AGROMETEOROLOGY
Article

https://doi.org/10.1590/1678-4499.20200501

# Physiological and productive aspects of cassava under different irrigation levels

Ricardo Barros Silva[1,*], Iêdo Teodoro[1], José Leonaldo de Souza[1], Ricardo Araújo Ferreira Júnior[1], Ivomberg Dourado Magalhães[1], Marcos Alex dos Santos[1], Guilherme Bastos Lyra[1], Gustavo Bastos Lyra[2], Gilson Moura Filho[3], Renan Cantalice de Souza[4], Lennon Kledson dos Santos Silva[1], Jônatas Vieira Santos[1], José Dailson Silva de Oliveira[1]

1. Universidade Federal de Alagoas – Câmpus de Engenharias e Ciências Agrárias – Laboratório de Irrigação e Agrometeorologia – Rio Largo (AL), Brazil.
2. Universidade Federal Rural do Rio de Janeiro – Departamento de Ciências Ambientais – Programa de Pós-Graduação em Engenharia de Biossistemas – Seropédica (RJ), Brazil.
3. Universidade Federal de Alagoas – Câmpus de Engenharias e Ciências Agrárias – Laboratório de Solo, Água e Planta – Rio Largo (AL), Brazil.
4. Universidade Federal de Alagoas – Câmpus de Engenharias e Ciências Agrárias – Laboratório de Manejo de Plantas Daninhas – Rio Largo (AL), Brazil.

**Received:** Dec. 5, 2020 | **Accepted:** Jul. 28, 2021

**Section Editor:** Ivo Gonçalves

***Corresponding author:** ricardoufal2010@gmail.com

**How to cite:** Silva, R. B., Teodoro, I., Souza, J. L., Ferreira Júnior, R. A., Magalhães, I. D., Santos, M. A., Lyra, G. B., Moura Filho, G., Souza, R. C., Silva, L. K. S., Santos, J. V. and Oliveira, J. D. S. (2021) Physiological and productive aspects of cassava under different irrigation levels. Bragantia, 80, e5321. https://doi.org/10.1590/1678-4499.20200501

**ABSTRACT:** The aim of this research was to evaluate the physiological and productive aspects of irrigated cassava crop. The statistical design used was randomised blocks, with six treatments and four replications. The used treatments were irrigation levels, based on the crop evapotranspiration – $ET_C$ – ($L_0$ = 0% [rainfed], $L_1$ = 40%, $L_2$ = 80%, $L_3$ = 120%, $L_4$ = 160% and $L_5$ = 200% of the $ET_C$) and the analysed physiological variables were: gas exchange, the quantum efficiency of photosystem II (PSII) and the soil plant analysis development (SPAD) index. The growth and crop productivity were also evaluated through of the leaf area index (LAI), the number and productivity of commercial roots and total biomass. In this research, the total irrigation depth was defined as the irrigation depth plus the effective rainfall. The estimated $ET_C$ was 1,030 mm over the 12-month production cycle and the greatest value for LAI and SPAD were 7.6 and 57.4, respectively, obtained in irrigated areas with the level of 80% of the $ET_C$. While, in the areas irrigated with 120% of the $ET_C$, were obtained the highest values of root productivity (93 $Mg{\cdot}ha^{-1}$), total biomass yield (149 $Mg{\cdot}ha^{-1}$) and photosynthetic rate (22.4 μmol $CO_2{\cdot}m^{-2}{\cdot}s^{-1}$). On the other hand, with irrigation equivalent at 200% of the ETC were obtained the greatest values of internal $CO_2$ concentration (245 μmol $CO_2{\cdot}m^{-2}{\cdot}s^{-1}$), stomatal conductance (0.35 μmol $H_2O{\cdot}m^{-2}{\cdot}s^{-1}$) and effective quantum efficiency (0.68).
**Key words:** *Manihot esculenta Crantz*, net photosynthesis, stomatal conductance, SPAD index, quantum yield, agricultural productivity.

## INTRODUCTION

The cassava (*Manihot esculenta Crantz*) is one of the main food crops of tropical countries and is considered an important source of energy for humans and animals (Pipatsitee et al. 2018). Due to the low cost of production, it has become a popular crop for medium and small farmers and it stands out as a plant of great socioeconomic importance. In Brazil, cassava is mainly cultivated for the production of starch and flour (Alves 2002).

Brazil produced 17.6 million tons of cassava roots in the 2018 harvest, with an average productivity of 14.64 $Mg{\cdot}ha^{-1}$. The northeast of Brazil is the second largest producer of cassava roots of the country (20% of domestic production), second only to the north region (36% of domestic production). In the 2018 harvest, the state of Alagoas was the 13th largest producer among Brazilian states, with a production of 394,000 tons and a yield of 11.62 $Mg{\cdot}ha^{-1}$ (IBGE 2018). In Alagoas, the cassava is traditionally grown by small producers using low-level technology. As a result, crops in Alagoas have been cultivated in the same areas for several decades, mostly without proper mechanisation, fertilisation and irrigation.

The lack of irrigation together with the seasonality of the rainfall is the main factor limiting cassava production in the northeast of Brazil. Reductions in root yield in the cassava depend mainly on the duration of the soil water deficit. The critical period of cultivation, in which cassava can be affected by the water deficit, occurs between the first and the fifth month after planting, when the root system and aerial part of the crop are established (Conceição 1979; El-Sharkawy 2007). Long periods of water deficit can cause losses of up to 59% in final root production, which shows the importance of water to the crop (Ezui et al. 2018; Verissimo et al. 2010). Therefore, it is observed that the rain seasonality in the Brazilian Northeast restricts the availability of water for irrigation in the region and this highlights the importance of studies that increase the efficiency in the use of water in the cultivation of cassava for greater productivity with less water waste.

As in other agricultural crops, a reduction in soil water availability generates an immediate response from this Euphorbiaceae: stomatal closure, which then causes a reduction in photosynthetic rate and leaf transpiration (El-Sharkawy 2007; Pipatsitee et al. 2018). On the other hand, under ideal conditions of soil moisture, the cassava maintains high stomatal conductance and internal $CO_2$ concentrations, ensuring a higher photosynthetic rate and greater biomass production. This highlights the importance of proper irrigation when cultivating cassava (Alves and Setter 2000).

Despite the existence of studies on cultivating cassava in response to irrigation levels (Mélo Neto et al. 2018; Odubanjo et al. 2011), there is little information on the physiological response of the irrigated crop in the coastal tablelands of the northeast of Brazil. For this reason, the aim of this study, was to evaluate gas exchange, photochemical efficiency, and biomass production in wild cassava grown under different irrigation levels in the coastal tablelands of Alagoas.

## MATERIAL AND METHODS

The experiment was done in the Rio Largo region, Alagoas, Brazil (9°27'58.7"S, 35°49'47.2"W, 127 m). According to the Thornthwaite and Mather classification, the climate is humid and megathermic, with a moderate water deficit during the summer and water surplus during the winter. The rainfall and mean annual temperature are 1,800 mm and 25.4 °C, respectively (Souza et al. 2005). The experimental period was from 27 June 2019 to 18 July 2020.

The soil of the experimental area is classified as a cohesive argisolic yellow latosol with a clayey texture (Embrapa 2013). The fertilizing of foundation and cover were made with based on the estimated extractions of nitrogen (N), phosphorus (P) and potassium (K) by the crop, as per Souza et al. (2009), with the application of 123 $kg{\cdot}ha^{-1}$ of N, 27 $kg{\cdot}ha^{-1}$ of P and 146 $kg{\cdot}ha^{-1}$ of K, using urea, superphosphate simple and potassium chloride as the respective sources. The coverage fertilization was split into two applications, one at 45 and other at 90 days after planting (DAP).

The planting was carried out on 27 June at a spacing of 1.0 × 0.5 m to form a population of 20,000 $plants{\cdot}ha^{-1}$. The variety used in the experiment was the Caravela, that is from short to medium production cycle, high productivity, and medium tolerance to pests and diseases (Guimarães et al. 2017). The propagules used were pieces of stalk with 20 cm length and five buds.

A randomised block design was adopted, with four replications. The treatments comprised six levels of irrigation: $L_0$ = 0% (rainfed), $L_1$ = 40%, $L_2$ = 80%, $L_3$ = 120%, $L_4$ = 160% and $L_5$ = 200% of the crop evapotranspiration ($ET_C$), estimated for the period that the crop was irrigated. Each experimental plot was 6.0 × 8.0 m (48 $m^2$) and 96 plants, giving a total area of 1,740 $m^2$.

The irrigation was done only between October 2019 and March 2020, corresponding to the dry station in the region (Souza et al. 2005), when the plants were at the intermediate stage of crop growth and development. The effective precipitation from June to September was sufficient to supply the water demand for cassava. During the irrigation period, in the crop intermediate phase, the crop coefficient ($K_C$) of the cassava was 1.0 and for the initial and final phases of the cultivation cycle were considered 0.35 and 0.45, respectively, as per the Royal Irrigation Department (RID 2010). The $ET_C$ ($mm{\cdot}day^{-1}$) was estimated by Eq. 1, with the weather data obtained from an automatic station (Micrologger – CR 1000, Campbell Scientific, Logan, Utah) installed 50 m from the experimental area that provided the $ET_0$ estimated by the method Penman–Monteith FAO automatically. The $ET_0$ data were collected at each irrigation for the $ET_C$ estimate.

$$ET_C = ET_0 * K_C \tag{1}$$

where $ET_0$ is the reference crop evapotranspiration estimated using the Penman–Monteith method - FAO (Allen et al. 1998), $K_C$ is the crop coefficient.

The irrigation system utilized was micro-sprinkler, with the emitters spaced 2.0 × 3.0 m apart. The mean flow of each emitter was 50 L·h$^{-1}$, at an application intensity of 8.33 mm·h$^{-1}$. The uniformity of the irrigation system was 95%. Volumetric soil moisture in the experimental area at field capacity was 0.2445 and 0.1475 m$^{3}$·m$^{-3}$ at the permanent wilting point, both determined in the laboratory from the soil water retention curve using the Richards pressure chamber (Richards 1965). An irrigation frequency of three days was used depending on the percentage of accumulated $ET_C$ (treatments) in that period, with any rainfall that occurred during the irrigation period being deducted from the applied amount of water. The ten-day water balance of the crop was determined using the Thornthwaite–Mather method for each irrigation level, as per Pereira et al. (2002), in order to explain cassava productivity gains and losses. The effective rainfall was calculated by subtracting the water excess (determined from the crop water balance) from the total rainfall. The total available water depth during the crop cycle was considered as the effective rainfall plus the applied irrigation depth.

Measurements of the physiological variables were made, including the net rate of photosynthesis (A), intercellular $CO_2$ concentration (Ci), transpiration rate (E), leaf temperature (Tf), stomatal conductance (gs) and instantaneous water-use efficiency (A/E). These variables were obtained using an infrared gas analyser (IRGA, ADC model LCi, Hoddesdon, UK) with a 2,000 mmol photons·m$^{-2}$·s$^{-1}$ photosynthetic photon flux density, based on the light response curve as determined for cassava (Fig. 1). These evaluations were made in December of 2019, sixth month after planting, between 08:00 and 10:00 h on sunny day, in the fully expanded fifth leaf of the two central plants of the experimental plot, counting from top to bottom from the apex of the main branch of the plant. Conceição (1979) affirms that the most critical period or the period of greatest sensitivity to water stress for the cassava crop is from planting to the fifth month of cultivation. Instantaneous water-use efficiency was calculated as the ratio between photosynthesis and transpiration (A/E).

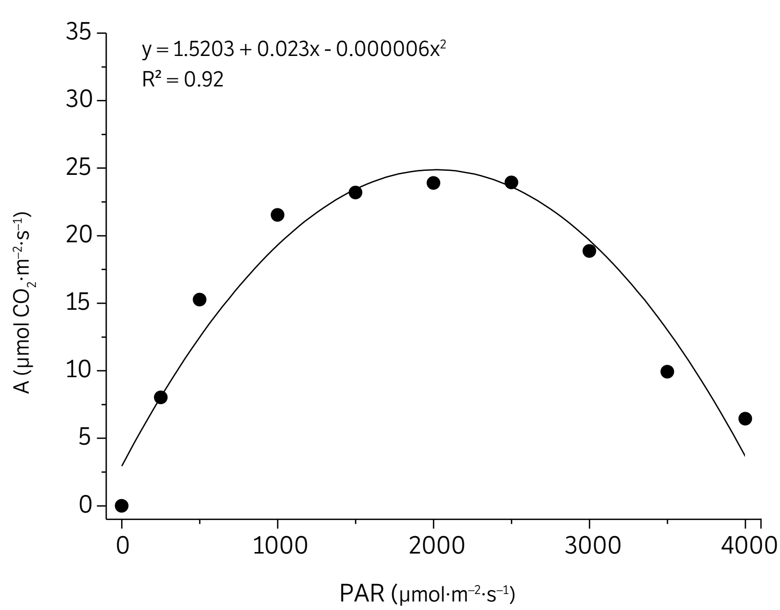


**Figure 1.** Light response curve as determined by cassava plants, in the Rio Largo (AL), Brazil region, from June 2019 to June 2020.

At the same time, also was analysed chlorophyll-a fluorescence, with the aid of a light modulation fluorometer (OptiSciences, model OS1-FL, Hudson, USA) to determine the potential quantum yield (Fv/Fm) and effective quantum efficiency of photosystem II (ΦPSII). The leaves under analysis were adapted to the dark for 30 min using metal clips to obtain the ΦPSII. The leaf chlorophyll content was also determined indirectly using the plant analysis development (SPAD)-502 chlorophyll meter (Soil Plant Analysis Development Section, Minolta Camera Co., Osaka, Japan). The leaf area index

(LAI) was determined every two months throughout the crop cycle, with the aid of an LAI 3100 area meter (Li-Cor, Lincoln, Nebraska, USA). To determine the LAI, leaves were removed from one plant in the working area and then scanned. The resulting values for leaf area (LA, $cm^2$) were used to estimate the ratio between the ground area and the plant cover (LAI).

During the final harvest at the end of the experiment (355 DAP), the production components were evaluated: number of commercial roots per plant (NCR), productivity of commercial roots (RP, in tonnes per hectare, $Mg \cdot ha^{-1}$), leaf productivity (LP, $Mg \cdot ha^{-1}$), stem productivity (SP, $Mg \cdot ha^{-1}$) and total biomass (TB, root, stem and leaf, $Mg \cdot ha^{-1}$). To determine these variables, three average plants from the useful area of each plot were split up and weighed on a 0.001 g precision balance (Toledo, Pix 3 Plus, São Bernardo do Campo, Brazil). The commercial roots were considered as having a diameter greater than 2 cm and a length greater than 10 cm, as per Tironi et al. (2015).

The data were submitted to analysis of variance ($p < 0.05$) and, when significant, to regression analysis (Ferreira 2018). The results and discussion were carried out according to the respective regression curves, with the maximum estimated values and the main values obtained by the studied irrigation levels being presented.

## RESULTS AND DISCUSSION

The mean minimum air temperature ($T_{MIN}$; mean of all daily minimum temperatures) during the experimental period was 21.3 °C (± 1.6), ranging from 17.5 °C (28 August 2019) to 23.6 °C (23 January 2020). The mean maximum air temperature ($T_{MAX}$; mean of all daily maximum temperatures) was 30.1 °C (± 2.1), varying from 35.7 °C (24 November 2019) to 23.9 °C (15 June 2020). The overall average air temperature ($T_{MX}$, mean of all daily average temperatures) was 25.1 °C (± 1.5), and varied between 21.2 °C (1 August 2019) and 28.1 °C (6 March 2020). This shows that the average temperature in the region of Rio Largo, AL, is within the optimal range (25 to 29 °C) for the growth and development of the cassava (Alves 2002). For relative humidity (RH), the overall daily mean was 74.2% (± 6.8), with lower values between November 2019 and January 2020 and a mean of 66.1% (± 3.1) (Fig. 2).

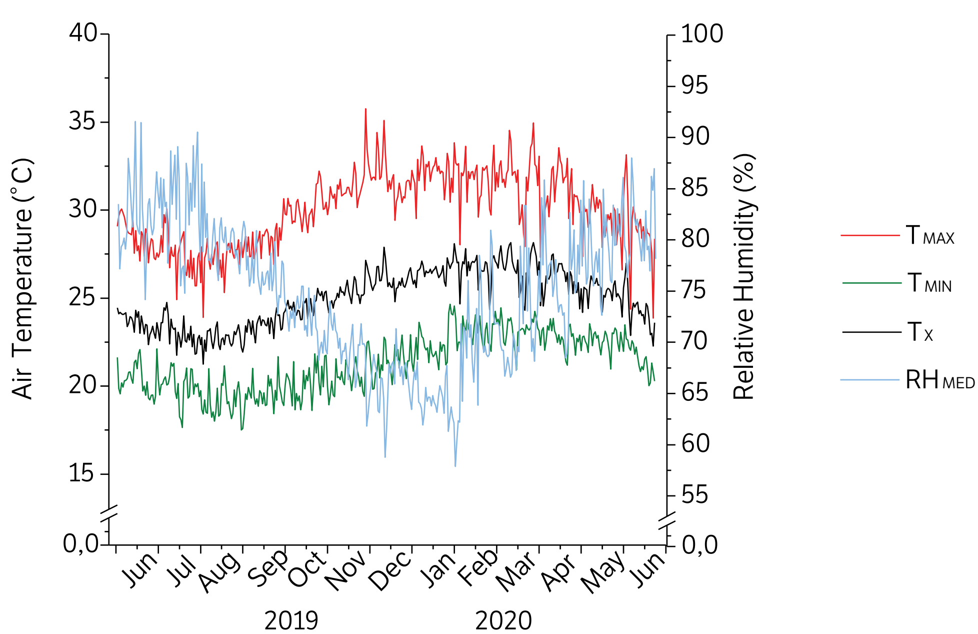


**Figure 2.** Daily minimum ($T_{MIN}$), average ($T_X$) and maximum ($T_{MAX}$) temperatures, and mean daily relative humidity (RHMED) in Rio Largo (AL), Brazil, from June 2019 to June 2020.

The accumulated rainfall during the experimental period was 1,847 mm. The rainiest month was April (364 mm) and the least rainy was November (7.4 mm). Alves (2002) confirms that cultivating the cassava requires 800 mm, well distributed throughout the year. The total reference evapotranspiration ($ET_0$) during cultivation was 1,454 mm. The highest values for $ET_0$ were recorded between late September and early February, with a mean of 4.8 (± 0.7) mm·day$^{-1}$. And the cassava crop evapotranspiration ($ET_C$) for the period of cultivation (355 days) was 1,030 mm, with a mean of 3.0 (± 1.8) mm·day$^{-1}$ (Fig. 3).

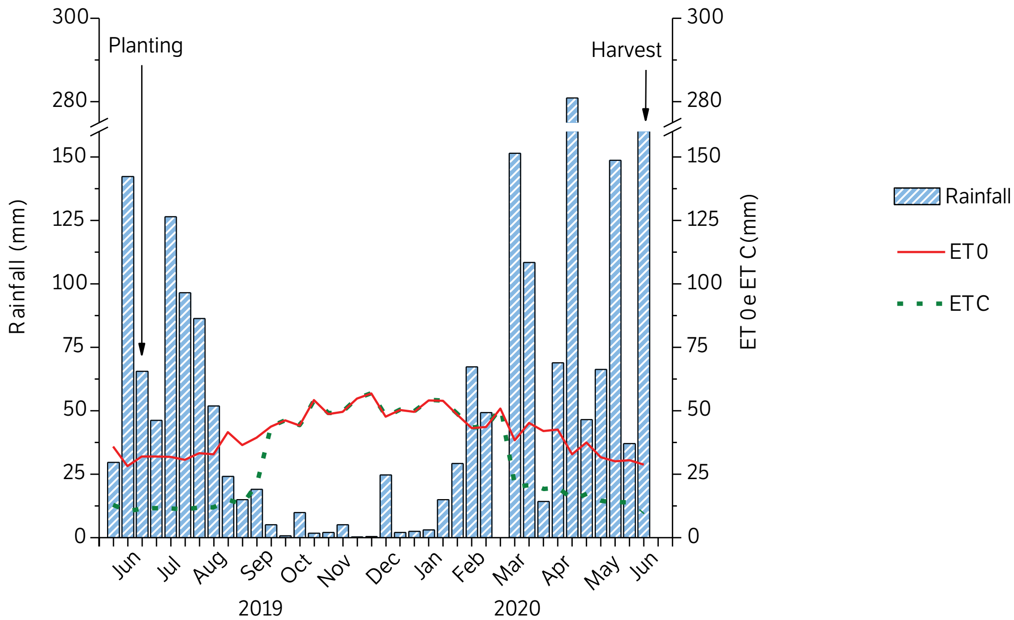


**Figure 3.** Rainfall, reference evapotranspiration ($ET_0$) and crop evapotranspiration ($ET_C$) in Rio Largo (AL), Brazil, from June 2019 to June 2020.

Table 1 shows the total of applied irrigation depths that varied from 134 to 906 mm, between $L_1$ (40% of the $ET_C$) and $L_5$ (200% of the $ET_C$), for percentage $ET_C$, effective rainfall, sum of the effective rainfall plus irrigation and the split and total agricultural productivity of the cassava, in the region of Rio Largo, AL.

**Table 1.** Total ($R_{TOTAL}$) and effective rainfall ($R_{EFFECT}$), total gross applied irrigation depths (irrigation), the sum of $R_{EFFECT}$ and irrigation (total depth) and split and total agricultural productivity observed during the production cycle of the cassava, in Rio Largo region, AL, Brazil, from June 2019 to June 2020.

| Levels | $R_{EFFECT}$ | Irrigation | Total depth | Split agricultural productivity | | | |
|---|---|---|---|---|---|---|---|
| | | | | Root | Stem | Leaf | Total |
| % $ET_C$ | mm | | | Mg·ha$^{-1}$ | | | |
| Rainfed | 522 | 0 | 522 | 31.41 | 31.38 | 11.71 | 74.50 |
| $L_1$ – 40 | 522 | 134 | 656 | 67.57 | 33.79 | 14.18 | 115.54 |
| $L_2$ – 80 | 510 | 307 | 817 | 82.63 | 35.71 | 14.30 | 132.64 |
| $L_3$ – 120 | 456 | 507 | 963 | 100.08 | 41.36 | 15.49 | 156.94 |
| $L_4$ – 160 | 317 | 701 | 1.018 | 96.49 | 43.18 | 14.97 | 154.65 |
| $L_5$ – 200 | 117 | 906 | 1.023 | 75.80 | 41.62 | 13.45 | 130.87 |
| RTOTAL = 1,847 mm | | | | | | | |

The water balance of the cassava crop for the different irrigation levels during the experimental period is presented in Fig. 4. The influence of the irrigation level is obvious during the intermediate growth and development phase of the crop, a period in which the irrigated plants achieved greater canopy growth.

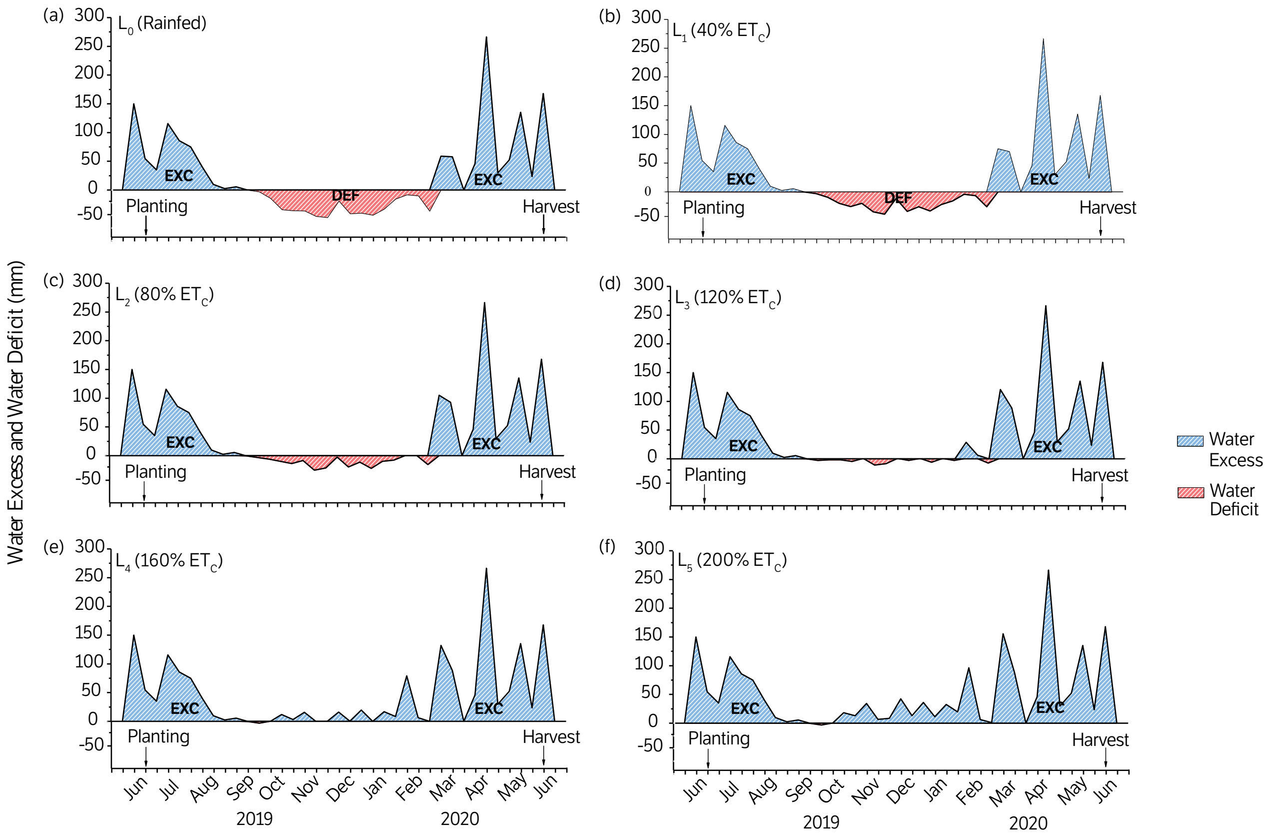


**Figure 4.** Ten-day water balance of the cassava crop, cultivated under different irrigation levels: $L_0$ (a), $L_1$ (b), $L_2$ (c), $L_3$ (d), $L_4$ (e) and $L_5$ (f), with highlight to excess and deficit water, in Rio Largo (AL), Brazil, from June 2019 to June 2020.

The total water deficit for the cassava crop without irrigation ($L_0$, rainfed) was 508 mm, concentrated between the last 10 days of September 2019 and the first 10 days of February 2020 (dry period of the region), during this period the accumulated rainfall was 102 mm, 5.6% of the total rainfall during the experiment. This highlights the need for irrigation during this period. The water excess in the rainfed areas ($L_0$, rainfed) was 1,323 mm, and occurred from June to September 2019 and from February to June 2020, the period with the greatest accumulation of rainfall (1,744 mm), equivalent to 94.4% of the total rainfall (Fig. 4a). During the irrigation period (13 October 2019 to 13 March 2020), the total accumulated rainfall was 212 mm, and the accumulated $ET_0$ and $ET_C$ was 462 mm. During this period, $ET_0$ and $ET_C$ were equals because the $K_C$ of the cassava crop was equal to 1.0. In the irrigated plots with $L_1$ (40% of the $ET_C$) and $L_2$ (80% of the $ET_C$), a respective water deficit of 372 and 211 mm was also recorded, with a water excess for these treatments of 1,323 and 1,335 mm, respectively (Figs. 4b and 4c). As on some days it rained a few hours after irrigation, a water excess was seen in the irrigated plots (even in areas with deficit irrigation). Conceição (1979) and Alves (2002) claim that prolonged water deficits up to the fifth month after planting hinder the establishment of cassava in the field, with a negative effect on the phenological phases of root and leaf growth. For the areas irrigated with $L_1$ and $L_2$, the water deficit was 134 and 295 mm less than the deficit suffered in the rainfed area, showing that, at these irrigation levels, cassava also tends to undergo a reduction in productive potential, albeit less marked.

The results for water balance in the areas irrigated with $L_3$ (120% of the $ET_C$), indicated an accumulated water deficit of 65 mm and a total water excess of 1,389 mm (Fig. 4d). This small water deficit occurred due to problems with logistics and the water supply system. Furthermore, plots irrigated with $L_4$ (160% of the $ET_C$) and $L_5$ (200% of the $ET_C$) presented the same accumulated water deficit of 5.0 mm, even with different irrigation depths, 1,528 and 1,728 mm respectively (Figs. 4e and 4f). Between the last ten-days of September and the first ten-days of October 2019, all treatment suffered a water deficit of 5.0 mm between the end of the rainy season in the region and the beginning of irrigation, which took place only during the second ten days period of October. However, El-Sharkawy (2007) confirms that a short period of water deficit will not greatly reduce productive potential in the cassava, due to tolerance mechanisms for water restriction. The different values for water excess were a result of variations in the total amount of applied water, based on the treatments.

The irrigation levels caused a significant difference ($p < 0.01$) in the variables of gas exchange, net photosynthetic rate, intercellular $CO_2$ concentration, stomatal conductance and transpiration rate. Chlorophyll-a fluorescence was significant ($p < 0.01$) for effective quantum efficiency and the SPAD index. Significant effects were found ($p < 0.05$) for the components of production and growth, such as the production of commercial roots, total biomass and leaf area index (Table 2). The other variables (potential quantum yield, instantaneous water-use efficiency, leaf temperature, number of commercial roots per plant, stem and leaf productivity) were not significant, so they were not discussed.

**Table 2.** Analysis of variance of the physiological and production variables of cassava cultivated under different irrigation levels in the Rio Largo region (AL), Brazil, from June 2019 to June 2020.

| SQUARE ROOT | | | | | | |
|---|---|---|---|---|---|---|
| Physiological variables (180 DAP) | | | | | | |
| Source of variation | D.F. | SPAD | ΦPSII | Fv/Fm | A | Ci |
| Irrigation depth | 5 | 175.644** | 0.039** | 0.001$^{ns}$ | 67.845** | 1,917.531** |
| Block | 3 | 4.471$^{ns}$ | 0.002$^{ns}$ | 0.000$^{ns}$ | 10.982* | 348.828ns |
| Linear | 1 | 117.780$^{ns}$ | 0.177** | 0.001$^{ns}$ | 254.069** | 7,122.531** |
| Quadratic | 1 | 540.614** | 0.002$^{ns}$ | 0.005$^{ns}$ | 70.757** | 323.910$^{ns}$ |
| Residual | 15 | 27.430 | 0.007 | 0.000 | 2.353 | 245.996 |
| C.V. (%) | | 10.70 | 14.84 | 3.65 | 7.76 | 6.86 |
| | | GS | A/E | Tf | E | LAI |
| Irrigation depth | 5 | 0.041** | 0.673$^{ns}$ | 0.522$^{ns}$ | 2.933** | 2.923* |
| Block | 3 | 0.003$^{ns}$ | 0.116$^{ns}$ | 0.876$^{ns}$ | 0.200$^{ns}$ | 0.909$^{ns}$ |
| Linear | 1 | 0.189** | 1.912$^{ns}$ | 1.837$^{ns}$ | 12.209** | 0.964$^{ns}$ |
| Quadratic | 1 | 0.003$^{ns}$ | 0.105$^{ns}$ | 0.394$^{ns}$ | 1.396** | 9.052** |
| Residual | 15 | 0.043 | 0.275 | 0.183 | 0.107 | 0.702 |
| C.V. (%) | | 19.82 | 7.84 | 1.39 | 9.55 | 15.94 |
| Production Components (355 DAP) | | | | | | |
| | | NCR | RP | CP | FP | TB |
| Irrigation depth | 5 | 2.800$^{ns}$ | 2,481.877* | 94.287$^{ns}$ | 7.075$^{ns}$ | 3,674.575* |
| Block | 3 | 2.500$^{ns}$ | 439.664$^{ns}$ | 16.403$^{ns}$ | 9.888$^{ns}$ | 350.899$^{ns}$ |
| Linear | 1 | 2.057$^{ns}$ | 6,078.690** | 412.930$^{ns}$ | 8.617$^{ns}$ | 10,245.917** |
| Quadratic | 1 | 4.526$^{ns}$ | 6,132.062** | 19.599$^{ns}$ | 24.166$^{ns}$ | 7,682.608* |
| Residual | 15 | 3.133 | 693.529 | 75.103 | 11.726 | 1,218.286 |
| C.V. (%) | | 24.42 | 34.80 | 22.90 | 24.43 | 27.37 |

C.V. = Coefficient of variation.

The net photosynthetic rate ("A") in the cassava adjusted well to the quadratic model to different irrigation depth. The lowest value (11.0 $\mu mol\ CO_2 \cdot m^{-2} \cdot s^{-1}$) was seen under $L_0$ (rainfed). This shows that, the rate of "A" in the cassava is reduced due to the water deficit. While the maximum rate (22.5 $\mu mol\ CO_2 \cdot m^{-2} \cdot s^{-1}$) was found under a total estimated irrigation depth of 959 mm, resulting in an increase of 104% in the value for net photosynthesis compared to the lowest value. This total estimated irrigation depth that provided the maximum "A" is only 4 mm smaller than the total 963 mm of $L_3$ (120% of the $ET_C$) and this indicates that $L_3$ among the studied treatments obtained the highest "A" (22.4 $\mu mol\ CO_2 \cdot m^{-2} \cdot s^{-1}$). When the soil was exceedingly moist with $L_5$ (200% of the $ET_C$), equivalent to a total irrigation depth (effective rainfall plus irrigation) of

1,023 mm, the water excess reduced the photosynthetic rate by approximately 2.0%, in relation to the highest value obtained by the quadratic model curve, reaching 22.0 μmol $CO_2 \cdot m^{-2} \cdot s^{-1}1$ (Fig. 5a). These values are close to those found by Verissimo et al. (2010) and Pipatsitee et al. (2018), who obtained 17.32 and 26.92 μmol $CO_2 \cdot m^{-2} \cdot s^{-1}$ respectively in cassava plants under full irrigation. The authors point out that under water stress, the photosynthetic rate and stomatal opening are the most affected mechanisms in the cassava, resulting in a further effect on other mechanisms, such as internal $CO_2$ concentration and plant transpiration, with a consequent reduction in productivity. Antwi et al. (2017) confirm that a soil water excess promotes a drop in the oxygen concentration, which causes stomatal closure and a reduction in the photosynthetic rate, negatively affecting plant growth and development.

The highest value for internal $CO_2$ concentration (Ci), was 245 μmol $CO_2 \cdot m^{-2} \cdot s^{-1}$, seen under $L_5$ (200% of the $ET_C$), this value is higher than those seen in areas without irrigation $L_0$ (rainfed), which had the lowest value, 200 μmol $CO_2 \cdot m^{-2} \cdot s^{-1}$, respectively, resulting in a fall of 18% in the Ci (Fig. 5b). This reduction in Ci shows that when cassava is subjected to a water deficit, $CO_2$ acquisition by the crop is restricted due to the accumulation of Ci in the leaf mesophile, which is directly associated with stomatal closure and a reduction in $CO_2$ assimilation (Magalhães et al. 2017). Cruz et al. (2017) state that stomatal closure occurs under water stress and the diffusion of $CO_2$ from the air to the chloroplast is restricted, which generates smaller intercellular $CO_2$ concentrations in the cassava plants. It can be seen that in the $L_0$ (rainfed) areas, internal $CO_2$ concentrations are lower and, as a result, photosynthetic rates under these treatments are also lower, as shown in Fig. 4a.

The rate of transpiration ("E") increased significantly in the areas irrigated and the maximum value of "E", 4.05 μmol $H_2O \cdot m^{-2} \cdot s^{-1}$, was obtained under the estimated total irrigation depth of 1,093 mm. And, among the studied irrigation levels, $L_5$ (200% of the $ET_C$), equivalent to the total depth of 1,023 mm, was the one that came closest to the maximum value, having obtained the highest value of "E", 4.01 μmol $H_2O \cdot m^{-2} \cdot s^{-1}$. Under $L_0$ (rainfed) plots, with an effective rainfall of 522 mm, the lowest value was 1.9 μmol $H_2O \cdot m^{-2} \cdot s^{-1}$, a 52% reduction in the rate of transpiration for the cassava in relation to the maximum value obtained with 1,093 mm (Fig. 5c). A similar result (4.2 μmol $H_2O \cdot m^{-2} \cdot s^{-1}$ was found by Palta (1983) in cassava plants under full irrigation; the author also found that longer period than one week with no irrigation can reduce the rate of transpiration. In general, plants under water stress show rapid stomatal closure, preventing water loss by transpiration. Magalhães et al. (2017) reported that a reduction in the rate of transpiration is one of the first responses of the plant to water stress. In addition to the soil water content, some weather elements, such as air temperature, wind speed and relative humidity play a part in the transpiration process of the plant (Wiriya-Alongkorn et al. 2013).

The highest value for stomatal conductance (gs; 0.35 μmol $H_2O \cdot m^{-2} \cdot s^{-1}$) was obtained with the application of $L_5$ (200% of the $ET_C$), generating a gain of 218% in relation to the lowest value estimated (0.13 μmol $H_2O \cdot m^{-2} \cdot s^{-1}$) under $L_0$ (rainfed) conditions (Fig. 5d). Other researches already demonstrate similar behaviour for this variable in the cassava under different irrigation levels (Cruz et al. 2016; El-Sharkawy 2007; Turyagyenda et al. 2013). Pipatsitee et al. (2018) point out that stomatal conductance in the cassava is highly sensitive to water scarcity in the soil and this also affects the physiological mechanisms of the plant. Medrano et al. (2002) confirm that the gs mechanism accounts for most of the internal and external factors of the plant, as it is linked to the overall effect of water stress on the physiological variables. Veríssimo et al. (2010) state that evapotranspiration and relative humidity in the growth environment are directly related to rainfall, irrigation and the incidence of solar radiation, which act on the vapour pressure deficit (VPD) of the environment, especially under conditions of prolonged water stress (rainfed), increasing water loss from the plant to the environment through the stomata and leading to lower stomatal conductance, corroborating the results of the present study.

The leaf area index (LAI) had a quadratic adjustment in all treatments (areas with different levels of irrigation). The $L_0$ treatment (rainfed) was influenced by the scarcity of rain between the last ten days of September 2019 and the first ten days of February 2020, during this period it rained only 103 mm; and this caused the planting LAI to remain stagnant and to return to growth only after the beginning of the rains in the second ten-day period of February 2020, when it rained 63 mm. By the quadratic regression equation, the maximum estimated LAI of cassava crop without irrigation ($L_0$; rainfed) was equivalent to 8.4, reached at 700 DAP, a relatively long period for the cassava cultivation to reach the maximum accumulation of leaf mass, which makes it difficult to cassava harvest in one year period (research period), since the plants have not completed their phenological cycle and have allocated insufficient photoassimilates in their root system (Fig. 6a). This was because the crop suffered a prolonged water deficit due to the scarcity of rainfall mentioned above.

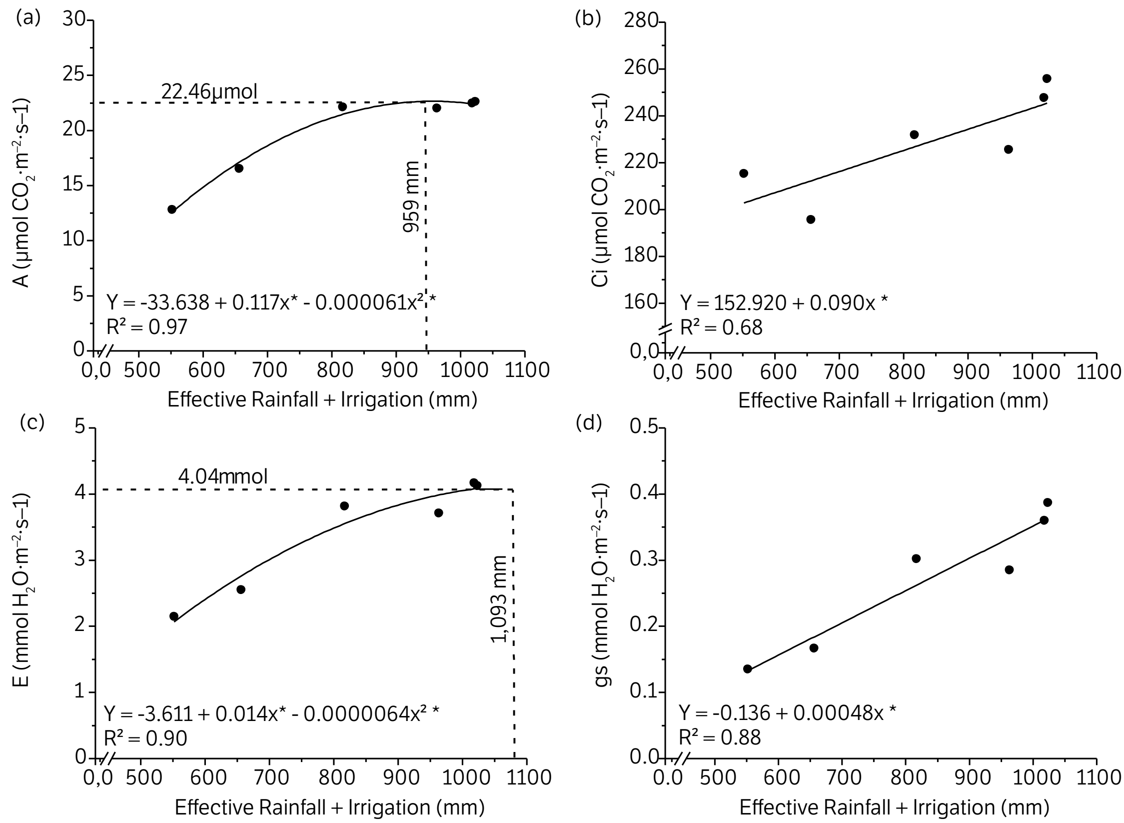


**Figure 5.** (a) Net photosynthetic rate (A; μmol $CO_2 \cdot m^{-2} \cdot s^{-1}$); (b) Internal $CO_2$ concentration (Ci; μmol $CO_2 \cdot m^{-2} \cdot s^{-1}$); (c) Transpiration (E; μmol $H_2O \cdot m^{-2} \cdot s^{-1}$); (d) Stomatal conductance (gs; μmol $H_2O \cdot m^{-2} \cdot s^{-1}$) of cassava cultivated under different irrigation levels, in Rio Largo (AL), Brazil, from June 2019 to June 2020.

* Significant by the t test at 5% probability.

Among the irrigated treatments, the highest maximum LAI was 7.6 observed in the areas irrigated with the level of irrigation $L_2$ (80% of the $ET_C$), equivalent to the total depth of 817 mm in the 12-month cycle of cassava crop. The $L_5$ irrigation level (200% of the $ET_C$), equivalent to the largest total depth of 1,023 mm, obtained the lowest maximum LAI, estimated at 4.4 (Fig. 6). Odubanjo et al. (2011) studied the growth and production of cassava irrigated in a tropical environment at a density of 10,000 plants per hectare, and observed an LAI of 4.3 under full irrigation, while under rainfed conditions the LAI was reduced to 2.5, which shows the highest LAI in irrigated plants. According to El-Sharkawy (2007), water deficit conditions generate a reduction in the cassava leaf area and, therefore, the LAI can be an indicator of water stress suffered by the crop. Under these conditions, cassava leaf abscission occurs with the objective of generating smaller size leaves, aiming at reducing the leaf area and a lesser loss of water through transpiration. Leaf abscission is regulated by the hormone ethylene and cassava under water stress produces higher amounts of this hormone that regulates leaf loss in response to a lack of water. In addition to the water deficit, higher levels of irrigation, such as $L_5$ (200% of the $ET_C$), generate lower LAI and this indicates that excess water reduces the leaf area of cassava.

The maximum SPAD index (57.44) was found at an estimated total irrigation depth of 830 mm in the cassava cycle, value near to that obtained with $L_2$ (80% of $ET_C$), with total irrigation of 817 mm, which obtained the SPAD index of 57.40. Whereas the lowest value (37) was obtained in the L0 (rainfed) areas. Accumulated amounts greater than 830 mm reduced this index by 17% (47) in areas irrigated with $L_5$ (200% of the $ET_C$), as shown in Fig. 7a. The higher values for the SPAD index indicate greater chlorophyll synthesis and, consequently, greater photosynthetic activity of the plant (Gil et al. 2002). This is corroborated by the results of the present research, where the behaviour of the SPAD index and of the net photosynthetic rate are similar, indicating that the increase in leaf chlorophyll resulted in photosynthetic gains of the plant and showing that leaf chlorophyll content in the cassava is linked to the water status of the plant.

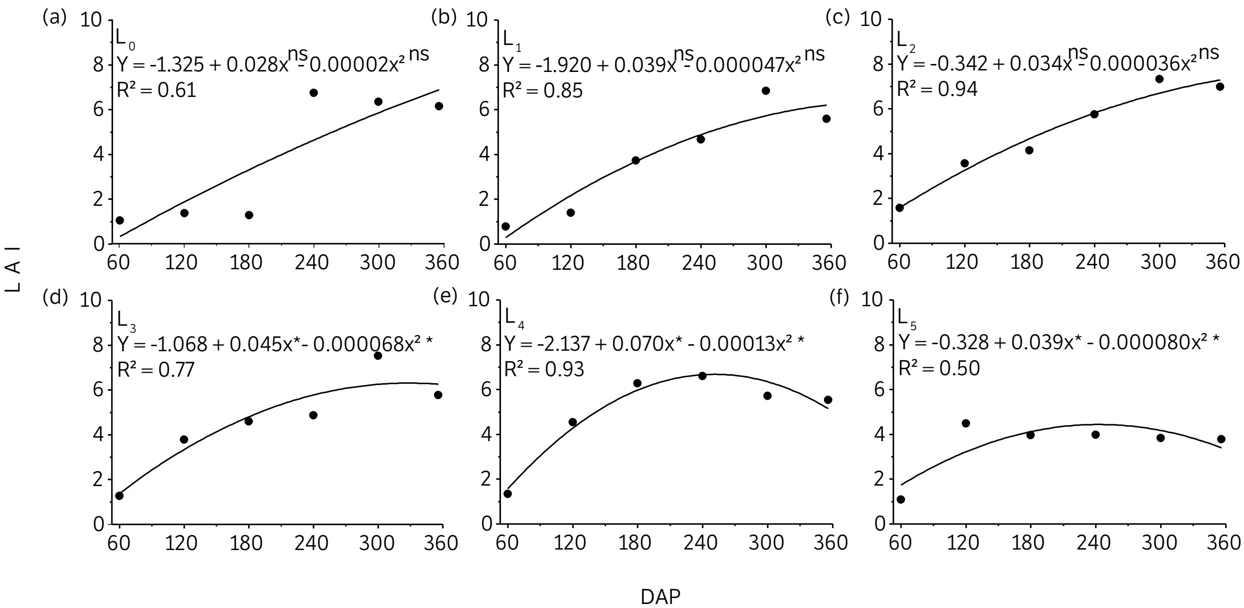


**Figure 6.** Leaf area index (LAI) of the cassava, cultivated under different irrigation levels: (a) $L_0$, (b) $L_1$, (c) $L_2$, (d) $L_3$, (e) $L_4$ and (f) $L_5$, in Rio Largo (AL), Brazil, from June 2019 to June 2020.

* Significant by the t test at 5% probability.

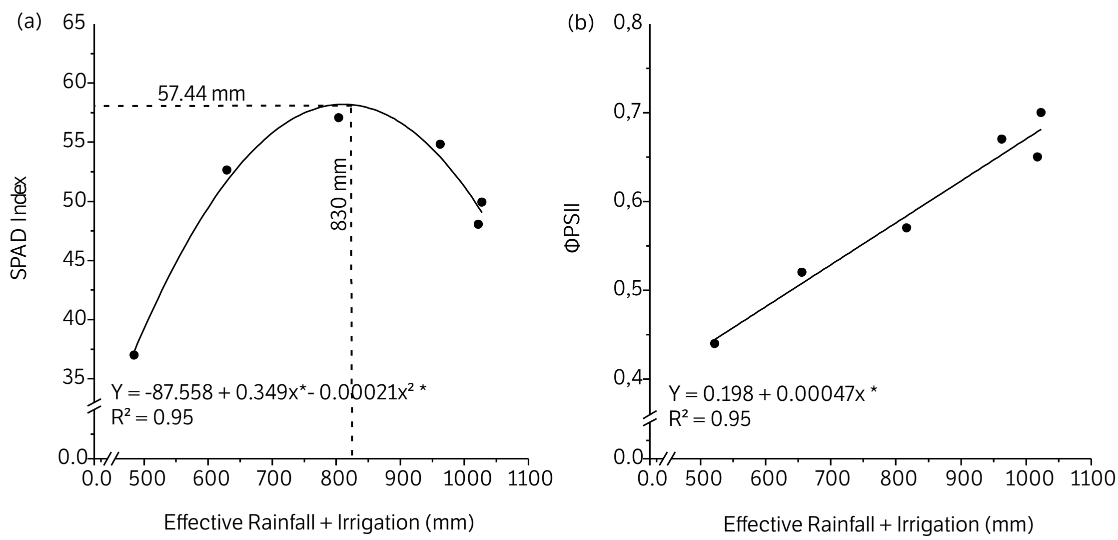


**Figure 7.** (a) SPAD index and (b) effective quantum efficiency (ΦPSII) of the cassava crop, cultivated under different irrigation levels, in the Rio Largo (AL), Brazil, region from June 2019 to June 2020.

* Significant by the t test at 5% probability.

The lowest value (0.44) for effective quantum efficiency (ΦPSII) was found in plots cultivated under $L_0$ (rainfed). While the highest value (0.68) was found in areas irrigated with $L_5$ (200% of the $ET_C$), equivalent to a total irrigation depth of 1,023 mm, an increase of 54% in the ΦPSII (Fig. 7b). In a study of the physiological behaviour of the cassava due to rainfall seasonality, it was found that during the dry season the mean ΦPSII in cassava genotypes is 0.58, while during the rainy season, the mean value rises to 0.70 (Santanoo et al. 2019). This behaviour was similar to that seen in the present research, where plants grown under greater water availability obtained the highest values for ΦPSII. Magalhães et al. (2017) show that a soil water deficit causes damage to photosystem II (PSII), reduces energy capture by the reaction centres and causes irregularities in photochemical energy dissipation, which reduces energy capture efficiency. Under rainfed conditions, the wild cassava showed a lower ΦPSII, possibly due to the damage caused to PSII by the prolonged period of water deficit. Whereas in the plots irrigated with $L_5$ (200% of the $ET_C$), electron transport through the photosystem was more efficient.

Although the highest internal $CO_2$ concentration, stomatal conductance and effective quantum efficiency are obtained with $L_5$ (200% of the $ET_C$), this level of irrigation is not recommended because, in principle, the productivity of roots and total biomass are the main objectives of cassava cultivation, and the highest values of these production components were obtained in areas with irrigation of 120% of the $ET_C$ ($L_3$) as shown below in Fig. 8. Furthermore, the millimetre of irrigation applied is quite expensive and any amount of water applied more increases the costs of the operation without increasing agricultural productivity and consequently decreases the enterprise's profit.

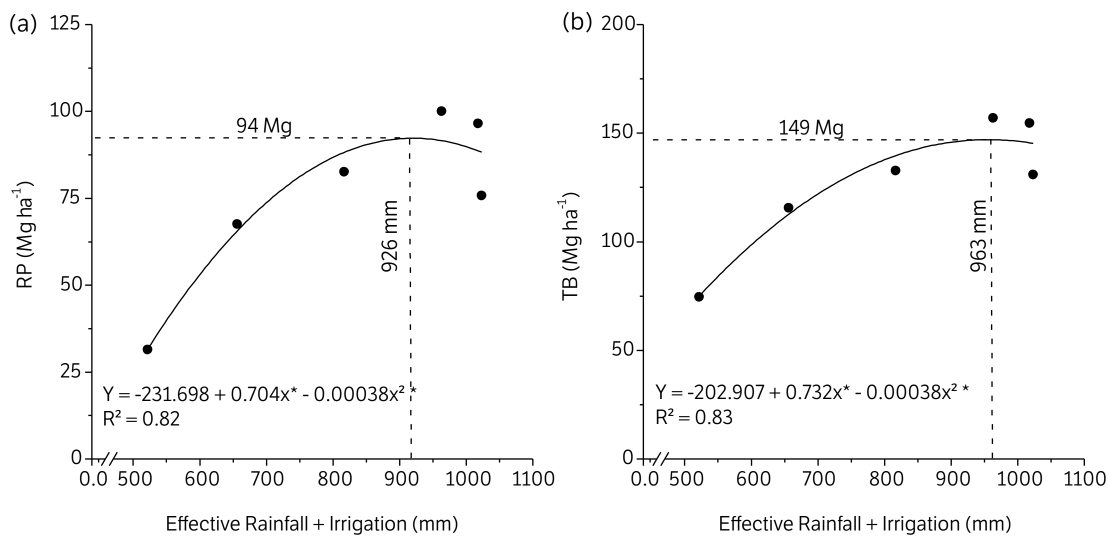


**Figure 8.** (a) Productivity (Mg·ha⁻¹) of commercial roots (RP) and (b) total biomass (TB) of the cassava crop cultivated under different irrigation levels, in the Rio Largo region (AL), Brazil, from June 2019 to June 2020.

* Significant by the t test at 5% probability.

The maximum productivity of commercial roots (RP) was 94 $Mg \cdot ha^{-1}$, obtained under 926 mm of total irrigation depth estimated, value near to that obtained with $L_3$ (120% of the $ET_C$, total irrigation depth of 963 mm), which was 93 $Mg \cdot h^{-1}$. Under $L_3$ the greatest total biomass productivity (root, stem and leaf; TB = 149 $Mg \cdot ha^{-1}$) was also obtained. This performance was 194 and 99% higher than the yield of cultivated plots under $L_0$ (rainfed), which obtained the lowest yields, 32 and 75 $Mg \cdot ha^{-1}$ of RP and TB, respectively (Fig. 8a and 8b). Polthanee and Srisutham (2018), studying production components in the cassava, observed greater root production under conditions of full irrigation (52 $Mg \cdot ha^{-1}$), with a yield of 22 $Mg \cdot ha^{-1}$ under rainfed conditions. These results were, in percentage, equivalent to those of the present research and confirm the productive potential of irrigated cassava.

The data showed that cassava grown under water stress adopts tolerance mechanisms for drought to obtain greater efficiency in water use, such as: reduction of stomatal conductance, transpiration and leaf area. Under these conditions, the net photosynthetic rate is affected and results in lower agricultural productivity. This highlights the importance of irrigation for the cassava in regions with poor rainfall distribution, such as the northeast of Brazil.

## CONCLUSION

The annual cassava evapotranspiration in the Rio Largo, AL region, is around 1,030 mm. This results in a water deficit of 508 mm in the annual cultivation cassava cycle, in rainfed areas, since the total effective rainfall is only 522 mm. The greatest value for LAI and SPAD was 7.6 and 57.4, respectively, obtained under the irrigation level of 80% of the $ET_C$. While in the areas irrigated with 120% of the $ET_C$ are obtained the highest: productivity of commercial roots (93 Mg·ha$^{-1}$), total biomass yield (149 Mg·ha$^{-1}$) and photosynthetic rate (22.4 µmol $CO_2$·m$^{-2}$·s$^{-1}$). On the other hand, in the areas irrigated with 200% of the ETC are obtained the greatest: internal $CO_2$ concentration (245 µmol $CO_2$·m$^{-2}$·s$^{-1}$), stomatal conductance (0.35 µmol $H_2O$·m$^{-2}$·s$^{-1}$) and effective quantum efficiency (0.68).

## AUTHORS' CONTRIBUTION

**Conceptualization:** Silva R. B., Teodoro I. and Souza J. L.; **Methodology:** Silva R. B., Teodoro I., Souza J. L., Ferreira Júnior R. A., Santos M.A., Lyra G. B. and Lyra G. B.; **Investigation:** Silva R. B., Teodoro I., Souza J. L., Magalhães I. D., Silva L. K. S., Santos J. V., Oliveira J. D. S., Moura Filho G. and Souza R. C.; **Writing – Original Draft:** Silva R. B., Teodoro I. and Souza J. L.; **Writing – Review and Editing:** Silva R. B., Teodoro I. and Souza J. L.; **Funding Acquisition:** Teodoro I.; **Supervision:** Silva R. B., Teodoro I. and Souza J. L.

## DATA AVAILABILITY STATEMENT

Data will be available upon request.

## FUNDING

Coordenação de Aperfeiçoamento de Pessoal de Nível Superior
[https://doi.org/10.13039/501100002322]
Finance Code 001

Conselho Nacional de Desenvolvimento Científico e Tecnológico
[https://doi.org/10.13039/501100003593]

Fundação de Amparo à Pesquisa do Estado de Alagoas
[https://doi.org/10.13039/501100003401]

## ACKNOWLEDGMENTS

We would like to thank all employees of the Campus of Engineering and Agricultural Sciences at the Federal University of Alagoas for their assistance in this work.

## REFERENCES

Allen, R. G., Pereira, L. S., Raes, D. and Smith, M. (1998). Crop evapotranspiration: Guidelines for computing crop water requirements [FAO Irrigation and drainage paper 56]. Rome: FAO.

Alves, A. A. C. (2002). Cassava botany and physiology. In R. J. Hillocks, J. M. Thresh and A. C. Bellotti (Eds.), Cassava: Biology, Production and Utilization (p. 67-89). New York: Wallingford. https://doi.org/10.1079/9780851995243.0067

Alves, A. A. C. and Setter, T. L. (2000). Response of Cassava to Water Deficit: Leaf Area Growth and Abscisic Acid. Crop Science, 40, 131-137. https://doi.org/10.2135/cropsci2000.401131x

Antwi, B. O., Asante, S. K. and Yeboah, J. (2017). Drought assessment for reduced climate impact on cassava production. Journal of Applied Sciences, 17, 12-21. https://doi.org/10.3923/jas.2017.12.21

Conceição, A. J. (1979). A mandioca. Cruz das Almas: UFBA; Embrapa; Bnb; Brascan Nordeste.

Cruz, J. L., Alves, A. A. C., LeCain, D. R., Ellis, D. D. and Morgan, J. A. (2016). Elevated $CO_2$ concentrations alleviate the inhibitory effect of drought on physiology and growth of cassava plants. Scientia Horticulturae, 210, 122-129. https://doi.org/10.1016/j.scienta.2016.07.012

Cruz, J. L., Coelho Filho, M. A., Coelho, E. F. and Santos, A. A. (2017). Salinity reduces carbon assimilation and the harvest index of cassava plants (*Manihot esculenta Crantz*). Acta Scientiarum, 39, 545-555. https://doi.org/10.4025/actasciagron.v39i4.32952

El-Sharkawy, M. A. (2007). Physiological characteristics of cassava tolerance to prolonged drought in the tropics: Implications for breeding cultivars adapted to seasonally dry and semiarid environments. Brazilian Journal of Plant Physiology, 19, 257-286. https://doi.org/10.1590/S1677-04202007000400003

[Embrapa] Empresa Brasileira de Pesquisa Agropecuária. (2013). Sistema brasileiro de classificação de solos. Rio de Janeiro: Embrapa.

Ezui, K. S., Leffelaar, P. A., Franke, A. C., Mando, A. and Giller, K. E. (2018). Simulating drought impact and mitigation in cassava using the LINTUL model. Field Crops Research, 219, 256-272. https://doi.org/10.1016/j.fcr.2018.01.033

Ferreira, P. V. (2018). Estatística experimental aplicada às Ciências Agrárias. Viçosa: UFV.

Gil, P. T., Fontes, P. C. R., Cecon, P. R. and Ferreira, F. A. (2002). Índice SPAD para o diagnóstico do estado de nitrogênio e para o prognóstico da produtividade da batata. Horticultura Brasileira, 20, 611-615. https://doi.org/10.1590/S0102-05362002000400020

Guimarães, D. G., Prates, C. J. N., Viana, A. E. S., Cardoso, A. D., Texeira, P. R. G. and Carvalho, K. D. (2017). Caracterização morfológica de genótipos de mandioca (*Manihot esculenta Crantz*). Scientia Plena, 13, 090201. https://doi.org/10.14808/sci.plena.2017.090201

[IBGE] Instituto Brasileiro de Geografia e Estatística. (2018). Levantamento sistemático da produção agrícola. IBGE. [Accessed Aug. 21, 2020]. Available at: https://sidra.ibge.gov.br/tabela/188#resultado

Magalhães, I. D., Lyra, G. B., Souza, J. L., Teodoro, I., Cavalcante, C. A., Ferreira, R. A. and Souza, R. C. (2017). Physiology and Grain Yield of Common Beans under Evapotranspirated Water Reposition Levels. Irrigation and Drainage Systems Engineering, 6, 183. https://doi.org/10.4172/2168-9768.1000183

Medrano, H.; Escalona, J. M.; Bota, J.; Gulías, J. and Flexas, J. (2002). Regulation of photosynthesis of $C_3$ plants in response to progressive drought: stomatal conductance as a reference parameter. Annals of botany, 89, 895-905. https://doi.org/10.1093/aob/mcf079

Mélo Neto, D. F., Coelho, D. G., Andrade, M. T. and Alves, J. O. (2018). Initial growth of cassava plants cv. Mossoró under different water regimes. Revista Agro@mbiente On-line, 12, 191-199. https://doi.org/10.18227/1982-8470ragro.v12i3.5155

Odubanjo, O. O., Olufayo, A. A. and Oguntunde, P. G. (2011). Water use, growth, and yield of drip irrigated cassava in a humid tropical environment. Soil and Water Research, 6, 10-20. https://doi.org/10.17221/45/2009-SWR

Palta, J. A. (1983). Photosynthesis, transpiration, and leaf diffusive conductance of the cassava leaf in response to water stress. Canadian Journal of Botany, 61, 373–376. https://doi.org/10.1139/b83-043

Pereira, A. R., Angelocci, L. R. and Sentelhas, P. C. (2002) Agrometeorologia: Fundamentos e aplicações práticas. Guaíba: Agropecuária.

Pipatsitee, P., Eiumnoh, A., Praseartkul, P., Taota, K, Kongpugdee, S., Sakulleerungroj, K. and Cha-um, S. (2018). Application of infrared thermography to assess cassava physiology under water deficit condition. Plant Production Science, 21, 398-406. https://doi.org/10.1080/1343943X.2018.1530943

Polthanee, A. and Srisutham, M. (2018). Growth, yield and water use of drip irrigated cassava planted in the late rainy season of North Eastern Thailand. Indian Journal Agricultural Research, 52, 554-559. https://doi.org/10.18805/IJARe.A-339

Richards, L. A. (1965). Physical conditions of water in soil. In C. A. Black, D. D. Evans, J. L. White, L. E. Ensminge and F. E. Clark (Eds.), Methods of Soil Analysis: Part 1 Physical and Mineralogical Properties, Including Statistics of Measurement and Sampling, 9.1 (p. 128-152). Madison: ASA; CSSA; SSSA. https://doi.org/10.2134/agronmonogr9.1.c8

[RID] Royal Irrigation Department. (2010). Crop coefficient. Thailand. RID. [Accessed Apr. 04, 2019]. Available at: http://water.rid.go.th/hwm/cropwater/CWRdata/Kc/kc_th.pdf

Santanoo, S., Vongcharoen, K. and Banterng, P., Vorasoot, N., Jogloy, S., Roytrakul, S. and Theerakulpisut, P. (2019). Seasonal Variation in Diurnal Photosynthesis and Chlorophyll Fluorescence of Four Genotypes of Cassava (Manihot esculenta Crantz) under Irrigation Conditions in a Tropical Savanna Climate. Agronomy, 9, 206. https://doi.org/10.3390/agronomy9040206

Souza, L. S.; Silva, J. and Souza, L. D (2009). Recomendação de calagem e adubação para o cultivo da mandioca. Cruz das Almas: Embrapa.

Souza, J. L., Nicácio, R. M. and Moura, M. A. L. (2005). Global solar radiation measurements in Maceió, Brazil. Renewable Energy, 30, 1203-1220. https://doi.org/10.1016/j.renene.2004.09.013

Tironi, L. F., Uhlmann, L. O., Streck, N. A., Samboranha, F. K., Freitas, C. P. O. and Silva, M. R. (2015). Desempenho de cultivares de mandioca em ambiente subtropical. Bragantia, 74, 58-66. https://doi.org/10.1590/1678-4499.0352

Turyagyenda, L. F., Kizito, E. B., Ferguson, M., Baguma, Y., Agaba, M., Harvey, J. J. W. and Osiru, D. S. O. (2013). Physiological and molecular characterization of drought responses and identification of candidate tolerance genes in cassava. AoB Plants, 5, plt007. https://doi.org/10.1093/aobpla/plt007

Verissimo, V., Cruz, S. J. S, Pereira, L. F. M., Silva, P. B., Teixeira, J. D., Ferreira, V. M. and Endres, L. (2010). Trocas gasosas e crescimento vegetativo de quatro variedades de mandioca. Revista Raízes e Amidos Tropicais, 6, 232-240.

Wiriya-Alongkorn, W., Spreer, W., Ongprasert, S., Spohrer, K., Pankasemsuk, T. and Müller, J. (2013). Detecting drought stress in longan tree using thermal imaging. Maejo International Journal of Science and Technology, 7, 166-180. https://doi.org/10.14456/mijst.2013.14