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Article

Radiation Use Efficiency for Cowpea Subjected to Different Irrigation Depths Under the Climatic Conditions of the Northeast Of Pará State

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Abstract

This study aims to determine the cowpea efficiency in absorbing and using solar radiation according to different irrigation depths under the climatic conditions of the northeast of Pará State. The experiment was carried out on 2014 and 2016 in an experimental design of randomized blocks, which consisted in six blocks with four treatments, in which different irrigation depths the reproductive phase were applied, as follows: T100, T50, T25 e T0, that corresponded to 100%, 50%, 25% e 0% of the crop evapotranspiration, respectively. The absorbed photosynthetically active radiation, leaf area index (LAI), total aerial dry matter (TADM) and grain yield were measured. The extinction coefficient (k) was obtained by nonlinear regression between the fraction of absorbed PAR (fPARinter) and the LAI. The radiation use efficiency (RUE) was calculated by linear regression between the TADM and the accumulated absorbed PAR. The water deficit imposed by the treatments had a significant influence on the LAI, TADM and cowpea yields. The water deficit did not significantly influenced k – it ranged between 0.83 for T100 and 0.70 for T0. The RUE showed significant behaviors regarding the treatments with adequate water supply and treatments under water deficit, ranging from 2.23 to 1.64 $g \cdot MJ^{-1}$, respectively.

Keywords: vigna unguiculata, radiation interception, extinction coefficient, water deficit.

Eficiência do Uso da Radiação para o Caupi Submetido a Diferentes Lâminas de Irrigação nas Condições Climáticas do Nordeste Paraense

Resumo

Objetivou-se neste trabalho determinar a eficiência do feijão-caupi em interceptar e usar a radiação solar quando submetido a diferentes lâminas de irrigação nas condições climáticas do nordeste paraense. O experimento foi realizado em 2014 e 2016 em delineamento experimental de blocos casualizados, com seis blocos e quatro tratamentos, que consistiram diferentes laminas de irrigação na fase reprodutiva, sendo T100, T50, T25 e T 0 correspondente a 100%, 50%, 25% e 0% da evapotranspiração da cultura. Realizou-se medição da radiação fotossinteticamente ativa (PAR) interceptada, do índice de área foliar (LAI), da matéria seca total da parte aérea (TADM) e produtividade. O coeficiente de extinção (k) foi obtido através de regressão não linear entre a fPARinter e o LAI. A eficiência de uso da radiação (RUE) foi obtida pela regressão linear entre a TADM e a radiação PARinter acumulada. O déficit hídrico imposto pelos tratamentos influenciou significativamente as respostas no LAI, TADM e produtividade do feijão-caupi. O k não foi influenciado significativamente pelo déficit hídrico, apresentando variação de 0,83 no T100 e 0,70 no T 0. A RUE apresentou resposta significativa entre os tratamentos com suprimento hídrico adequado e os tratamentos sob déficit hídrico, variando de 2,23 a 1,64 $g \cdot MJ^{-1}$, respectivamente.

Palavras-chave: vigna unguiculata, radiação interceptada, coeficiente de extinção, déficit hídrico.

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1. Introduction

Although cowpea (*Vigna unguiculata L.*) does not present a significant production in Brazil when compared to common bean (*Phaseolus vulgaris L.*) (Santos *et al.*, 2014) due to the use of cultivars with low productive potential and low technological investment in its cultivation, it stands out as a food source of great economic and social importance, which generates employment and incomings for the families of the North and Northeast regions (Torres *et al.*, 2015).

Biotic and abiotic factors, such as pests, diseases, soil physicochemical properties, climatic variations and remarkably the amount of solar radiation and precipitation strongly influence the annual production of this crop (Teixeira *et al.*, 2015). These factors contributed significantly to a reduction in cowpea production of 33 thousand t and a decrease from 76 to 43 thousand ha of cropland over the decade 2004-2013, with an average yield of 669 kg·ha^{-1} according to FAPESPA (2015).

When crops have all their requirements for water and nutrients fulfilled and there are no phytosanitary issues, the most limiting abiotic factor for potential productivity is, frequently, solar irradiation, since it has a direct relation to the photosynthetic rate and photosynthesis is the basic source of energy for physiological processes (Kunz *et al.*, 2007) that govern both growth and development.

The relation between organic matter accumulated during the cycle of a crop and the amount of solar radiation absorbed in the same period by the plants is called radiation use efficiency (RUE) (Monteith and Moss, 1997). RUE indicates that the yield of organic dry matter depends directly on photosynthetically active radiation the plant absorbs and on the efficiency with which it uses this energy for photosynthesis.

The efficiency in the use of solar radiation varies according to the approached cultivar and the environmental conditions to which the plant is submitted. It may or may not reduce as the plant absorbs higher radiation amounts and when the plant undergoes into water limitations (Kunz *et al.*, 2007).

Therefore, the importance of studies that consider the variables of growth, development, and productivity of the cowpea in the region is noticeable. It is noteworthy that the effects of the climate in its cultivation, as a form of assistance in the agricultural planning and in the most appropriate management of the culture aiming greater productivities must be considered. Thus, this work aims to determine the efficiency of the cowpea in intercepting and using the solar irradiation when submitted to different irrigation depths under the climatic conditions of the northeast of Pará State.

2. Material and Methods

The field experiment was carried out on 2014 and 2016 in two adjacent areas of 1.5 ha and 0.5 ha, respectively, in the school farm of the Federal Rural University of Amazon in Castanhal, Pará. The local climate is characterized as Am – according to Köppen climate classification – tropical climate, presenting a moderate dry season with an average annual rainfall of 2,000 to 2,500 mm. The driest period of the year occurs between the months of June and November, while the rainiest period occurs from December to May.

Two soil samples were taken. The first one was an undisturbed sample to achieve the physical characterization. The other one, was a deformed sample at the depth of 0 to 20 cm in pursuance of chemical analysis. The samples were analyzed by the soil laboratory of Embrapa Amazônia Oriental. The results are shown in Table 1 and Table 2.

The sowing was carried out on September 09th and September 17th, 2014 and 2016, respectively. The cultivar BR3-Tracuateua of cowpea was sown by a manual seeder. The space design had 0.5 m between planting lines and 0.1 m between plants, thus, totalizing 200,000 plants per hectare. Regarding the fertilization, it was performed according to the soil chemical analysis results. Thereby, an amount of 195 kg ha-1 of NPK chemical fertilizer, with a

Table 1 - Chemical properties of the soil at the experimental site

Year	pH (H_2O)	N (%)	P (mg·dm^3)	K^+ (mg·dm^{-3})	Na^+ (cmol$_c$·dm^3)	Ca^{2+} (cmol$_c$·dm^3)	Ca^{2+} + Mg^{2+} (cmol$_c$·dm^3)	Al^{3+} (cmol$_c$·dm^3)
2014	5.4	0.06	18	11.0	2.0	1.0	1.5	0.3
2016	4.9	0.05	2	26.0	9.0	0.5	0.8	0.8

Table 2 - Physical properties of the soil at the experimental site

Year	Sand (g·kg^1)	Silt (g·kg^1)	Clay (g·kg^1)	Bulk density (g·cm^3)	FC[1][1] (m^3·m^3)	PWP[2] (m^3·m^3)[2]
2014	804	116	80	1.41	0.22	0.07
2016	835	125	40	1.56	0.20	0.11

[1]field capacity, [2]permanent wilting point.

formulation of 6-18-15, was used at experiment performed on 2014. On the other hand, on 2016, a quantity of 210 kg ha-1 of NPK chemical fertilizer, with a formulation of 9-18-15 was applied as suggested by Embrapa Amazônia Oriental.

It was used an experimental design in randomized blocks, with six blocks measuring 22x20 m with four treatments, which consisted of different levels of water availability in the soil during the reproductive phase of cowpea. The T_{100} treatment consisted in the replacement of 100% of the water lost by crop evapotranspiration (ET_c); the T_{50} treatment had 50% of ET_c replaced; the T_{25} treatment obtained 25% of ET_c replaced; finally, the T_0 treatment did not have any part of the ET_c replaced through irrigation during the reproductive phase. Thus, the latter one remained exposed only to rain on 2014. In 2016, polypropylene panels were installed to prevent the entrance of rainwater over the reproductive phase at the T_0 treatment.

The daily irrigation depth was distributed through a drip irrigation system. The net irrigation depth (NID) was obtained considering the reference evapotranspiration (ET_0) calculated by the Penman-Monteith equation (Allen *et al.*, 2011). The data was collected from a weather station installed 3 km away from the experimental site, which belongs to the Instituto Nacional de Meteorologia (INMET). Subsequently, the ET_0 was multiplied by the crop coefficient (K_c) of each stage of the cowpea, which is available in the literature (Bastos *et al.*, 2008), to obtain the ET_c.

The gross irrigation depth (GID) was calculated considering the ratio between NID and the water application efficiency of the irrigation system. During the vegetative phase, the treatments received the irrigation depth corresponding to T_{100}. The treatments started on the 36^{th} day after sowing (DAS) on both years of experiment, when the crops reached the reproductive stage (R5). Then, they extended until the 57^{th} DAS on 2014 and 61^{st} DAS on 2016, the period when the grain maturation stage (R9) had begun.

The phenological development of the cowpea was daily evaluated by the selection of 1 meter long lines, with 10 plants each. The scale proposed by Gepts and Fernández (1982) was used, as described by Farias *et al.* (2015).

Data for the crop growth analysis were collected from the 9^{th} DAS on 2014 and the 15^{th} DAS on 2016, on a weekly step. The data collection was from two 20 meter lines in each treatment, from which five plants were taken in a linear meter. The sampling obeyed the randomized block design, with six replicates each. Each sample had its parts separated in stem, petiole, leaf, peduncle, flower, pod and grain (only when present). Subsequently, the samples were dried in an oven at 70 °C for 72 h, until they reached a constant weight, to measure the total aerial dry matter (TADM). The leaf area index (LAI) was determined by the disc method described by Benincasa (1988) using the dry matter of leaves.

The final yield was collected at the 63^{rd} DAS on 2014 and 73^{rd} DAS on 2016, in two previously separated planting lines in each treatment, from which three samples of 1 m^2 represented by 2 m long lines were collected.

An automated weather station was placed in the center of the experimental area to record incident photosynthetically active radiation, air relative humidity and temperature, soil volumetric water content, and rainfall. The amount of PAR reaching the soil surface was directly measured with linear-type sensors placed perpendicularly to the seedling lines. All sensors were connected to a CR10X datalogger (Campbell Scientific, Inc.) with readings programmed to every ten seconds, and averages and totals every ten minutes. To quantify the deficiencies imposed by the treatments submitted to the water deficit, the sequential water balance was performed according to Carvalho *et al.* (2011).

The fraction of the total PAR absorbed by cowpea was calculated as the difference between the amount of PARinc and PARtrans, which was then divided by PARinc. Radiation extinction coefficient (k) was obtained according to the methodology proposed by Zhou *et al.* (2016), through an exponential regression of FPARinter as a function of IAF, where k is the exponent.

In order to estimate the radiation use efficiency (RUE) by cowpea, a linear regression was performed between the TADM ($g \cdot m^2$) and the accumulated intercepted PAR ($MJ \cdot m^2$), whose angular coefficient of the line represents the RUE (Sinclair and Muchow, 1999). The growth data (LAI and TADM) and productivity were submitted to analysis of variance and the means were compared by the Tukey test ($p < 0.05$) through the statistical program Assistat. The program SAS, version 9.2, was used to perform the Dummy variables test ($p < 0.05$), to compare the linear regression equations of RUE. The mean error square (RMSE) for RUE was determined according to the methodology proposed by Loague & Green (1991).

3. Results and Discussion

The air temperature during the two-year experiment ranged between 22.1 and 34.6 °C, with averages of 27.1 °C and 27.3 °C on 2014 and 2016, respectively. Regarding the global radiation, its averages during the experiment were 19.22 and 20.11 $MJ \cdot m^2 \cdot d^1$ on 2014 and 2016, respectively. Overall, considering both experiments, the thermal limit remained within the standard, which is considered optimal for the cultivation of cowpea under the climatic conditions of the Northeast of Pará State (Farias *et al.*, 2015).

Figure 1 presents the total daily rainfall and daily average soil moisture during the cowpea cycle in both years. The total rainfall observed during 2014 (158 mm) and 2016 (153 mm) experiments is very close, with a small reduction of 3.15% in 2016. Approximately, 122 mm and 141 mm occurred in the vegetative phase and 36 mm and 12 mm in the reproductive phase of 2014 (Fig. 1a) and 2016 (Fig. 1b), respectively.

Throughout the two-year experiment, soil moisture remained high during the vegetative phase in response to rainfall and water supply through irrigation. Irrigation was done to make the soil available water close to the field capacity, but only when necessary. Nonetheless, some rainfall events at this phase caused water surplus in both years.

According to the differentiation of water supply during the reproductive phase, the availability of water in the soil varied among the treatments. Thus, there was an occurrence of water deficiency between the 38th and 41st DAS on 2014 at the treatments T_0, T_{25} and T_{50}. However, it was softened by some rainfall between the 42nd and 47th DAS. Right after this period, with the absence of rainfall, the treatments T_0, T_{25} and T_{50} reached a soil water content below readily available water at the 48th, 50th and 52nd DAS due to the progressive reduction in the amount of water content in the soil (Fig. 1a).

On 2016, (Fig. 1b) the treatments T_0, T_{25} and T_{50} underwent an earlier water deficit through the 43rd, 49th and 56th DAS, respectively. It occurred due to the absence of rainfall in this phase as compared to the 2014 year. In addition, on 2016, the treatment without irrigation (T_0)

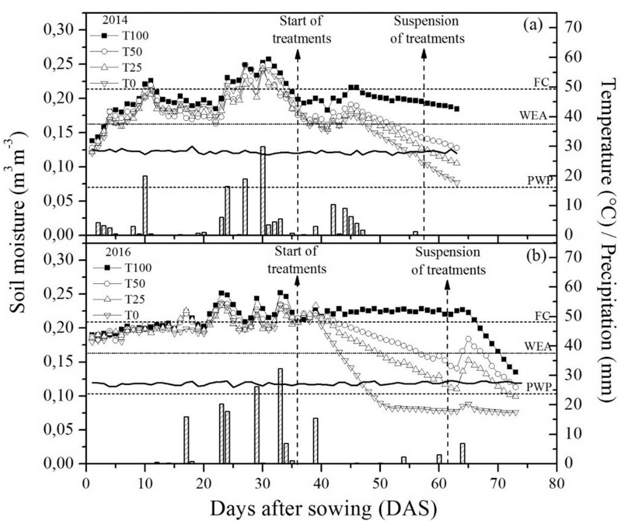

Figure 1. - Variation of soil moisture, air temperature and total precipitation in the experimental area during 2014 (a) and 2016 (b). FC: Field capacity; WEA: Water easily available; PWP: Permanent wilting point; — Air temperature; ▨ Precipitation; ■ T_{100}: Replacement of 100% of evapotranspiration of culture (ETc); ○ T_{50}: Replacement of 50% ETc; Δ T_{25}: Replacement of 25% ETc; ∇ T_0: Not have irrigation during the reproductive phase.

entered in water stress at the 48th DAS until the end of the experiment, leading to the consumption of all available water in the soil.

When the crops achieved the R9 stage (physiological maturity), the soil available water content (AWC) in each treatment was 22% and 0% in T_0; 36% and 12% in T_{25}; and 47% and 45% in T_{50}; on 2014 and 2016, respectively. Nascimento *et al.* (2004) found out that at the 60% level of AWC, the plant starts to decrease its production significantly. Thereby, it begins to present a greater variation in the components of production of this cultivar due to the greater water deficiencies imposed by the irrigation treatments.

At the year 2014, due to the high frequency of rainfall happening up to the 47th DAS, the AWC in the four treatments was little altered, since there was no effective control of the entrance of water in the soil. Thus, the treatments T_{50}, T_{25} and T_0 had total water deficits of only 8 mm, 19 mm, and 31 mm, respectively. On the other hand, at the year 2016, due to the reduction of rainfall and the installation of mobile coverings over the T_0 treatment, a greater control of water supply was achieved. The results show a greater change in soil moisture in all treatments. Therefore, T_{50}, T_{25} and T_0 faced water deficits of 22 mm, 41 mm, and 90 mm, respectively.

The water regime imposed during the vegetative phase allowed a similar pattern of absorption of PAR between the treatments in both years of experiment. There are different responses in the absorption of PAR between the four treatments from the 44th DAS (Fig. 2a). The effect of treatments on radiation absorption was more intense on the year 2016 (Fig. 2b) due to the absence of rainfall during the reproductive phase in that year. This is very different from what had been observed in 2014 with rainfall happening up to around the 46th DAS.

The maximum efficiency in radiation absorption was reached early on 2014, even before the beginning of the treatments, while on 2016 the maximum absorption of PAR (T_{100}) was only reached near the 44th DAS. This differentiated pattern in the absorption of PAR is a consequence of a differentiated production of dry matter and leaf area index observed between both years. Although the treatments had been carried out, respectively, under full and deficient irrigation during the vegetative and reproductive phase, the higher frequency of rainfall events on 2014 provided a more efficient wetting of the soil than only by the irrigation system. These conditions made the canopy of the cowpea becoming more coupled with the atmosphere. In other words, the crop started to depend less on the stomatal control for gas exchanges (Farias *et al.*, 2017), which indirectly could have contributed to the differences in production between the years.

The T_{100} treatment presented a longer duration in the maximum radiation interception, remaining at around

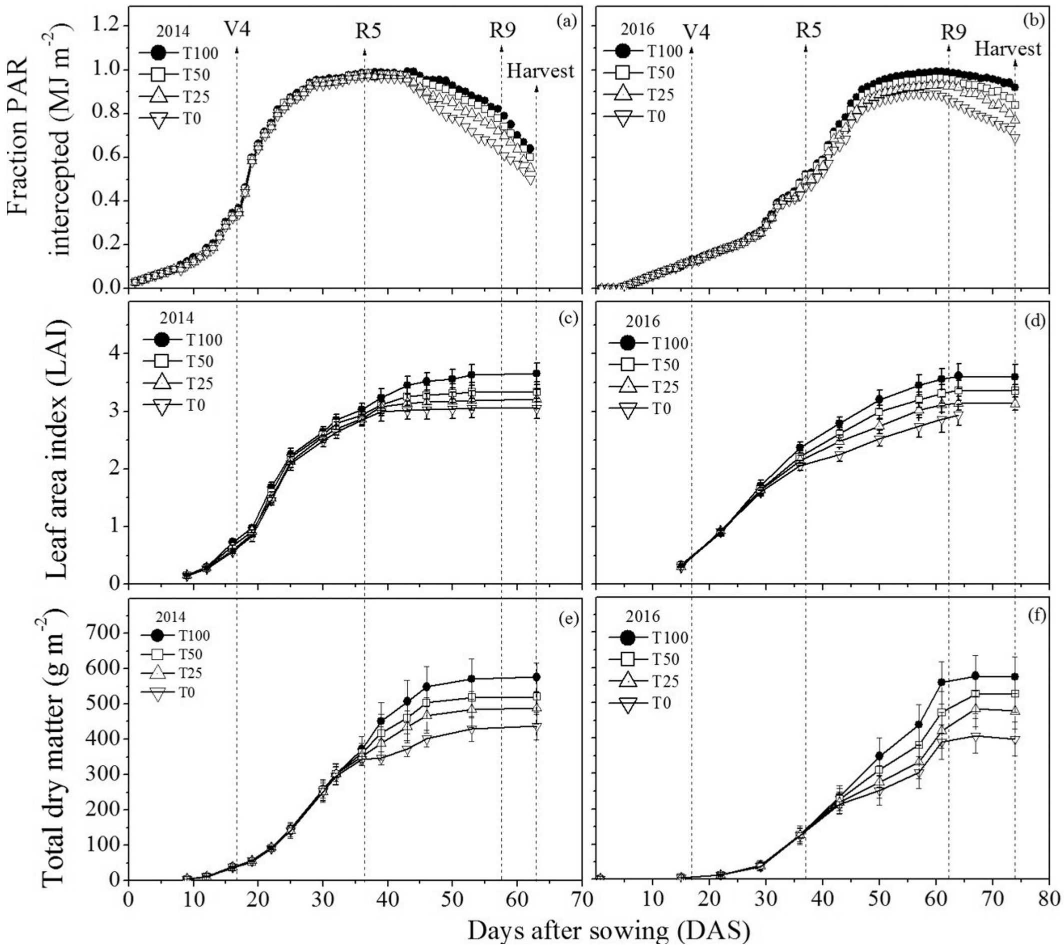

Figure 2. - Evolution of intercepted PAR fraction, leaf area index (LAI) and total aerial dry matter (TADM) fraction as a function of days after sowing on 2014 (a, c, e) and 2016 (b, d, f). V4: Third trifoliolate leaf (last vegetative stage); R5: Pre-flowering; R9: Maturation; ● T_{100}: Replacement of 100% of evapotranspiration of culture (ETc); □ T_{50}: Replacement of 50% ETc; Δ T_{25}: Replacement of 25% ETc; ∇ T_0: Not have irrigation during the reproductive phase.

eight days (38th and 45th DAS) on 2014 and six days (between 57th and 62nd DAS) on 2016, with a maximum efficiency of 99%. The T_{50} treatment remained absorbing with 98% efficiency for about seven days on 2014 (37th and 43rd DAS) and with 96% for five days on 2016 (39th and 43rd DAS). Regarding the T_{25} treatment, it intercepted a maximum of 97% of PAR for seven days (39th and 45th DAS) on 2014 and only 93% for four days on 2016 (46th and 49th DAS). In relation to the T_0 treatment, it presented the lowest interception values in both years, reaching 97% between 36th and 42nd DAS on 2014 and only 89% between 45th and 48th DAS on 2016.

The experimental area of 2014 had a maximum available water content 27% higher than the area of 2016 at the depth of 0-20 cm in result of a lower soil bulk density and higher clay content. This leads to larger amounts of micropores and, consequently, greater water retention. This higher capacity to store water associated with a higher frequency of rainfall events and a more efficient soil wetting directly influenced in the radiation absorption rate as well as in the growth of cowpea during the vegetative phase of 2014, which was 22% greater to the same phase of 2016.

At the end of the cycle, the radiation absorption decreased gradually in both years. This decrease occurred due to the natural process of leaf senescence, which causes the reduction of the LAI, then, reducing the area available to intercept the radiation (Bernardes *et al.*, 2014).

Significant responses ($p < 0.05$) were observed in LAI at 45th DAS between the treatments T_{100} and T_0 on 2014 (Fig. 2c). On 2016, the responses were noticed at 63rd DAS. The T_{100} differed statistically ($p < 0.05$) from all other treatments, whereas T_{50} and T_0 differed from each other and were equal to T_{25} (Fig. 2d). The results of both experiments confirm those found out by Bastos *et al.* (2011) who obtained maximal LAI values for cowpea close to those found in this study, therefore, indicating that as the crop accomplish LAI values over 3, its full development reaches a maximum absorption of PAR, when there are no limiting factors.

These results elucidate the negative effect that a low water availability has on the LAI, because as the water availability values get lower in the treatments, lower maximum LAI values are expected to happen. A mean reduction in LAI of 16% (2014) and 18% (2016) was observed comparing the T_0 to the T_{100} treatments in response to a total water deficit of 31 and 90 mm, respectively. A similar result was found by Nascimento *et al.* (2011), who obtained a reduction of 20% in the average LAI by studying the cowpea under water deficit. Regarding their results, it is a survival strategy of the plants submitted to water deficit, which reduce their leaf area to decrease its transpiration.

The TADM produced by the cowpea showed an increasing response as a function of the PARinter accumulation, with the peak production for all treatments at the 63^{rd} DAS on 2014 (Fig. 2e) and 67^{rd} DAS on 2016 (Fig. 2f). Regarding the Turkey test, they presented significant differences between the treatments T_{100}, T_{25} and T_0. In contrast, the T_{50} was statistically equal to the treatment without water deficit in both years.

The T_{100} treatments presented the highest TADM values, producing 575.64 $g{\cdot}m^2$ on 2014 and 576.32 $g{\cdot}m^2$ on 2016. Right after them, the T_{50} treatments come with 520.57 $g{\cdot}m^2$ (2014) and 525.27 $g{\cdot}m^2$ (2016). Then, T_{25} with 488.73 $g{\cdot}m^2$ (2014) and 483.12 $g{\cdot}m^2$ (2016). Finally, the T_0, which obtained the lowest results of TADM that are 437.74 $g{\cdot}m^2$ (2014) and 406.39 $g{\cdot}m^2$ (2016). Even with the previous observed differences between the years regarding the interception of light, leaf area and their own growth throughout the cycle, it is possible to notice that the cowpea could reach similar values of total aerial biomass at the end of the cycle.

The TADM of T_0 was penalized in 24% on 2014 and 30% on 2016 in comparison to the T_{100} treatment. This difference between both years may have occurred due to the lack of an efficient control of water supply in 2014 – differently from the 2016 experiment, in which the mobile coverings ensured that T_0 did not receive any water replacement during the reproductive phase. Therefore, on 2016 there was a greater accumulated water deficiency of 90 mm during the reproductive phase.

Although the treatments T_{50} and T_{25} had been exposed to environmental conditions in both experiments, both had a reduction in TADM, which corresponded to 10% and 15% on 2014 and to 9% and 16% on 2016, respectively. The major difference in the TADM reduction between the experiments on 2014 and 2016 as a function of the T_{50} and T_{25} treatments is related to the progressive increase of water deficit, since the total water demand of the crop was not met. Thus, further restricting growth and development of the culture happened (Campos *et al.*, 2010).

The experimental results show that the lower water availability, the lower the TADM production, since as the plant perceives the water limitation in the soil, it adopts strategies to reduce water loss. Thereby, it induces the stomata to close in attempt to avoid dehydration and a

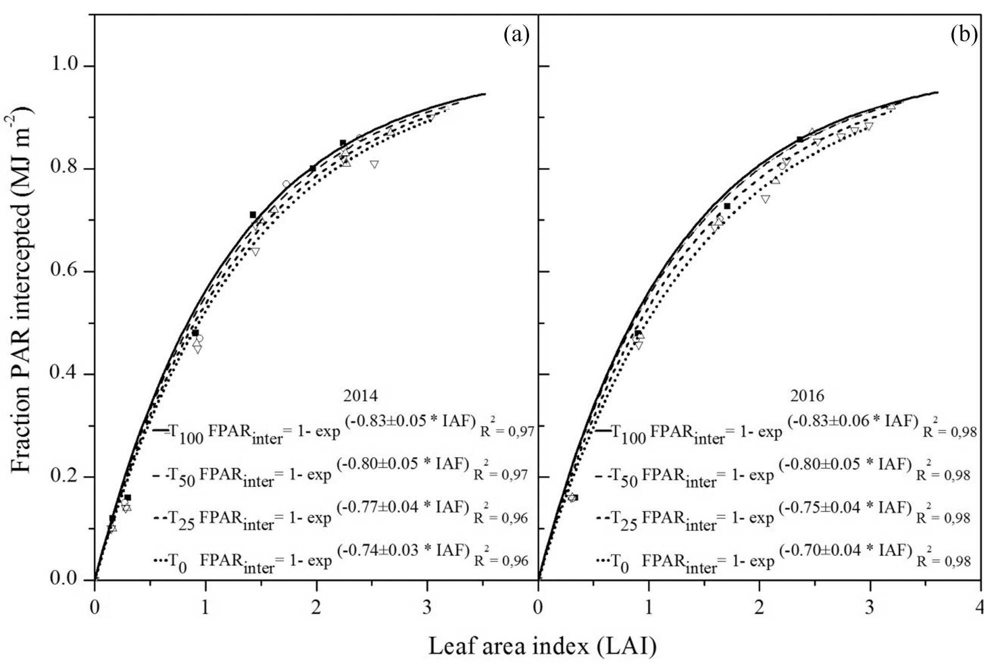

Figure 3. - Variation of the extinction coefficient of light (k) as a function of four different water regimes of 2014 (a) and 2016 (b). — T_{100}: Replacement of 100% of evapotranspiration of culture (ETc); - - T_{50}: Replacement of 50% ETc; —T_{25}: Replacement of 25% ETc; .... T_0: Not have irrigation during the reproductive phase.

collapse in its tissues. As a result, lower gas exchange rates start to be carried out, reducing the assimilation of CO_2 and, consequently, decreasing the TADM (Nascimento *et al.*, 2011).

The coefficient of extinction in the cowpea correlated with the amount of water available in the soil. Once the water content in the soil was reduced, the values of k began to decrease. However, there was no significant difference between treatments (Fig. 3). Therefore, it is notable that the architecture of the cowpea canopy was influenced by the different water regimes to which each treatment was submitted. Thus, there was a reduction in the amount of radiation incident on the soil, which contributed to a lower evaporation and, consequently, evapotranspiration. As a result, soil moisture remained high, especially in the T_{100} treatment in both experiments.

The values found during the two experiments ranged from 0.70 to 0.83, close to those obtained by Tesfaye *et al.* (2006) and Teixeira *et al.* (2015) who observed average values were equal to 0.86 and 0.79 for the Roba-1 and Pérola cultivars, both under good water conditions, respectively. The k values may vary according to the cultivated species. Higher k values are obtained when the spatial arrangement of the canopy is more uniform with a greater number of horizontally positioned leaves (Truong *et al.*, 2015).

Tesfaye *et al.* (2006) suggest that the coefficient of light extinction (k) could be used as a selection criteria for leguminous grain plants to identify cultivars that are able to adjust their canopy in response to water deficit at different stages of growth.

There was not statistical difference ($p > 0.05$) in the RUE for the four treatments during the vegetative phase during the four years of the experiment, as they were subjected to the same water availability, which lead to an average RUE of 2.03±0.08 $g{\cdot}MJ^{-1}$ in 2014 and 2.23±0.06 $g{\cdot}MJ^{-1}$ in 2016 (Fig. 4).

In this phase, the leaves of cowpea show diaheliotropic behavior. However, during the reproductive phase, the absorption of radiation on treatments T_{50}, T_{25} and T_0 was reduced as water deficits were imposed, and plants started showing paraheliotropic behavior, as a measure to reduce water loss through transpiration.

Santos *et al.* (2006) observed that paraheliotropic leaves subjected to low water availability show higher degree of direct solar radiation escape during the time of highest evaporation rate, when compared to plants under proper water supply.

During the reproductive phase, RUE varied as a function of water availability (Fig. 4), reaching 2.11±0.07 $g{\cdot}MJ^{-1}$ (T_{100}), 1.96±0.05 $g{\cdot}MJ^{-1}$ (T_{50}), 1.86±0.07 $g{\cdot}MJ^{-1}$ (T_{25}), and 1.68±0.06 $g{\cdot}MJ^{-1}$ (T_0) for the experiment of 2014, and 2.23±0.04 $g{\cdot}MJ^{-1}$, 1.99±0.03 $g{\cdot}MJ^{-1}$, 1.84 ±0.04 $g{\cdot}MJ^{-1}$, and 1.64±0.03 $g{\cdot}MJ^{-1}$ for the treatments T_{100}, T_{50}, T_{25}, and T_0 of 2016, respectively.

The superiority of RUE for T_{100} is probably not due to differences in leaf area index in T_{100} compared to T_{50}, T_{25}, and T_0, but to characteristics of leaf arrangement and inclination of leaves for the absorption of incident radiation (Ruiz and Bertero, 2008). Cowpea shows heliotropic leaf movement, which controls light absorption by adjusting the angle of inclination of leaves, in such a way that allow sun rays to reach them almost perpendicularly, therefore maintaining high photosynthetic rates throughout the day (Pastenes *et al.*, 2005).

Thus, the change from heliotropism to paraheliotropism during the reproductive phase led to a smaller radiation use efficiency for treatments subjected to water deficit, since they reduced the absorption of light and hence the production of photoassimilates.

On 2014 the greater number of rains and, therefore, greater occurrence of cloudy days provided an increase in diffuse radiation, which favored the absorption of radiation by shaded leaves inside the canopy of the crop (Caron *et al.*, 2014). Thus, the highest RUE of treatments under water deficit in 2014 compared to 2016 may be due to the greater contribution of leaves inside the canopy of the crop in using solar radiation to produce biomass, which increases together with the diffuse radiation.

The average RUE during the cowpea cycle for treatments T_{100} and T_{50} of both years is in the expected range of RUE for C_3 plants, which is from 2.0 to 4.5 $g{\cdot}MJ^{-1}$, growing on optimal conditions of water and radiation (Costa *et al.*, 1997). Treatments T_{25} and T_0 in both years of experiment have the smallest averages of RUE for the crop cycle, absorbing 12% and 20% less radiation in 2014 and 17% and 26% less radiation in 2016, respectively, compared to T_{100} of each year.

The average values of RUE for T_{100} confirms Tesfaye *et al.* (2006), who obtained average values of RUE of about 2.16 $g{\cdot}MJ^{-1}$ for *Vigna unguiculata* in field experiments in Ethiopia. The RUE of 2.10±0.06 and 2.23±0.04 $g{\cdot}MJ^{-1}$ obtained in the treatments T_{100} of 2014 and 2016 for cowpea are consistent with the highest values found in scientific literature under non-stressing water availability.

The yields of cowpea beans on the 2014 and 2016 experiments were negatively influenced by the different levels of water in the soil. They presented a significant difference ($p < 0.05$) among all treatments, with averages for treatments on 2014 of 1,569 $kg{\cdot}ha^{1}$ (T_{100}), 1,234 $kg{\cdot}ha^{1}$ (T_{50}), 1,002 $kg{\cdot}ha^{1}$ (T_{25}), and 792 $kg{\cdot}ha^{1}$ (T_0), with reductions of 21% in T_{50}, 36% in T_{25} and 50% in T_0. On the other hand, the averages on 2016 were 1,597 $kg{\cdot}ha^{1}$ (T_{100}), 1,295 $kg{\cdot}ha^{1}$ (T_{50}), 1,069 $kg{\cdot}ha^{1}$ (T_{25}), and 684 $kg{\cdot}ha^{1}$ (T_0) with reductions of 19% in T_{50}, 33% in T_{25} and 57% in T_0.

The results obtained prove the studies of Nascimento *et al.* (2011). They obtained a reduction of 60% when comparing treatments with irrigations during the whole cycle and the treatments exposed to water deficit. Since

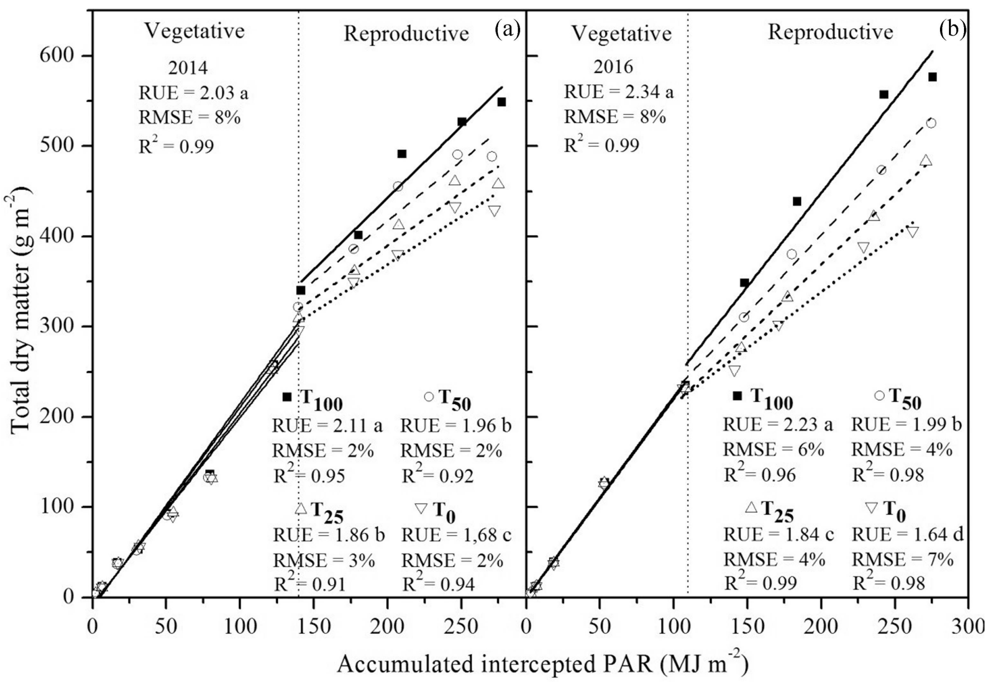

Figure 4. - Solar radiation use efficiency of cowpea submitted to different water regimes in 2014 (a) and 2016 (b). RUE: Radiation use efficiency; RMSE: Mean error square; R^2: Correlation coefficient; ■ T_{100}: Replacement of 100% of evapotranspiration of culture (ETc); ○ T_{50}: Replacement of 50% ETc; Δ T_{25}: Replacement of 25% ETc; T_0: Not have irrigation during the reproductive phase.

the water deficit make the physical and metabolic processes of the plant unfeasible and cause a reduction in productivity, since water is responsible for the opening of stomata and maintenance of transpiration (Bastos *et al.*, 2011).

4. Conclusion

A significant reduction in the LAI and in the grain yield was observed for all the treatments under water deficit, as well as a reduction in total aerial dry matter of treatments T_{25} and T_0, in both years.

In the experimental years, the extinction coefficient was not significantly affected by the water deficit imposed during the reproductive phase, although the treatments showed differences in LAI.

The different water regimes negatively influenced the RUE of cowpea. The crop reduced significantly its efficiency through the treatments T_{100} and T_0 in both years.

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