



Revista Caatinga

ISSN: 0100-316X

ISSN: 1983-2125

Universidade Federal Rural do Semi-Árido

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Revista Caatinga, vol. 30, no. 3, July-September, 2017, pp. 748-759
Universidade Federal Rural do Semi-Árido

DOI: 10.1590/1983-21252017v30n323rc

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COWPEA LEAF AREA, BIOMASS PRODUCTION AND PRODUCTIVITY UNDER DIFFERENT WATER REGIMES IN CASTANHAL, PARÁ, BRAZIL¹

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ABSTRACT – This work evaluated the effect of soil water availability on growth and productivity variables of cowpea in northeastern Pará, Brazil. The experiment was carried out in a field of 2,100 m² at the experimental site of the Federal Rural University of Amazon, during the driest season of the years 2011, 2012 and 2013, in a completely randomised design with two treatments (irrigated and non-irrigated), both with 12 replications in the reproductive phase (2012 and 2013). Growth and productivity data were submitted to analysis of variance with two variation factors (water regime and experimental year) at 5% probability. Student's t-test at 5% probability was used in the means of the stomatal conductance data, since this was monitored only in 2012. Final biomass production presented a reduction of 54.3% in 2012 and 26.4% in 2013 as a result of water deficit (DEF) of 76 and 26 mm, respectively. Mean stomatal conductance was reduced by 73% in the grain-filling stage as a result of the lower water availability during this period. Average cowpea productivity under water deficit reached 1,257 kg ha⁻¹ in 2012 and 1,396 kg ha⁻¹ in 2013. The reduction in water supply over the reproductive period significantly decreased production by 72 and 41% (F test, p < 0.05) in 2012 and 2013, respectively. An accumulated water deficit during the reproductive phase caused a maximum LAI reduction of 47% in 2012 (DEF of 76 mm) and of 13% in 2013 (DEF of 26 mm).

Keywords: *Vigna unguiculata*. Productivity. Water availability.

PRODUÇÃO DE ÁREA FOLIAR E BIOMASSA E PRODUTIVIDADE DO FEIJÃO-CAUPI SOB REGIMES HÍDRICOS EM CASTANHAL, PARÁ

RESUMO - O objetivo deste trabalho foi avaliar o efeito da disponibilidade de água no crescimento e produtividade do feijão-caupi cultivado no Nordeste do estado do Pará, Brasil. O experimento foi realizado em uma área de 2.100 m² na Fazenda Escola da Universidade Federal Rural da Amazônia, durante o período menos chuvoso de 2011, 2012 e 2013, em um delineamento inteiramente casualizado com dois tratamentos (irrigado e não irrigado), com 12 repetições na fase reprodutiva (2012 e 2013). Dados de crescimento e de produtividade foram submetidos a análise de variância com dois fatores de variação (regime hídrico e ano experimental) a 5% de probabilidade. Utilizou-se o teste t de Student a 5% de probabilidade nas médias de condutância estomática por ser monitorada apenas em 2012. A produção final de biomassa apresentou redução de 54,3% em 2012 e de 26,4% em 2013 devido a ocorrência de uma deficiência hídrica (DEF) de 76 e de 26 mm, respectivamente. A condutância estomática média foi reduzida em 73% na fase de enchimento de grãos devido a menor disponibilidade de água nesta fase. A produtividade média do caupi sob baixa deficiência hídrica atingiu 1.257 kg ha⁻¹ em 2012 e 1.396 kg ha⁻¹ em 2013. A redução da água diminuiu em 72% e 41% o rendimento do caupi (teste F, p < 0,05) em 2012 e 2013, respectivamente. A deficiência hídrica acumulada na fase reprodutiva causou redução de 47% no máximo IAF em 2012 (DEF de 76 mm) e de 13% em 2013 (DEF de 26 mm).

Palavras-chave: *Vigna unguiculata*. Produtividade. Disponibilidade hídrica.

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¹Received for publication in 04/04/2016; accepted in 11/28/2016.

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INTRODUCTION

Cowpea (*Vigna unguiculata* L. Walp) has a high socioeconomic importance in Brazil and is one of the most important sources of protein (CARVALHO et al., 2012) and of great importance in the basic diet of the poor population (BORGES et al., 2012). The high genetic variability (ANDRADE et al., 2010) and high adaptability to a variety of environmental conditions (NEVES et al., 2009), coupled with a high nutritional level (CARVALHO et al., 2012) and low production costs (MODESTO JUNIOR; ALVES, 2012), make cowpea beans an excellent option against hunger in the poorest regions of the world.

Water availability is one of the most important environmental factors in plant growth control (NASCIMENTO; PEDROSA; SOBRINHO, 2004), and although the Amazon region presents a high volume of rainfall compared to other regions of Brazil, the climatic regime of this area limits cowpea production to the first half of the year, when water is readily available without the need for alternative supply through irrigation.

Previous studies in other regions of Brazil have shown that different levels of water in the soil influence the growth and grain yield of this crop and, depending on the cultivar adopted, the effect of water availability becomes more significant. Silva and Neves (2011) cultivated 20 cowpea genotypes in the Northeast of Brazil, with productivities ranging between 669 and 1,070 kg ha⁻¹ under dry conditions and between 982 and 1,832 kg ha⁻¹ under irrigation. This represents an average increase of 69% in productivity as a result of water supply. Although cowpea has a large relevance in the State of Pará, its production and productivity has been decreasing since 2003 due to several technical, commercial, political and, above all, climatic problems (REBELLO; COSTA; FIGUEIRÓ, 2011).

Depending on the place and time of the year, mainly in the Brazilian Northeast, the cultivation conditions of the species are considered adverse,

with the occurrence of water deficiency coupled with high temperatures, which requires production strategies where water acts as the limiting factor (RAMOS et al., 2012). Due to the economic importance of this crop for the region, this study aims to evaluate the effect of soil water availability on grain growth and yield of cowpea. The experiment was performed over a period of three years under irrigated and non-irrigated conditions.

MATERIAL AND METHODS

The experiment was carried out from 2011 to 2013 in the northeastern region of the state Para, at the experimental site of the Federal Rural University of Amazon, about 80 km from the city of Belém. The field was located in an area with 0.21 ha of cowpea cultivation (1°19'24.48"S; 47°57'38.20"W). The regional climate, according to the Koppen classification, is Ami. Maximum and minimum temperatures are 35 and 18°C, respectively, with an average annual temperature of 26°C. Average relative humidity and annual rainfall are 80% and 2,571.6 mm, respectively (TENÓRIO et al., 1999).

An automatic weather station was installed at the experimental area to monitor the meteorological variables. It consisted of a datalogger (CR10X, Campbell Scientific) and a multiplexer (AM16/32A, Campbell Scientific) configured to generate averages every 10 minutes. Data of temperature (Tar), relative air humidity (RH), global radiation (Rg), volumetric soil water content (US) through time domain reflectometry (TDR) and precipitation were sampled.

For physical and chemical soil characterisation, samples were collected throughout the experimental area at depths of 0 to 0.2 m. Soil samples were analysed at the soil laboratory of the Federal Rural University of Amazon (UFRA). The soil was classified as a sandy loam textured Latosol; the results of the analyses are shown in Table 1. Due to logistic reasons, the area used in 2011 was different from that used in 2012 and 2013.

Table 1. Chemical and physical soil parameters in the experimental site of UFRA, Castanhal-PA, in the three experiments.

Soil chemical characteristics (0-0.20 m)								
	pH	P	Na ²⁺	Ca ²⁺	Mg	Ca ²⁺ +Mg ²⁺	Al ³⁺	SOM
Year	(in H ₂ O)	(mg dm ⁻³)	(cmol _c dm ⁻³)			(g kg ⁻¹)		
2011	5.9	31.56	-	1.43	0.67	-	0.24	2.82
2012/13	4.7	2	12	1	0.50	1.1	0.45	9.11
Soil physical characteristics (0-0.20 m)								
	Clay	Silt	Sand	Soil density	Field capacity	Permanent wilting point	Critical humidity	Available water capacity
Year	(g kg ⁻¹)			(kg dm ⁻³)	(m ³ m ⁻³)		(mm cm ⁻¹)	
2011	120	110	760	1.55	0.19	0.085	0.114	1.63
2012/13	110	120	770	1.46	0.21	0.11	0.126	1.46

The soil was prepared at the end of the rainy season of the region. Seeds were sown mechanically, adopting a spacing of 0.5 m between rows, averaging 10 plants per linear meter. Overall density was 200,000 plants per ha. Prior to sowing, the seeds were treated with both fungicide and insecticide. Seeding was carried out on August 10, September 25 and October 1 of 2011, 2012 and 2013, respectively, at a rate of 13-15 m⁻¹ seeds. During sowing, soil fertilisation, based on the results of the chemical analysis, was performed using a chemical fertiliser (urea, triple superphosphate and potassium chloride) of the formulation 0:60:40 kg ha⁻¹ of N, P and K. Over the experimental time, herbicides and insecticides were used when necessary. Physiological maturation was reached on October 5, November 22 and November 26 of 2011, 2012 and 2013, respectively.

The cultivar used was BR3 Tracueteua, which presents a habit of indeterminate growth, prostrate size and a cycle of 60-70 days; it is the most recommended cowpea cultivar for the climatic

conditions of the eastern part of Para State (FREIRE FILHO et al., 2009). In addition, it presents moderate tolerance to high temperatures and water deficits (NASCIMENTO et al., 2011).

The experiment was carried out in an area of 30 x 70 m (≈ 0.21 ha) in two distinct locations within the site. The first one was a fallow area during 2011 and the second area, selected based on logistic reasons, was in an area previously covered with a secondary forest in 2012 and 2013. The distance between the two areas was 300 m. The delineation was completely randomised with 12 replicates (12 plots) of 10 x 7 m. In 2011, the 12 plots were submitted to natural rainfall conditions (dryland), while in 2012 and 2013, in another experimental area, the plots were submitted to two treatments, irrigated and non-irrigated, totalling 24 experimental plots; 12 plots were irrigated and 12 were non-irrigated (Figure 1). Initially up to stage V4, the planting was submitted to an irrigation system without distinction of treatment in order to establish and standardise the crop (in 2012 and 2013).

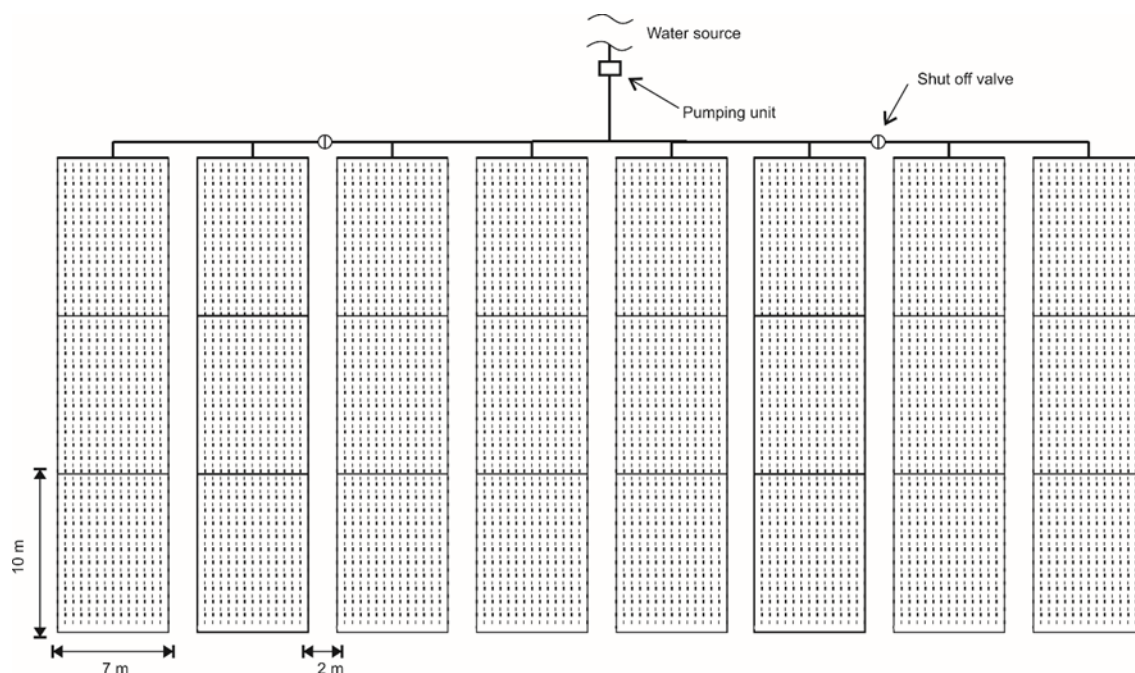


Figure 1. Schematic design of the experimental area and irrigation system.

Irrigation was performed using a drip irrigation system with drip tapes with a distance of 0.20 m between drippers. Mean flow rate, as measured in the field, was 0.602 L h⁻¹ per dripper, with a service pressure of 3 mwc. The dripping tapes used were made of additive polyethylene, with a nominal diameter of 16 mm and with integrated insert type emitters. They were positioned on the surface of the soil with each tape serving one planting line. When the plants reached the R5 stage, about 30 days after sowing (DAS), representing beginning of the reproductive phase, the experimental delineation was started with 12 plots

and 2 treatments, irrigated and non-irrigated (in 2012 and 2013).

The water blade applied during the experiment was controlled as a function of time according to the flow of the emitters, using manometers, registers and timer. Irrigation time was determined daily as a function of crop evapotranspiration (ET_c) of the previous day. The value of ET_c was calculated from the daily reference evapotranspiration (ET_o) obtained by the Penman-Monteith method (ALLEN et al., 2011). The data was obtained from an INMET (National Institute of Meteorology) meteorological station at

the Federal Institute of Pará, Campus Castanhal, 3 km from the experimental area, and measured as a function of the crop coefficient of cowpea (BASTOS et al., 2008).

To calculate the actual evapotranspiration of the crop (ET_r) and the water deficit, the Thornthwaite and Mather method, modified by Pereira (2005), was adopted. It considers the available water capacity (AWC) of the experimental area (Table 1) and the effective depth of the radicular system visually observed in the field.

Phenological development was analysed daily according to the method of identification of crop stages described in Farias et al. (2015). Basically, continuous monitoring starts from germination, with three replicates per treatment of plots that consisted of lines of 1 meter in length, containing 10 plants in average.

Data for growth analysis was collected twice a week from the 10 DAS. We collected 5 plants per 0.5 linear meter in each treatment. The samples were separated into leaflets, petioles, stalks, peduncles, flowers, pods and grains. Data were oven-dried at 70°C until constant weight, on average 56 hours, and weighed on a digital scale with precision of 0.01 g. At the time of harvesting, three plots of 1 m², represented by lines of 2 linear meters previously defined for grain yield (PG), were selected. Leaf area was obtained by collecting six leaf discs per plant, totalling 30 discs per sample. The disc samples were carefully collected from the middle third of the fully expanded central leaflet. Leaf area index (LAI) was estimated considering these measures (discs areas) and the dry weight of the sampled leaves (BENINCASA, 2003).

In the experiment performed in 2012, stomatal conductance (gs) of the culture was evaluated through a steady-state porometer (model Type AP4 - Delta-T Devices). Measurements were carried out during the day, between 8 a.m. and 4 p.m., on the abaxial faces of the central leaflet of the third leaf from the fully expanded apex (NASCIMENTO et al., 2011). Three plants in each treatment were sampled. We selected three evaluations days, representing the period of reproduction (R7 stage) at 41 DAS, grain filling (R8 stage) at 47 DAS and, finally, physiological maturation (R9 stage) at 58 DAS, respectively. Here, we justify the presentation of the results only for 2012, as this was the only year in which we had the equipment available for use in the field.

Total shoot biomass, LAI and grain yield data were submitted to analysis of variance with 5% probability. We considered two variation factors (treatment and experimental year) and the interaction between them. Student's t-test at 5% probability was used to identify significant differences in the means

of cowpea conductance data submitted to both treatments, irrigated and non-irrigated.

RESULTS AND DISCUSSION

During the entire experiment, air temperatures ranged between 20.15 and 34.11°C, with a daily average of 27.56; 27.17 and 27.03°C in 2011, 2012 and 2013, respectively. Mean daily relative air humidity over the three years were 83.41, 79.73 and 85.42%, respectively. These are optimum conditions for cowpea development, considering that this crop is adapted to warm climates (BASTOS et al., 2008; NASCIMENTO et al., 2011). Mean incident solar irradiance and average reference evapotranspiration observed during the experiment corresponded to 18.91, 17.78 and 17.86 MJ m⁻² d⁻¹ and 3.77, 3.21 and 3.12 mm day⁻¹, respectively, for 2011, 2012 and 2013.

These results indicate that although the conditions were similar between the experiments, the year 2011 was considerably warmer and with greater energy availability. In addition, it presented a higher atmospheric demand for water vapor compared to other years. On the other hand, the experiment in 2013 occurred in a less hot and humid environment, requiring a lower atmospheric demand for water vapor. The difference in the meteorological conditions between the years acted as a factor of additional variation in the results obtained for the cowpea growth variables, as there was a significant interaction between treatments and experimental year (Table 3).

Figure 2 shows rainfall and soil moisture data during the cycle of cowpea cultivation over the three years of the experiment. Although the experiment was carried out in the season with the lowest rainfall, in order to be able to submit the cowpea to the absence of water in the reproductive phase, some precipitation was observed, mainly during the vegetative phase and at the end of the crop cycle. This was especially the case for the year 2013, in which a greater amount of rain was observed (Figure 2). Under these conditions, the irrigation blade was corrected as a function of precipitation (Figure 2).

Cumulative rainfall values between sowing and physiological maturation (≈ 56 DAS) of 139.8 mm in 2011 and 76.56 mm in 2012 were observed, which is normal during this period of the year. Rainfall values of 107.5 and 66.1 mm occurred in the vegetative phases and of 32.3 and 10.4 mm in the reproductive phases of 2011 and 2012, respectively. Nonetheless, in the year 2013, total rainfall in the same stages was 111.8 and 153.2 mm, totalling 265 mm during the growth cycle.

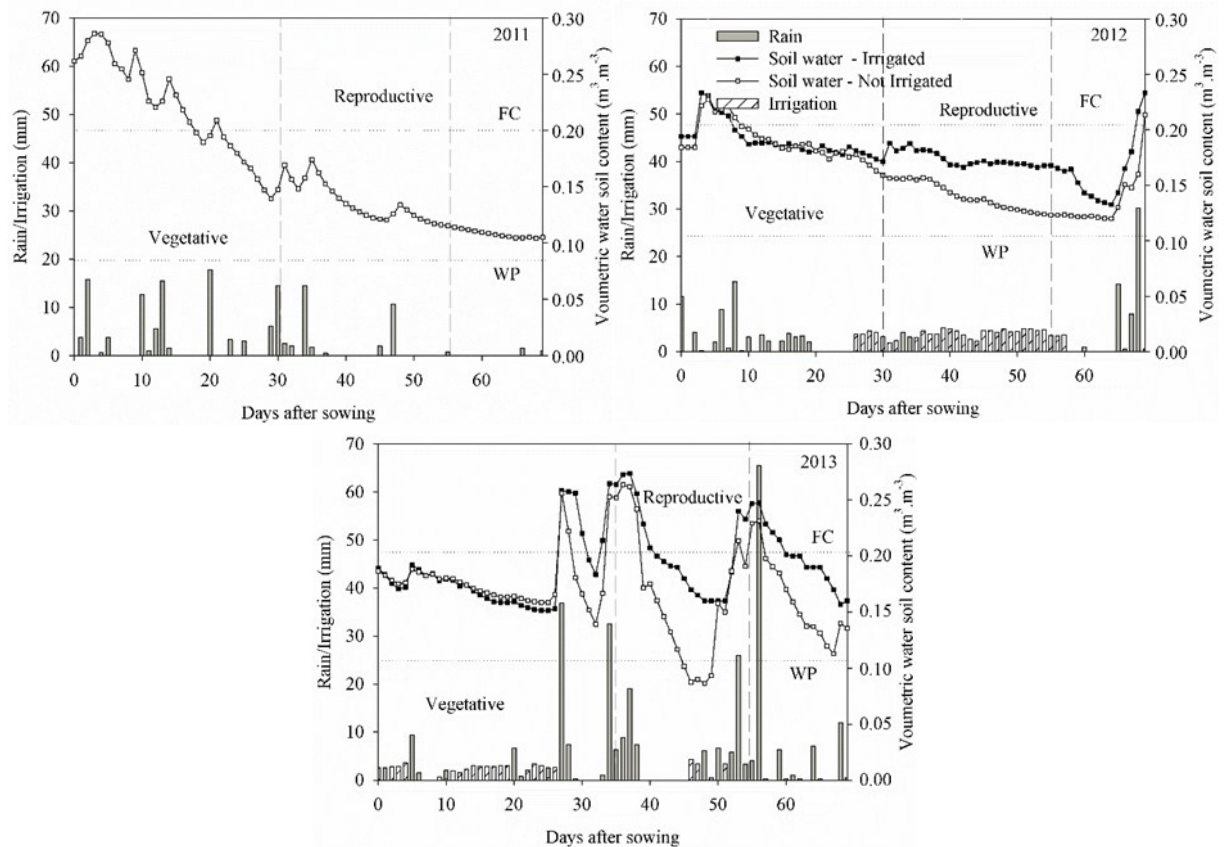


Figure 2. Rainfall and soil water variability during the experimental period. Castanhal, PA, 2011-2013.

Soil moisture remained high over the vegetative phase due to rainfall and water supply from the irrigation system; irrigation was supplied only in 2012 and 2013. Soil water content was always kept close to field capacity (Figure 2). It is noticeable that as a result of the rainfall in 2011 and 2013, soil water content achieved levels higher than field capacity on several occasions. Thus, the occurrence of a water surplus favoured plant growth (Table 1).

Based on this analysis and considering the physical characteristics of the soil, we conclude that the experiment of 2011 offered adequate conditions of water supply due to the greater capacity of water storage in the soil (Table 1). Thereby, water was the main factor impacting cowpea growth, especially during the reproductive phase when the rain had

ceased, since, unlike in the other years where irrigation was provided, water requirements were exclusively met by water stored in the soil.

Despite the occurrence of rain during the reproductive phases of 2012 and 2013, the absence of irrigation caused a significant reduction in soil water content in the non-irrigated treatment. Thus, a cumulative water deficit of 76 and 26 mm was observed in both years, respectively (Table 2). After 30 DAS, when the treatments were started in 2012 and 2013, a continuous reduction in soil water content was observed. This was most likely the result of the natural exhaustion of soil reserves due to the absence of irrigation and, at a rate higher than observed in 2011, due to the lower water storage capacity in the new area (Table 1).

Table 2. Water consumption, applied water blade (rain + irrigation) and water deficit in the experiment (DEF).

Year	Total ETc (mm)		Total blade (mm)		ETc fraction (%)		Total ETc (mm)		DEF (mm)	
	Veg	Rep	Veg	Rep	Veg	Rep	Veg	Rep	Veg	Rep
2011	-	-	-	-	-	-	-	-	-	-
	Irrigated	-	-	-	-	-	-	-	-	-
Non-irrigated	100.9	114.8	107.5	32.3	106	28	89.7	59.5	11.2	49.6
	2012	Veg	Rep	Veg	Rep	Veg	Rep	Veg	Rep	Veg
Irrigated	83.3	106.2	84.9	103.7	102	98	76.1	102.9	7.2	3.2
	Non-irrigated	83.3	106.2	84.9	10.4	102	9.8	76.1	30.4	7.2

Table 2. Continuation.

Year	Total ETc (mm)		Total blade (mm)		ETc fraction (%)		Total ETc (mm)		DEF (mm)	
	Veg	Rep	Veg	Rep	Veg	Rep	Veg	Rep	Veg	Rep
Irrigated	119.4	88.7	159.6	164.3	137	185	110.3	73.5	9.1	18.7
Non-irrigated	119.4	88.7	159.6	153.2	137	172	110.3	66.1	9.1	26.2

During the vegetative period (0 to 30 DAS), total water demand, represented by ETc, was 100.9, 83.3 and 119.4 mm in 2011, 2012 and 2013, respectively. During the reproductive phase (up to 56 DAS), total water demand was 114.8, 106.2 and 88.7 mm, respectively. This variation generated a total demand from sowing to physiological maturation of 215.7, 189.5 and 208.1 mm, respectively. According to Andrade Junior et al. (2003), cowpea requires a minimum of 300 mm of precipitation in order to obtain high production values in some regions of Brazil, without the need for irrigation.

Throughout the experiment in 2011, cowpea received a total water (rain) amount that corresponded to 64.8% of its demand for evapotranspiration. In contrast, in the experiment if 2012, this total was 189.5 mm ($\approx 99.5\%$ of total ETc) and 93.7 mm ($\approx 50.3\%$ of total ETc) of water, in the irrigated and non-irrigated treatment, respectively; which was offered by both rainfall and irrigation (in the irrigated treatment) (Table 2).

In the 2011 experiment, water was only supplied through rainfall and corresponded to approximately 106 and 28% of the water demand in the vegetative and reproductive phases, respectively. However, although the plantation had received only 28% of its water demand in the reproductive phase, the higher water storage capacity in the soil resulted in a lower water deficit than that observed in 2012, which corresponded to 50 mm.

The occurrence of only 10.4 mm of rain in the reproductive phase of 2012 indicates that cowpea received no more than 10% of its demand for the phenological phase in this treatment. This fact caused a water deficiency of 76 mm at this stage, corroborating the hypothesis that the crop experienced water stress during its most critical phase in the non-irrigated treatment of 2012. Similar results have been observed by Nascimento et al. (2011).

The experiment in 2013, on the other hand, occurred under conditions where water supply exceeded the demand. Although the year 2013 experienced high rainfall, which provided 185 and 172%, respectively, of the demand for ETc during the reproductive phase in the irrigated and non-irrigated treatment, a large part of the rainfall occurred on consecutive days, such as the rainfall

events between 30 and 40 DAS and 50 and 60 DAS (Figure 2). This suggests that excess and, subsequently, surface drainage occurred; this would also have greatly contributed to soil moisture values, which were well above field capacity. The water capacity of the experimental area was only 36.5 mm for the effective depth of the root system considered (25 cm).

However, within the reproductive period of 2013, in particular between 38 and 48 DAS, the absence of rainfall caused a rapid consumption of soil water, due to the physical characteristics of the soil (Table 1), leading to critical soil humidity. Nonetheless, there was a subsequent increase in soil water content as a result of concentrated rain events between 50 and 60 DAS. This may have contributed to the observed difference in biomass and LAI between the treatments evaluated in this year. When analysing the cycle as a whole, the volume of water available from rainfall and irrigation exceeded the water demand of the crop (Table 2), preventing water lack. However, in spite of the higher rainfall in 2013, water deficits of 19 and 26 mm were observed during the reproductive phase in the irrigated and non-irrigated treatments, respectively (Table 2).

There was a significant effect ($p < 0.05$) of the interaction between treatments (irrigated and non-irrigated) and experimental year for most of the analysed variables, except for total biomass at 41 DAS (Table 3). The data in Table 3 indicate that it is not possible to analyse the results together, except for the total biomass right after the beginning of the treatments, since the experimental period contributed to the differences found for each treatment.

Figure 3 presents the biomass production of the above ground parts under dry and irrigated conditions for the three experimental years. It is noticeable that cowpea did not show any difference in biomass production during the vegetative phase because there was no water limitation. However, there was a significant difference (test F, $p < 0.05$) shortly after the beginning of the treatments (Figure 3a). In the experimental site and under optimal water conditions, cowpea can reach a mean total biomass of $176.6 \pm 4.18 \text{ g m}^{-2}$ up to the onset of flowering. During this phase, a water deficit of 11, 7 and 9 mm was observed for 2011, 2012 and 2013, respectively.

Table 3. Summary of the combined variance analysis of total shoot biomass at 41 DAS (g m^{-2}), final total biomass (g m^{-2}), leaf area index (LAI) at physiological maturation and productivity (g m^{-2}) as a function of the irrigated and non-irrigated condition and the experimental year (2012 and 2013).

Source of variation	DF	Mean squares			
		Biomass at 41 DAS	Final biomass	LAI	Productivity
Treatment	1	58,320*	553,300*	26.81*	67,090*
Experiment	1	5,234*	81,640*	10.43*	11,410*
Interaction	1	275	62,790*	6.84*	3,450*
Residual	44	1,002	8,721	0.66	302.8

*Significant at 5% probability by test F.

In 2012 and 2013, under irrigation, albeit with a slight water deficit during the growth cycle of 10.4 mm and 27.8 mm, respectively, final average total biomass production reached 528.31 ± 32.41 and $538.45 \pm 32.41 \text{ gm}^{-2}$, respectively. When analysing the significant effect of water availability (F test, $p < 0.05$), it can be observed that final biomass production of the above ground part was reduced by 54.3% in 2012 and by 26.4% in 2013. This was most likely due to the water deficiency in the reproductive phase (Table 2), which reached 241.2 ± 14.83 and $396.06 \pm 46.57 \text{ g m}^{-2}$ under natural field conditions in 2012 and 2013, respectively. Although the experiment of 2011 has occurred under dry conditions and an accumulated water deficit of

50 mm in the reproductive phase (Table 2), the final production of total shoot biomass was $466.47 \pm 5.96 \text{ g m}^{-2}$, only 12.5% lower than the value obtained under conditions of low water deficiency in 2012 and 2013 (Table 2).

This slight difference demonstrates the importance of the soil water storage capacity in plant water supply, since the experimental area in 2011 had a greater storage capacity (Table 1). As storage capacity was associated with the high water supply by rainfall in the vegetative phase and some rain events occurring in the reproductive phase, a certain amount of water remained in the soil at levels above the critical humidity for a long period within the reproductive phase (Figure 2).

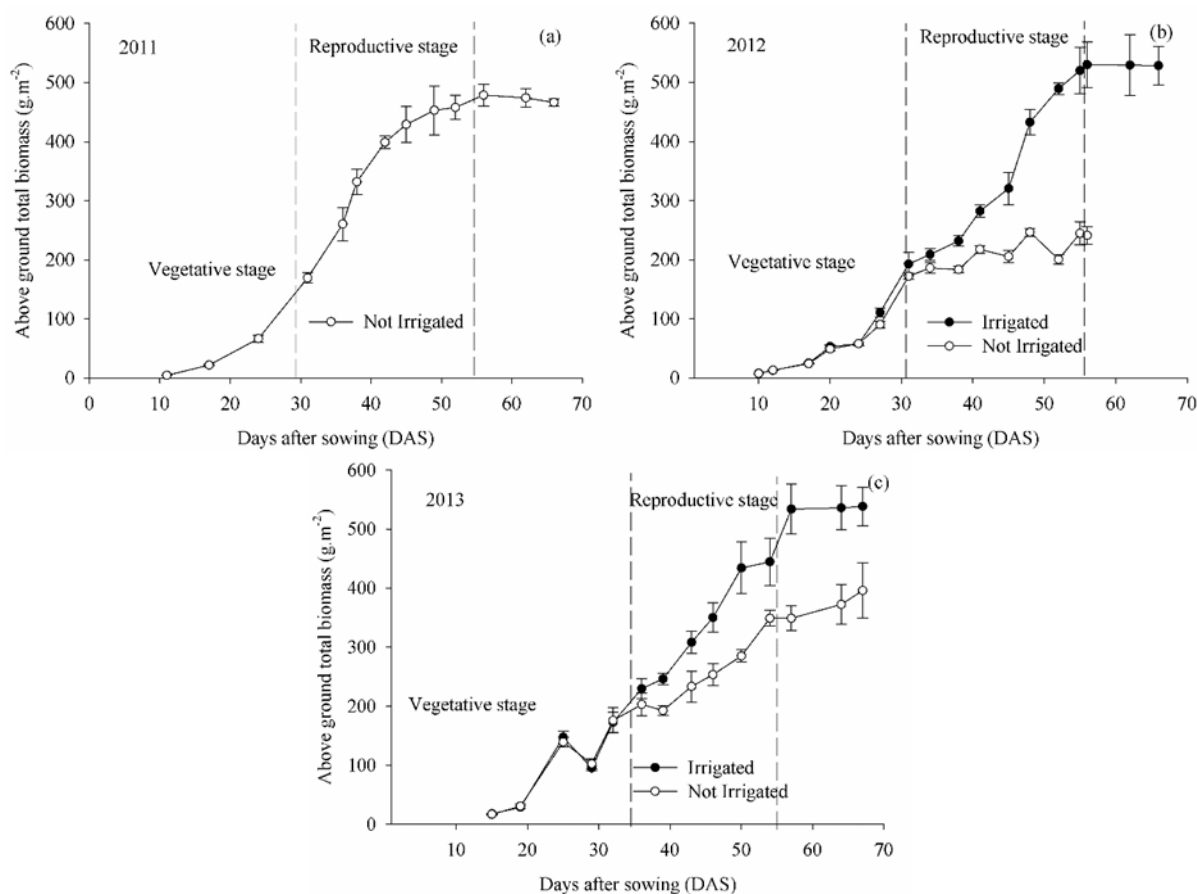


Figure 3. Total biomass of the aerial part of cowpea under irrigated and non-irrigated conditions in Castanhal, PA, in 2011 (a), 2012 (b) and 2013 (c).

Water stress interferes with several physiological plant processes. In the case of cowpea, other authors have observed significant reductions of physiological processes as a result of water stress, such as stomatal conductance and leaf water potential (MENDES et al., 2007; NASCIMENTO et al., 2011) as well as total chlorophyll content of leaves (BASTOS et al., 2011). As a consequence, the weight of the aerial parts is reduced.

Although cowpea is classified as tolerant to both water deficiency and excess soil water (NASCIMENTO et al., 2011), Mendes et al. (2007) demonstrated that the absence of water replacement in the reproductive phase at intervals of 7 to 8 days significantly reduced the number of pods produced in two cultivars. Also, water stress at intervals of 15 to 20 days in the vegetative phase delayed the onset of flowering. Bastos et al. (2011), studying the cultivar Tracuateua – 192, found significant differences in the number of pods per plant, number of grains per pod, weight of 100 grains and productivity when

subjected to moderate water stress in the reproductive phase.

Figure 4 shows the LAI variability along the growth cycle in the three experimental years. It is noticeable that cowpea significantly reduces its leaf area to the smallest sign of lack of soil water (Figure 4b). This has also been observed by Bastos et al. (2011, 2012). The maximum LAI value reached by cowpea in the irrigated treatment was 3.29 ± 0.15 at 48 DAS in 2012 and 3.26 ± 0.19 at 50 DAS in 2013, during the reproductive phase. The opposite was observed in the non-irrigated treatment, where the maximum value was only 1.75 ± 0.09 in 2012 and 2.84 ± 0.17 in 2013, about 4 and 9 days after the start of treatments, respectively. Leaf area production in 2011 reinforces the hypothesis that cowpea has developed under adequate conditions of water availability, although it was a dryland condition and in the presence of accumulated water deficiency of 50 mm, which is lower than that observed in 2012.

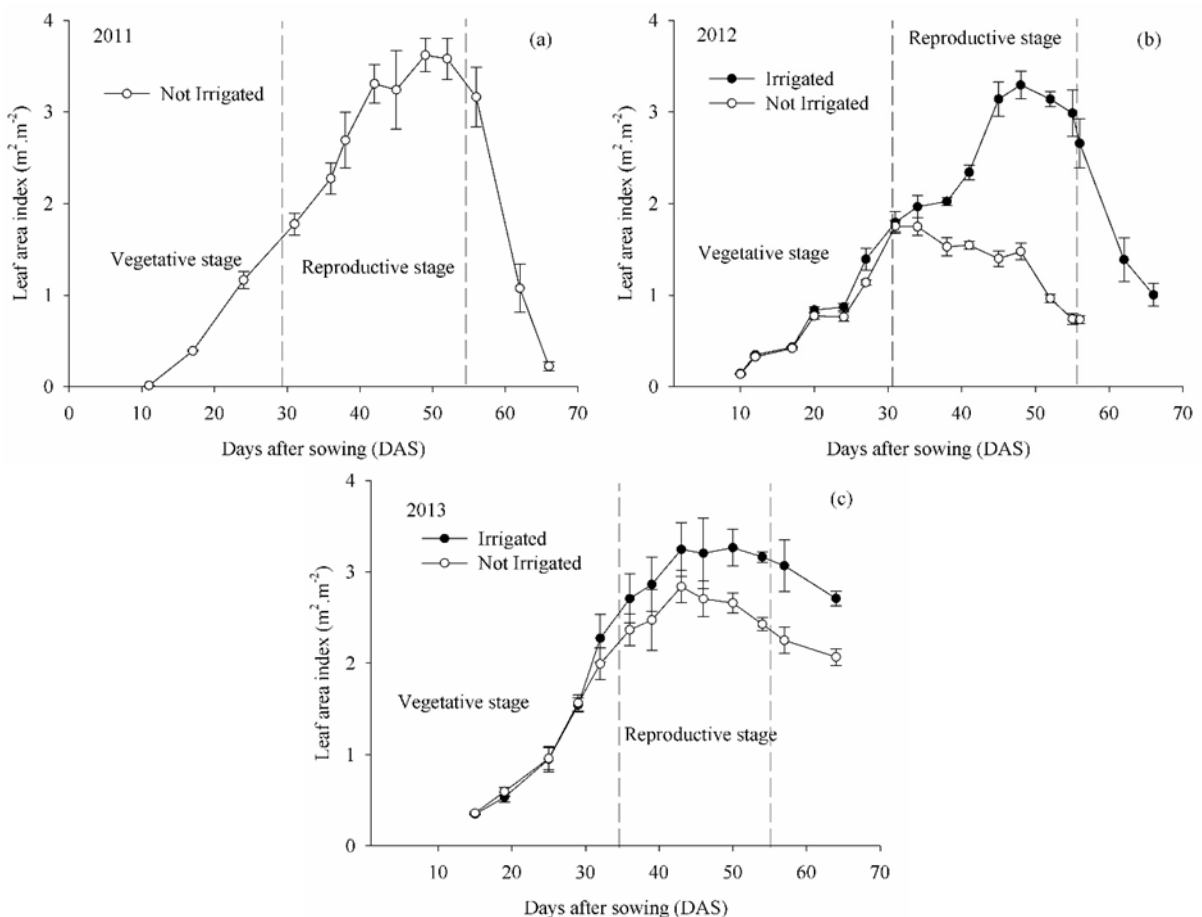


Figure 4. Leaf area index of cowpea under irrigated and non-irrigated conditions in Castanhál, PA, in 2011 (a), 2012 (b) and 2013 (c).

The results found for the year 2012 show that cowpea cannot maintain leaf area production after being submitted to water stress. In addition, under these conditions and with a water deficit of 76 mm, the reduction in maximum LAI reached 47%, a value very close to that found by Bastos et al. (2011) for

the same cultivar; they obtained a reduction of 44% at maximum LAI by imposing water stress to cowpea plants in the reproductive phase. The observed leaf area reduction is most likely a survival strategy to reduce transpiration surface.

According to Nascimento et al. (2011),

among 20 genotypes evaluated, the cultivar Tracueteua - 192 was intolerant to drought when experiencing water deficit in the reproductive phase. The same authors showed that the water deficit caused a greater reduction in leaf water potential and greater stomatal closure in the cultivar, resulting in a greater reduction in photoassimilate production and, subsequently, lower productivity.

Figure 5 shows the diurnal curve of stomatal conductance at 41, 47 and 58 DAS (phases R7-R8-R9), corresponding to 11, 15 and 28 days after the beginning of the water restriction in the

non-irrigated treatment during the experiment in 2012. In phase R7, the maximum g_s value for the irrigated treatment was $896.03 \text{ mmol m}^{-2} \text{ s}^{-1}$, between 10 a.m. and mid-day. Maximum conductance in the non-irrigated condition occurred early in the day, at around 8 a.m., reaching only $319.16 \text{ mmol m}^{-2} \text{ s}^{-1}$, showing a continuous reduction in the following hours. The same pattern of temporal variability of g_s was observed in phases R8 and R9, with significant differences (t-test, $p < 0.05$) between irrigated and non-irrigated conditions.

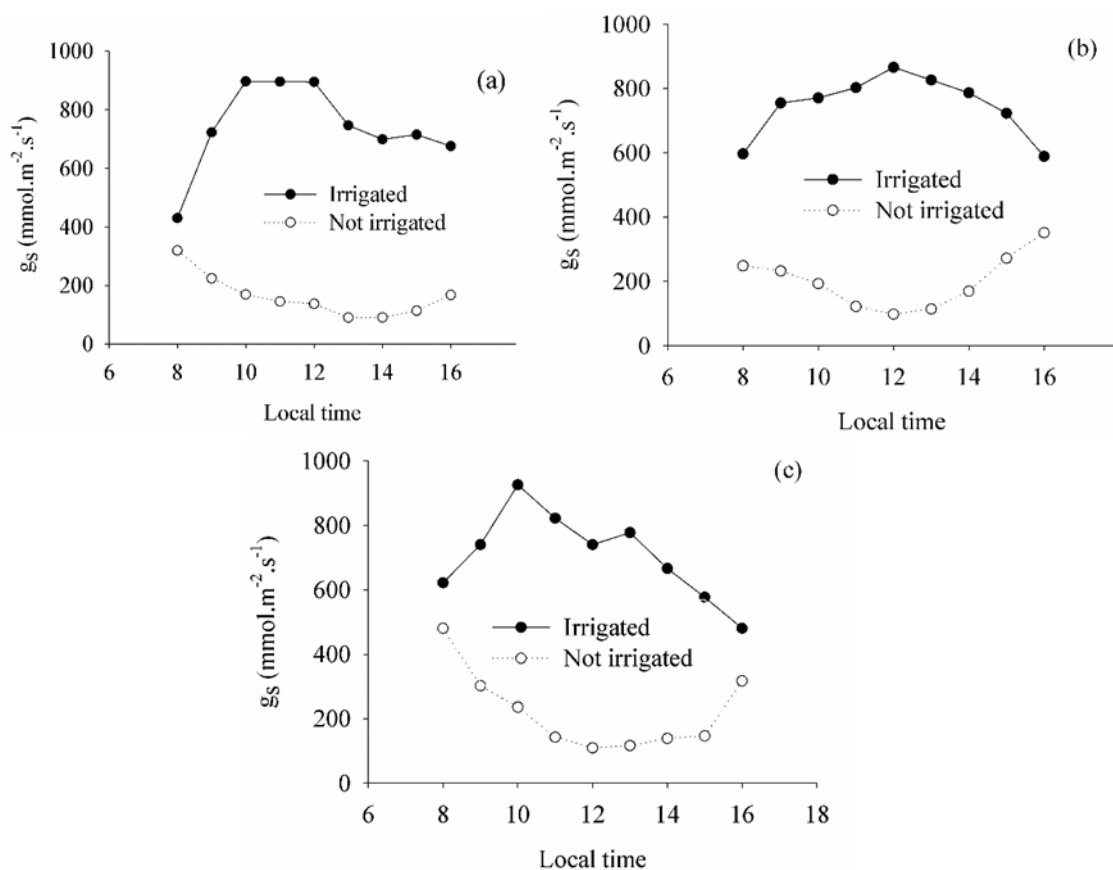


Figure 5. Diurnal cycle of stomatal conductance of irrigated and non-irrigated cowpea in the R7 (a), R8 (b) and R9 (c) phases in the 2012 experiment.

Regarding the lower water supply during the reproductive phase in the non-irrigated treatment in 2012 and the presence of an accumulated water deficit of 76 mm in the phase, stomatal conductance ranged from 161.56 to $221.11 \text{ mmol m}^{-2} \text{ s}^{-1}$. This corresponded to an average reduction of 73.45% compared to the irrigated treatment (Table 3). Previous studies on cowpea in different regions have shown that the variability of g_s was similar to that observed in this study, with water availability being the main source stomatal conductance variation (DUTRA et al., 2015; MENDES et al. 2007).

Results of Paiva et al. (2005), obtained for the common bean, show that reduced water supply caused a decrease in stomatal conductance in the reproductive phase. The values ranged from

610.89 to $726.64 \text{ mmol m}^{-2} \text{ s}^{-1}$ when irrigated at 40% of the consumption of available soil water and from 256.01 to $440.85 \text{ mmol m}^{-2} \text{ s}^{-1}$ when exposed to environmental conditions of the experiment.

Considering that stomatal control is an important characteristic of plants to limit water loss through reduction in stomatal conductance and consequent stomatal closure (PAIVA et al., 2005), we expected significant reductions in production and productivity of cowpea in the region. Such reductions were expressed by the low values of conductance under the non-irrigation conditions of 2012, which were a result of increasing water deficit from the R7 phase to physiological maturation (Table 4).

Table 4. Mean values of stomatal conductance (g_s , in $\text{mmol m}^{-2} \text{s}^{-1}$), volumetric soil water content (US, in $\text{m}^3 \text{m}^{-3}$) and accumulated water deficit (DEF, in mm) for irrigated and non-irrigated cowpea plants between the 41 and 58 DAS (Phase R7 to R9) in 2012.

Phases	R7			R8			R9		
	g_s	US	DEF	g_s	US	DEF	g_s	US	DEF
Irrigated	742.0* (± 42.8)	0.168* (± 0.02)	1.8	745.78* (± 27.74)	0.171* (± 0.016)	2.5	705.60* (± 38.9)	0.164* (± 0.02)	3.4
Non-irrigated	161.6* (± 21.0)	0.14* (± 0.03)	21.7	199.53* (± 24.25)	0.132* (± 0.017)	40.5	221.11* (± 36.1)	0.123* (± 0.02)	84

*Significant difference between the means in the column by Student's t-test ($p < 0.05$). Values in parenthesis correspond to standard error.

There was a significant decrease (F test, $p < 0.05$) in productivity due to the lower supply of water in the non-irrigated treatment (Table 5) in 2012 and 2013. Cowpea yield between 2011 and 2013 ranged from 1,115 to 1,396 kg ha^{-1} . Such yields are common for this region (OLIVEIRA et al., 2011) and occur as a response to a total water supply (rain + irrigation) of 140 and 324 mm up to physiological maturation, corresponding to the values of total water deficit in the reproductive phase between 50 and 3 mm. Similar results have been found by Freire Filho et al. (2009), who studied the yields of several cultivars used in the northeast of the

state Para in order to identify the most promising ones. They obtained a variation of 638 to 1,782 kg ha^{-1} for the cultivar BR3-Tracuateua. Bastos et al. (2002) evaluated the cultivar BR14-Mulato in the state of Piauí and obtained a productivity of 1,140 to 2,056 kg ha^{-1} .

Although some cowpea cultivars have a tolerance to water deficit, decreased water availability in the reproductive phase caused a significant reduction in the yield of the cultivar Tracuateua. This confirmed its sensitivity to water lack, as also verified by Nascimento et al. (2011) and Bastos et al. (2011).

Table 5. Grain productivity (PG) of cowpea, cultivar Tracuateua, under irrigated and non-irrigated cultivation.

	Productivity (kg ha^{-1})		
	2011	2012	2013
Irrigated	-	1,257.19 (± 39.20)*	1,396.09 (± 72.09)*
Non-irrigated	1,114.65 (± 36.92)	339.98 (± 15.48)*	817.94 (± 67.93)*

*Significant difference between the means in the column by the F test ($p < 0.05$). Values in parenthesis correspond to standard error.

The lack of irrigation in the reproductive phase was responsible for a significant reduction in cowpea productivity (72 and 41%, F test, $p < 0.05$) in 2012 and 2013, providing only 340 and 818 kg ha^{-1} of the final yield, respectively (Table 4). These results corresponded to a water supply (rainfall) during the reproductive phase of only 10.4 mm, which is about 10% of the total E_{Tc} of the phase (106.2 mm) in 2012 and of 153 mm in 2013 that caused the presence of a water deficit in the 76 and 26 mm phases, respectively (Table 2).

Although the water supply in 2013 was higher than the water demand of this phase, it occurred on three to four consecutive days. Thereby, a water surplus due to the soil water capacity was generated. Then, within about nine days without any rain, between 39 and 47 DAS, soil moisture reached a critical value (Figure 2). This is in agreement with the results by Mendes et al. (2007), who demonstrated that the absence of water replacement in the reproductive phase, at intervals of 7 to 8 days, significantly reduces the number of pods produced by some cowpea cultivars. Nascimento et al. (2011) obtained an average reduction of 60% in the productivity of different cowpea cultivars by

reducing water supply from 300 to 190 mm in the Northeast of Brazil.

Maximum cowpea yields in Brazil vary between 1,400 and 2,900 kg ha^{-1} and are generally obtained under water availability conditions ranging from 370 to 570 mm (ANDRADE JUNIOR et al., 2002). The difference observed in the productivity of cowpea was caused by the lower water availability of the soil. Water deficits lead to a reduction in productivity by impeding photosynthesis, as water is responsible for stomatal opening and maintenance of transpiration. Such processes are essential for carbon dioxide to become permeable in the leaf mesophyll (BUCHANAN; GRUISSEM; JONES, 2000).

The results of Nascimento et al. (2011) show that the same cultivar used under the climatic conditions in the northeastern part of Brazil can reach a productivity of 1,024 kg ha^{-1} when grown under full irrigation. On the other hand, however, it has a low productivity (171 kg ha^{-1}) when it experiences a moderate water deficit in the reproductive phase, associated to 75% depletion of available water in the soil.

Studies on cowpea in Roraima, conducted by Oliveira et al. (2011), corroborate the grain yield

results obtained in this experiment. According to the authors, the lowest irrigation depth (187 mm) reduced grain yield by 43.3%, considering that the highest water blade, 273 mm, yielded a productivity of 1,420.51 kg ha⁻¹.

According to Coelho (2003), adequate water supply by irrigation enables the plant to maintain a continuous flow of water and nutrients from the soil to the leaves. This benefits the growth, flowering and fruiting of the plant, thus resulting in an increased productivity. Considering the fact that high water deficits drastically affect the performance of some cowpea cultivars (NASCIMENTO; PEDROSA; SOBRINHO, 2004), further studies are needed to evaluate the level of water deficit tolerated by the cultivar BR3 Tracueteua under the climatic conditions of Northeastern Brazil.

CONCLUSIONS

The cultivar BR3 Tracueteua showed significant productivity reduction as a response to water deficit in the reproductive phase, between 26 and 76 mm imposed in the non-irrigated treatment.

Maximum leaf area index was reduced by 13% under water deficit in the reproductive phase of 26 mm and by 47% when submitted to a water deficit of 76 mm.

Availability of soil water associated with low water deficiencies between 11 and 34 mm contributed to the production of total biomass and grain yield of cowpea in the study region.

ACKNOWLEDGEMENTS

We thank the National Council for Scientific and Technological Development (CNPq, Brazil) for its financial support to this research through the Universal Project (process n° 483402/2012-5) and the stipend of research productivity for the first author (process n° 311145/2013-2). In addition, we acknowledge Professor Eduardo Tavares Paes from UFRA for his assistance with statistical analysis.

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