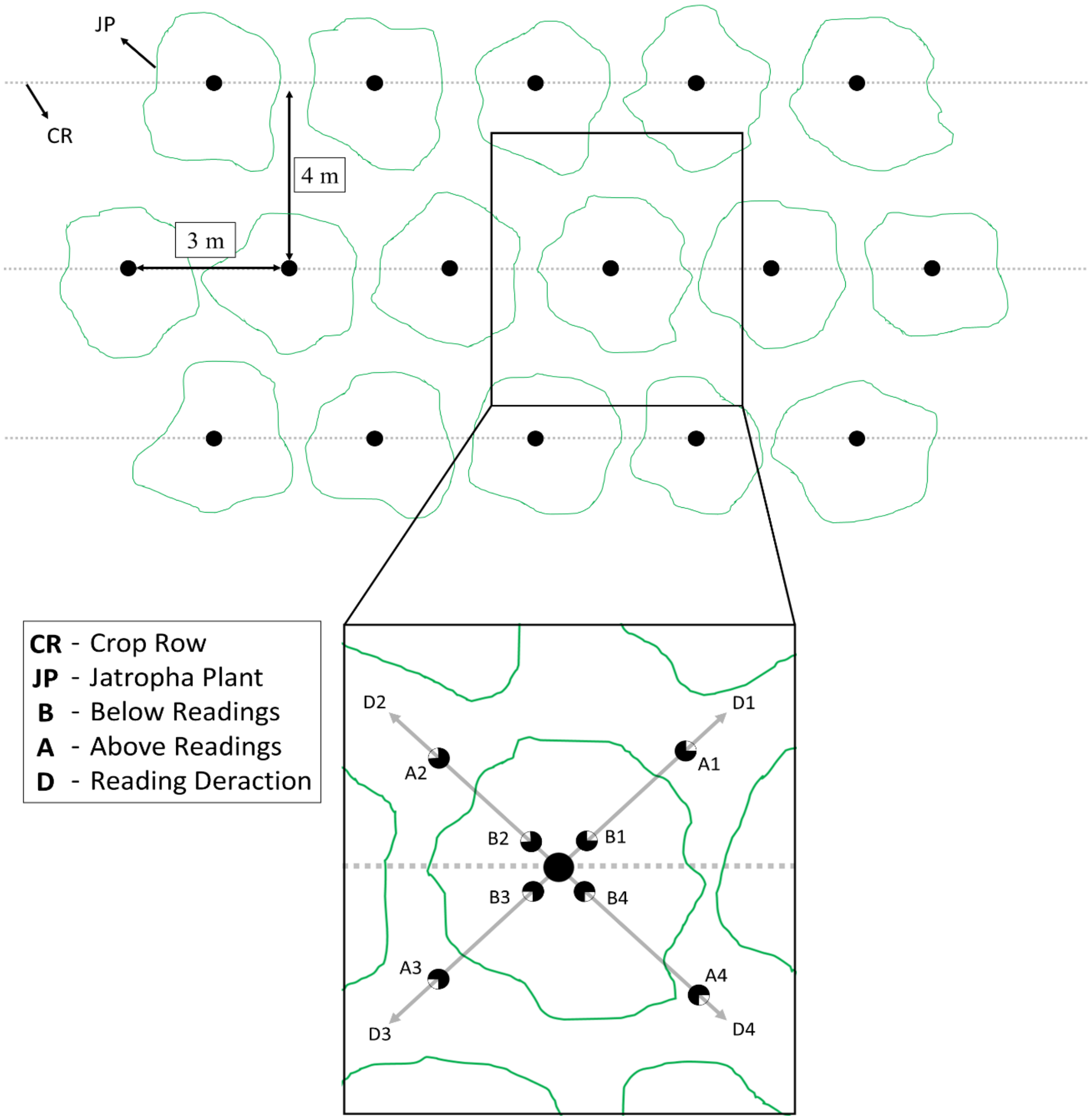

Figure 3.1 - Field layout of jatropha nut and the four crosswise row directions of above and below readings of LAI-2200 Plant Canopy Analyzer readings

After performing the four direction readings, the equipment provides the pattern measurement and, in order to transform the results from pattern measurements, it was necessary to recalculate the data using the LAI-2200 software (FV2200 v2.1.1). In Figure 3.2, it is presented the example of how the plant canopy shape was determined, considering x (plant canopy radius) and z (plant height) axes length (Figure 3.2A), and how to recalculate the data using LAI-2200 software (Figure 3.2B). Adding this information will provide a new LAI that meet to the plant canopy shape.

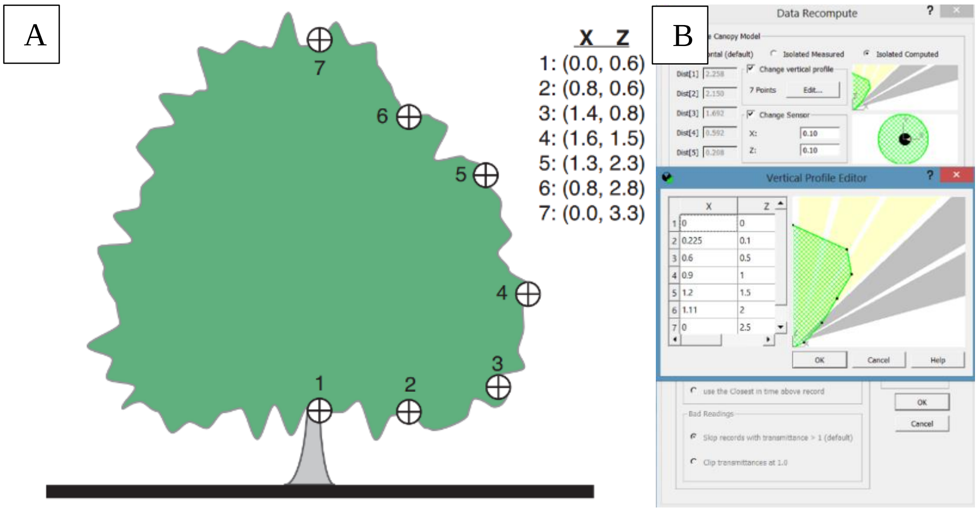

Figure 3.2 - Plant canopy shape determination (A) and data recalculate according for isolate plant measurement using FV2200 v2.1.1 Software (B)

In Figure 3.3, it is presented the field and laboratory sequence of estimated and real LAI determination for each plant, showing the plant that was chosen to perform the readings (Figure 3.3A) and the estimative of LAI by the sensor using the isolated plant method (Figure 4.3B). In sequence, all the leaves were manually removed from the plant (Figure 3.3C) to determine the real LAI by the destructive method using the CI-203 leaf area integrator (Figure 3.3D) (CID, 2016).

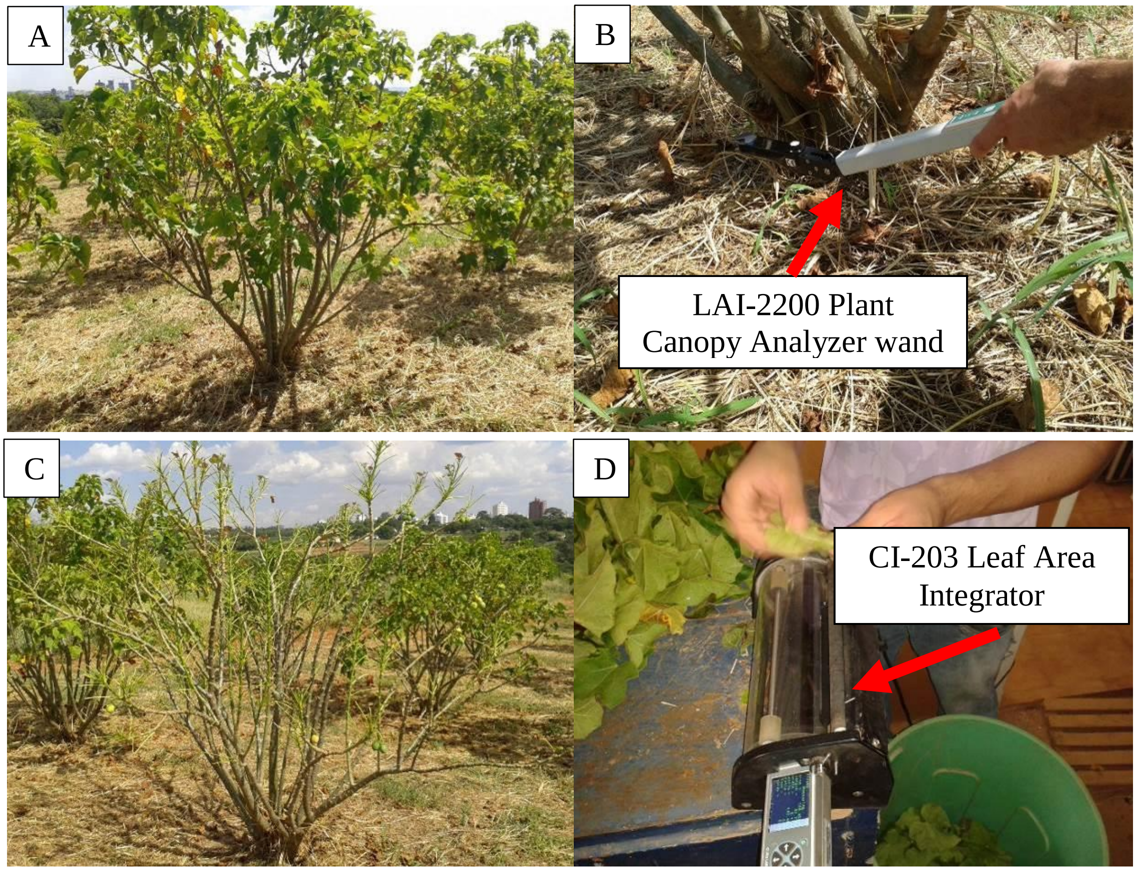

Figure 3.3 - Sequence of real and estimated LAI data measurement. Plant chosen (A); LAI-2200 reading (B); plant after leaves detachment (C); and real leaf area index determination by CI-203 leaf area integrator (D)

3.2.3 Statistical analysis

The statistical criteria to evaluate LAI-2200 performance on the estimative of LAI were based on the coefficient of determination (R^2), and the Person correlation coefficient (r). Also, it was used the root mean square error (RMSE), the Nash-Sutcliffe efficiency (NSE) (NASH; SUTCLIFFE, 1970), the Willmott index of agreement (d), and the index of confidence (c) proposed by Camargo and Sentelhas (1997) from the comparison between real LAI (LAI_R) and recomputed LAI (LAI_{E_R}), and LAI_R and pattern LAI (LAI_{E_P}).

3.3 Results and Discussion

In Figure 3.4 is presented the scatted analysis between LAI_R and LAI_{E_R} (Figure 3.4A), and between LAI_R and LAI_{E_P} (Figure 3.4B). Although the isolate plant measurement is the recommended methodology, the pattern measurement was also used due the advantage of not requiring to recalculate the data using the LAI-2200 software, saving time in comparison to isolate plant measurement.

During the estimated LAI measurements, plants height were between 1.8 m and 2.6 m (2.25 m average) and maximum canopy diameter ranging from 0.8 m to 2.7 m (2.0 m average). Estimated LAI ranged from 0.11 to 1.63 for LAI_{E_R} and from 0.22 to 0.88 for LAI_{E_P}, while LAI_R ranged from 0.10 to 1.12, with average values for LAI_{E_R}, LAI_{E_P}, and LAI_R of 0.69, 0.51, and 0.55, respectively. Both comparison presented positive correlation between real and estimated LAI and, with estimated LAI values by isolated plant measurement overestimated real LAI around 30%, and the estimated LAI values by pattern measurement underestimated real LAI only in 10%. By the equations presented in Figure 3.4, it is necessary to recalculate the LAI readings according to the proposed measurement methodology (Figure 3.4A for isolate plant and Figure 3.4B for pattern measurement). As result, the data will be transform to adequate values closer to real data.

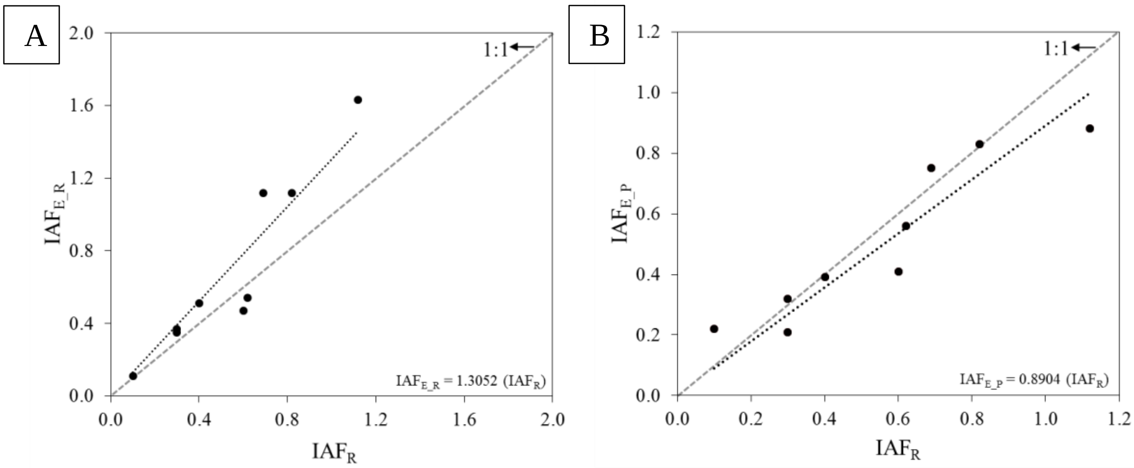

Figure 3.4 - Comparison between real leaf area index (LAI_R) and isolated plant measurement estimated leaf area index (LAI_{E_R}) (A) and pattern measurement estimated leaf area index (LAI_{E_P}) (B)

Both approaches were statistically analyzed and the results are presented in Table 3.1. It was observed that, for both LAI_{E_R} and LAI_{E_P} models, they presented high R^2 and r, showing a very good correlation between estimated and real LAI, with low RMSE for both case. According to the d and c indexes values, they presented values considered "great" for both LAI_{E_R} and LAI_{E_P} models, but with a slightly higher values for LAI_{E_P} in comparison with LAI_{E_R}. The NSE value represents the model efficiency, also it is possible to affirm if the model may or may not represent real data. According to the values of NSE for LAI_{E_R} and LAI_{E_P} models, they were considered acceptable, i.e., the model can be used to simulate real LAI in both measurement approaches. However, the LAI_{E_P} model had higher RMSE, NSE, d, and c values in comparison with LAI_{E_R} model, showing that LAI_{E_P} model presented better accuracy, precision, and smaller error. According to the analysis results presented in this study, for both measurement methodology approaches of LAI estimating for jatropha nut presented satisfactory performance, in which is possible to affirm that estimating LAI by LAI-2200 provides reliable LAI data.

Table 3.1 - Coefficient of determination (R^2), correlation coefficient (r), root mean square error (RMSE), Nash Sutcliffe efficiency (NSE), Willmott index of agreement (d), and Sentelhas-Camargo index of performance (c) values from the comparison between real LAI (LAI_R) and recomputed LAI (LAI_{E_R}), and LAI_R and pattern LAI (LAI_{E_P})

Comparison	R^2	r	RMSE	NSE	d	c
LAI_R vs LAI_{E_R}	0.8832	0.9398	0.2534	0.2541	0.8878	0.8607
LAI_R vs LAI_{E_P}	0.8713	0.9335	0.1174	0.8400	0.9509	0.9187

In the literature, it was found only one study that tested LAI-2000 (previous model of LAI-2200) on jatropha nut LAI estimation. This study was presented by Bahera et al. (BEHERA et al., 2010) and they found a linear regression for 90° field view cap with high R^2, showing that LAI-2000 had great estimative of LAI in jatropha nut plant. For others cultures it is possible to find many studies that tested and calibrated LAI-2000 and LAI-2200, but usually the studies presented measurements methodologies that met each canopy structure for each study situation, differing from the methodology used in our study. Dovey and Toit (2006), testing LAI-2000 estimates in young eucalypt forest with real LAI by destructive sample for 2 and 3 years old eucalypt plant, proposed two models (one for each year) that can be used to adequate LAI-2000 readings. Both models presented high R^2 (above 0.83), but for 2-year old and 3-year old the model underpredict and overpredict estimated LAI, respectively. Using many different indirect methods of determining LAI in medium size coffee trees (1.6 m height), Ribeiro et al. (2013) observed that LAI-2000 presented a cubic model with low R^2 (0.3023). Although the authors used the same measurement methodology presented in our study (isolate plant measurement), they mention that using LAI-2000 for medium size coffee trees is a non-fitted instrument due it provides useful LAI estimation. The authors proposed using others indirect methods such as lux meter device, plant size approach, and digital images in order to better estimate LAI for medium size coffee trees. With the objective of finding the best measurement approach of LAI-2000 estimation for soybean using the narrow-blue and wide-blue detectors, Malone, Herlbert and Holshouser (2002) observed that there was not statistically difference between estimated and real LAI for narrow-blue detector. In addition, as defoliation plant level increased, the ability of the sensor to provide adequate estimated LAI decreased, showing that the sensor has not the ability of distinguish leaves from others parts of the plants such as pods, stems, and petioles. In an experiment with two hybrid corn, LAI-2000, and others two LAI equipment, was tested by Wilhelm, Ruwe and Schlemmer (2000) using the short homogeneous canopy measurement. The authors found that for both hybrid LAI-2000 estimates provided positive correlation with a linear regression and R^2 higher than 0.75. Both models underestimated real LAI, so it is important to use the models to recalculate estimated LAI by LAI-2000.

The models proposed in this study using isolate plant and pattern measurement as well as those by Bahera et al. (2010) are considered essential to adequate the LAI reading on jatropha nut using LAI-2200. The user may choose which model is most suitable to his/her field situation, in which the reading will be performed according to the proposed model chosen. It is important to mention that the model meets the manufacturer recommendation is the isolated plant measurement, and this model must be considered the most appropriate when intents to determine LAI of jatropha nut.

3.4 Conclusions

The LAI-2200 Plant Canopy Analyzer provided good estimated LAI data and comparing its estimates with real LAI was essential to find and correct errors. The results presented in this study showed that, while isolate plant measurement overestimated around 30% of real LAI, the pattern measurement underestimated around 10%. Both models were considered adequate according to the statistical parameters results and they can be used to correct estimated LAI in order to present better result of LAI for jatropha nut.

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