ISSN 1808-8546 (ONLINE) 1808-3765 (CD-ROM)

# PRODUTIVIDADE E EFICIÊNCIA DO USO DA ÁGUA DE CUPUAÇUZEIRO IRRIGADO NAS CONDIÇÕES CLIMÁTICAS DE CASTANHAL-PA, AMAZÔNIA BRASILEIRA

**DEBORAH LUCIANY PIRES COSTA [1]; IGOR CRISTIAN DE OLIVEIRA VIEIRA [2]; ERIKA DE OLIVEIRA TEIXEIRA[3]; MATHEUS YAN FREITAS SILVA[4]; MARIA DE LOURDES ALCÂNTARA VELAME[5] E PAULO JORGE DE OLIVEIRA PONTE DE SOUZA[6]**

[1] *Laboratório de Agrometeorologia, Universidade Federal Rural da Amazônia - Campus Belém – PA,* Av. *Tancredo Neves, nº 2501 – Terra Firme – CEP. 66.077-830, Belém, PA, Brasil, deborahpires.agro@gmail.com.*

[2] *Departamento de Ciências Exatas, Universidade Estadual Paulista Júlio de Mesquita Filho, Faculdade de Ciências Agrárias e Veterinárias de Jaboticabal, Via de Acesso Prof. Paulo Donato Castellane s/n, Bairro Rural, CEP. 14.884-900, Jaboticabal/SP, Brasil, cristianigor67@gmail.com.*

[3] *Laboratório de Agrometeorologia, Universidade Federal Rural da Amazônia - Campus Belém – PA,* Av. *Tancredo Neves, nº 2501 – Terra Firme – CEP. 66.077-830, Belém, PA, Brasil, eriikateixeira@hotmail.com.*

[4] *Laboratório de Proteção de Plantas, Universidade Federal Rural da Amazônia - Campus Belém – PA,* Av. *Tancredo Neves, nº 2501 – Terra Firme – CEP. 66.077-830, Belém, PA, Brasil, matheus.yan.silva@gmail.com.*

[5] *Laboratório de Agrometeorologia, Universidade Federal Rural da Amazônia - Campus Belém – PA,* Av. *Tancredo Neves, nº 2501 – Terra Firme – CEP. 66.077-830, Belém, PA, Brasil, alcantaravelame@gmail.com.*

[6] *Laboratório de Agrometeorologia, Universidade Federal Rural da Amazônia - Campus Belém – PA,* Av. *Tancredo Neves, nº 2501 – Terra Firme – CEP. 66.077-830, Belém, PA, Brasil, paulo.jorge@ufra.edu.br.*

## 1 RESUMO

O cupuaçuzeiro é uma espécie promissora para o desenvolvimento sustentável da agricultura na Amazônia, porém, ainda está no processo de domesticação, sendo necessário estudos fitotécnicos para otimizar a produção de seus frutos. O objetivo deste trabalho foi avaliar a produtividade e eficiência do uso da água (EUA) do cupuaçuzeiro sob diferentes disponibilidades hídricas no município de Castanhal, PA. O experimento foi conduzido entre os anos de 2018 e 2020, representando duas safras, com uso de irrigação por microaspersão em um plantio de 0,3 ha da cultivar BRS-Carimbó. O delineamento experimental foi inteiramente casualizado (DIC), com quatro, tratamentos e 10 repetições, os tratamentos aplicados foram: TS (sem irrigação - sequeiro), T50, T100 e T150, referentes a 50%, 100% e 150% da evapotranspiração de referência, respectivamente. Foi realizada análise de variância, utilizou-se o teste de Tukey ($p<0,05$) e análise de regressão. Os resultados demonstraram melhor desempenho no T100, sendo superior em 68% na produção de frutos que o TS, a produtividade e EUA ajustaram-se a modelos de regressão polinomiais. A EUA foi máxima no T100 (2,615 kg $ha^{-1}$ $mm^{-1}$) e mínima no TS (1,105 kg $ha^{-1}$ $mm^{-1}$) Logo, indica-se que a irrigação em pomares de cupuaçuzeiro seja igual a 100% da evapotranspiração de referência.

**Keywords:** *Theobroma grandiflorum* (Wild.Ex.Spreng.) Schum, irrigação, rendimento, consórcio, clima.

Recebido em 21/12/2020 e aprovado para publicação em 03/10/2021
DOI: http://dx.doi.org/10.15809/irriga.2022v27n1p1-15

**COSTA, D. L. P.; VIEIRA, I. C. DE O.; TEIXEIRA, E. DE O.; SILVA, M. Y. F.; VELAME, M. DE L. A.; SOUZA, P. J. DE O. P. DE**

**YIELD AND WATER USE EFFICIENCY OF IRRIGATED CUPUAÇU TREES UNDER THE CLIMATE CONDITIONS OF CASTANHAL-PA, BRAZILIAN AMAZON**

## 2 ABSTRACT

Cupuaçu tree is a promising species for the sustainable development of Amazonian agriculture. However, it is still in the domestication phase and requires phytotechnical studies to optimize fruit production. The objective of this study was to evaluate the yield and water use efficiency (WUE) of cupuaçu trees under different levels of water availability in the municipality of Castanhal-PA. The experiment was performed between 2018 and 2020 during two harvests, using micro-sprinkler irrigation in a 0.3 ha plantation of the BRS-Carimbó cupuaçu cultivar. The experimental design was completely randomized, with four treatments and 10 replications. The treatments were: TS (without irrigation - rainfed), T50, T100, and T150, referring to 50%, 100%, and 150% of the reference evapotranspiration, respectively. Analysis of variance and comparison of means were performed by the Tukey test ($p$<0.05), in addition to regression analysis. The results showed better performance in response to T100, which had fruit production 68% higher than TS. The results of yield and WUE were adjusted by polynomial regression, with maximum WUE for T100 (2.615 kg ha$^{-1}$ mm$^{-1}$) and minimum for TS (1.105 kg ha$^{-1}$ mm$^{-1}$). Therefore, irrigation must be equal to 100% of the reference evapotranspiration in cupuaçu plantations.

**Keywords:** *Theobroma grandiflorum* (Willd. ex Spreng.) K.Schum, irrigation, yield, intercropping, climate.

## 3 INTRODUCTION

The cupuaçu tree [*Theobroma grandiflorum* (Wild.ex. Spreng.) Schum is a tree-like plant species of tropical origin that is perennial and belongs to the Malvaceae family. Schum stands out for the production of its fruit, cupuaçu, which has great nutritional and socioeconomic importance (DIAS *et al*., 2019). Despite this relevance, it is a crop that is still in the process of domestication, and for this reason, technical information for its commercial production is necessary.

In the Amazon, the cupuaçu tree is cultivated in high floodplain and dry land soils, which are generally arranged in intercropping systems with other fruit trees, such as cocoa, açaí, banana or agroforestry systems (ALVES *et al*., 2014; ALVES *et al*., 2018).

The cupuaçu fruit is a berry with an elongated shape and rounded ends; it has a woody skin; its pulp is acidic and mucilaginous, yellowish, cream or white in color; and it has a pleasant flavor and active aroma (SOUZA *et al*., 2011). The cupuaçu fruit harvest occurs during the period of greatest rainfall, with production concentrated in the first quarter of the year (SOUZA *et al*., 2007).

This species is considered one of the most important for the development of sustainable agriculture in the Amazon region, as it has a dual purpose: providing pulp and seeds, in addition to adapting well to intercropping systems (TEIXEIRA *et al*., 2020). In the food market, cupuaçu pulp is widely consumed as juice, jelly, and ice cream and is also increasingly used in liqueurs and beers. The fruit almond is the raw material for the production of cupulate, which is cupuaçu chocolate (NUNES CLÍMACO *et al*., 2019). In addition to the food industry, cupuaçu is important in the cosmetics and pharmaceutical industries. Among the main reasons is the composition of its pulp, which is rich in phytochemicals, antioxidants, and vitamins essential for health, especially ascorbic acid (PUGLIESE *et al*., 2013).

Owing to the socioeconomic importance of the species, commercial cupuaçu plantations have grown in recent years (PEREIRA; ABREU; RODRIGUES, 2018). The state of Pará is one of the main producers, contributing 27,510 tons of fruit, with an average yield of 3,219 kg ha $^{-1}$, with production standing out in the municipalities of Acará, Tomé-Açu, and Moju, all located in northeastern Pará (SEDAP, 2020).

The cupuaçu tree has a reasonable tolerance to short periods of water deficit. However, when subjected to this type of deficiency, it may exhibit reductions in biomass, height, leaf area, and stem diameter, in addition to physiological changes that directly impact its productivity (CUNHA *et al*., 2018).

The state of Pará, located in the eastern Amazon, has climate types (Aw and Am) characterized by a period of lower rainfall throughout the year (ALVARES *et al*., 2014). In addition, the occurrence of climatic events, such as *El Nino*, which causes irregularities in precipitation and air temperature (DAVIDSON *et al*., 2012), can also cause impacts.

One solution to overcome these adversities is the use of irrigation in production systems to avoid water deficits and consequently decrease productivity. This is therefore an indispensable strategy for increasing the productivity of cupuaçu crops (SOUZA *et al*., 2019). Thus, irrigation is essential to ensure water supply and adequate production, especially in places where rainfall is irregular, such as the state of Pará (TESTEZLAF, 2017; RADIN; SCHÖNHOFEN; TAZZO, 2018). Meeting the water needs of this crop will allow its metabolism to function properly, which occurs through transpiration and photosynthetic processes, thus enabling productivity gains (PALHETA *et al*., 2018).

However, irrigation management must be efficient and rational, avoiding the waste of water and financial resources (ALMEIDA *et al*., 2019). One of the necessary pieces of knowledge for the proper use of irrigation is the determination of crop evapotranspiration and its crop coefficients, which have not yet been defined for cupuaçu. In this context, an alternative for farmers to apply appropriate irrigation depths is the observation of reference evapotranspiration (BELAY *et al*., 2019).

Knowledge of water use efficiency (WUE), which is characterized by the relationship between production and water inputs in the cultivation system, allows us to identify the real water needs of crops, providing an adequate water supply, reducing productivity losses, and ensuring a more sustainable use of water resources (OLIVEIRA, *et al*., 2011). The WUE varies according to the soil and climate factors and the species (ALI; KLEIN, 2014).

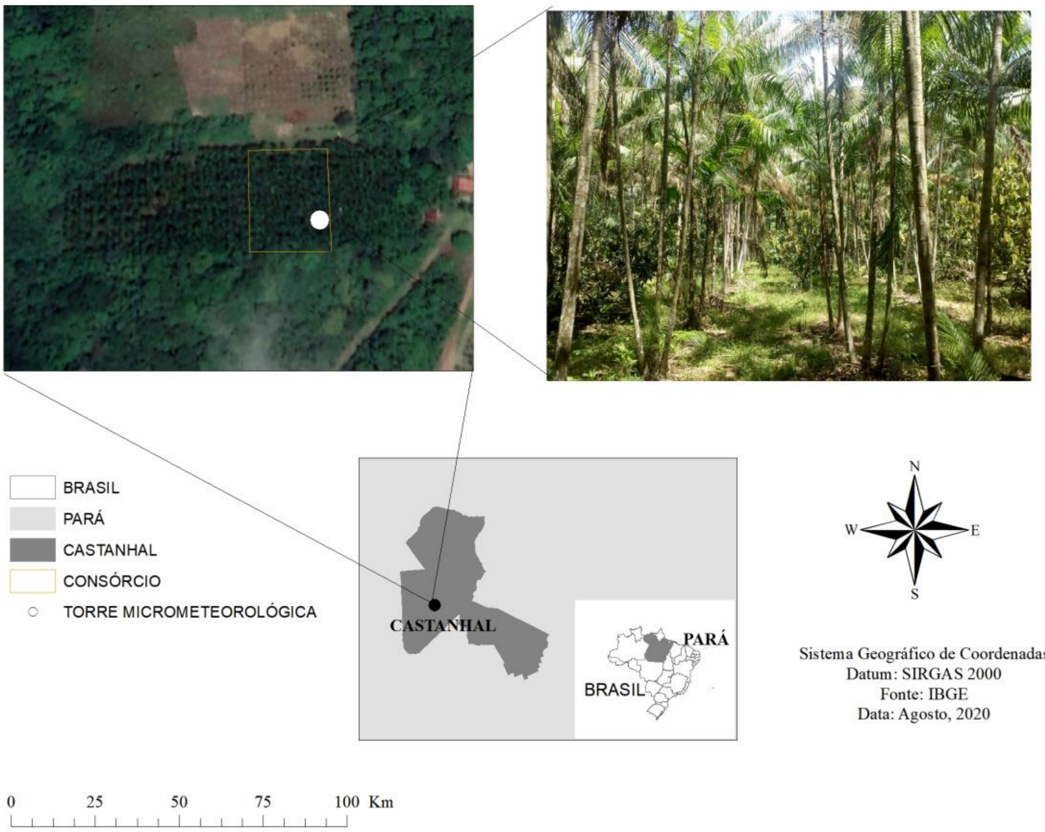
Although the cupuaçu tree has regional socioeconomic importance and great national and international market potential, there is insufficient research on its water demand and soil–plant–atmosphere interactions, as well as on the management practices of this irrigated crop. Therefore, the objective of this study was to determine the productivity and water use efficiency of cupuaçu trees grown at different irrigation depths in the municipality of Castanhal, Pará state, Brazil.

## 4 MATERIALS AND METHODS

### 4.1 Experimental area

The experiment was carried out in a commercial cupuaçu plantation with an area of 0.3 ha located in the municipality of Castanhal, PA, in the northern region of Brazil (1°19'24.48"S and 47°57'38.20"W) (Figure 1). The evaluations were carried out during the years 2018, 2019 and 2020, corresponding to the ages of seven, eight and nine years of planting, respectively. The soil of the area is classified as a dystrophic yellow Latosol with a sandy loam texture (EMBRAPA, 2018). The climate is the Am type according to the Köppen classification, which is characterized as humid tropical, with an average annual temperature of approximately 26°C and annual rainfall above 2,000 mm (ALVARES *et al*., 2014).

**Figure** 1Castanhal, Pará, Brazil.



The plantation was established in 2011. The soil was prepared with clearing, two harrowings, and dolomitic liming. The planting holes were 0.4 m × 0.4 m in size, and phosphate and nitrogen fertilizers were added. The cultivar used was BRS-Carimbó, with a spacing of 8 m × 8 m and intercropped rows of açai trees spaced 4 m × 8 m apart. Until the age of six, the crop was managed in a dryland system, that is, without irrigation.

In 2018, disturbed and undisturbed samples were collected for chemical and physical-hydraulic characterization of the soil at depths of 0–20 cm and 20–40 cm (Table 1). The analyses were carried out in the soil department of the Federal Rural University of Amazonia (UFRA).

**Table 1**cupuaçu plantation in Castanhal, PA.

| ***Attributes chemicals*** | **0-20 cm** | **20-40 cm** |
|---|---|---|
| pH ($H_2O$) | 5,320 | 4,940 |
| Matter organic (%) | 0.714 | 0.666 |
| Phosphorus (mg dm $^{-3}$) | 0.925 | 6,849 |
| Potassium (cmol $_c$ dm $^{-3}$) | 0.25 | 0.505 |
| Calcium (cmol $_c$ dm $^{-3}$) | 0.295 | 0.098 |
| Magnesium (cmol $_c$ dm $^{-3}$) | 0.097 | 0.097 |
| Aluminum (cmol $_c$ dm $^{-3}$) | 0.263 | 0.789 |
| ***Physical-water attributes*** | | |
| Sand (%) | 85,564 | 89,105 |
| Silt (%) | 9,545 | 3,079 |
| Clay (%) | 4,891 | 7,815 |
| Soil density (g cm $^{-3}$) | 1,417 | 1,893 |
| Field capacity (m $^3$ m $^{-3}$) | 0.213 | 0.570 |
| Permanent wilting point (m $^3$ m $^{-3}$) | 0.061 | 0.234 |

During the experimental evaluation years, the cupuaçu cultivation was managed with chemical fertilizer corresponding to 2.0 kg year $^{-1}$ of the chemical formulation (13% N, 11% P, 21% K + 2% Mg and 0.2% B) and organic fertilizer with the application of t ha $^{-1}$ castor oil. Both fertilizers were split into three applications throughout the year: May, September and December. Weed control was carried out quarterly through physical weeding via a brush cutter.

## 4.2 Monitoring weather conditions

**A** micrometeorological tower was set up in the experimental area, with sensors installed two meters above the plant canopy to monitor rainfall (TB4; *Hydrological Services*, Sydney, NSW, AUS), temperature and relative humidity (HMP45C; *Campbell Scientific Instrument*, Logan, UT, USA). These devices take readings every 10 seconds, and averages are stored every 20 minutes by a *datalogger* (CR1000, *Campbell Scientific Instrument*, Logan, UT, USA). The soil volumetric content was monitored via the time domain reflectometry (TDR) technique (CS616, *Campbell Scientific Instrument*, Logan, UT, USA), and TDR probes were inserted vertically into the soil at a depth of 0–0.3 m in each treatment, with soil volumetric content monitoring beginning in August 2018. Effective precipitation was determined from observations of internal precipitation and stem flow.

## 4.3 Irrigation treatments and management

The experiment was designed in a completely randomized design with four treatments and 10 replicates. Each treatment area was 743.85 m². The treatments consisted of different water availability values determined as a function of the daily reference evapotranspiration (ET0), which was estimated via the Penman–Monteith method (FAO 56) (ALLEN *et al*., 1998), since there is no information on the maximum evapotranspiration for the cupuaçu tree, which is defined as:

TS – rainfed treatment, 0% of ET0, that is, water input was only through rain;
T50 – irrigated treatment with 50% ET0;
T100 – irrigated treatment with 100% ET0;
T150 – irrigated treatment with 150% ET0.

Data for ET0 estimation were obtained from an automatic weather station managed by the National Institute of Meteorology (INMET), which is located 2.6 km from the experimental area. The irrigation depth was determined from daily ET0 values via Equation (1).

$$LB = (ET0 - Pef)/ef \qquad (01)$$

where:
LB – Irrigation gross depth (mm);
Pef – Effective precipitation (mm);
ef – Irrigation system efficiency (%).

The irrigation time for each treatment was estimated via Equation 2.

$$TI = \frac{LB}{IA} \qquad (02)$$

where:
TI – Irrigation time (h);
LB – Gross irrigation depth (mm);
IA – Water application intensity (mm $h^{-1}$).

The plants were irrigated daily during the second half of 2018 and 2019, when rainfall was lowest at the site. A microsprinkler irrigation system was used, with one emitter (microsprinkler) per plant, a working pressure of 5.5 mca and a flow rate of 34.0 L $h^{-1}$. The irrigation system efficiency was 86% and 94% in 2018 and 2019, respectively.

**4.5 Productivity and water use efficiency**

Productivity was measured by measuring fruit mass via a digital scale, which had a measuring capacity of 40.0 kg, sensitivity of 4.0 g and five-digit precision.

Two harvests were evaluated:

- 1st evaluation: 2018/2019 Harvest – fruits harvested in January, February and March 2019, which are fruits resulting from the phenology and environmental influence from April 2018 to March 2019;

- 2nd evaluation: 2019/2020 Harvest – fruits harvested in January, February and March 2020, referring to the influence of the months of April 2019 to March 2020.

Water use efficiency was obtained according to the methodology proposed by Inman-Bamber and Smith (2005), as per Equation 3.

$$EUA = \frac{P}{I + Pef} \qquad (03)$$

where:
USA- Water use efficiency (kg $ha^{-1}$ $mm^{-1}$);
P – Fruit productivity (kg $ha^{-1}$);
I – Irrigation estimated by reference evapotranspiration (mm $d^{-1}$);
Pef – Effective rainfall (mm $d^{-1}$).

To calculate the EUA, the sums of water inputs from effective precipitation and irrigation from April 2018 to March 2019 for the 2018/2019 harvest and from

April 2019 to March 2020 for the 2019/2020 harvest were considered.

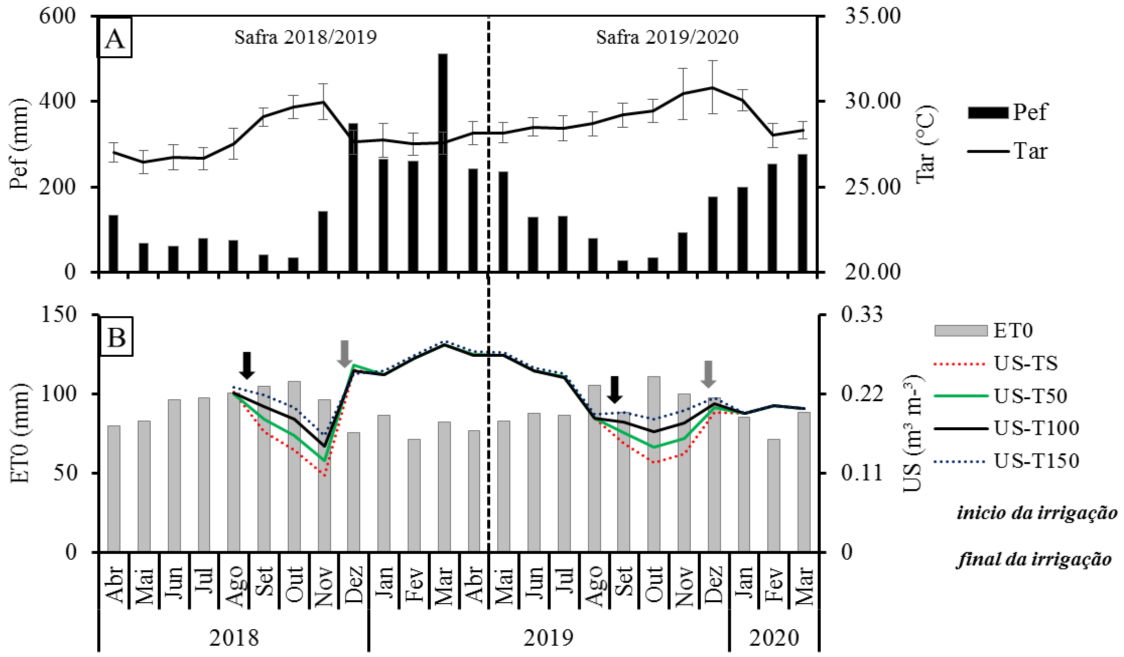
### 4.6 Statistical analysis

The data were subjected to analysis of variance (ANOVA) with the Tukey test ($p<0.05$). Significant responses were evaluated quantitatively via regressions. The statistical *software PAST (HAMMER, 2001)* was used for the statistical analyses.

## 5 RESULTS AND DISCUSSION

The average air temperature (Tar) throughout the experimental period was 28.41°C (± 1.23). In the first harvest, 2018/2019, Tar had an average value of 27.79°C, whereas in the second harvest, 2019/2020, the value recorded was 28.98°C, with the maximum values occurring in the second half of the year, mainly in the months of September, October and November. The total effective rainfall (Pef) during the experiment was 3,476.89 mm, with 2,020.14 mm in the first harvest and 1,873.92 mm in the second harvest. Rainfall in the municipality of Castanhal is poorly distributed throughout the year and is more concentrated between December and March (Figure 2A).

**Figure 2**Environmental variables between April 2018 and March 2020 in the experimental area with cupuaçu cultivation, Castanhal, Pará, Brazil. A. Effective precipitation (Pef) and mean air temperature (Tar). B. Reference evapotranspiration (ET0) and volumetric soil moisture (US) of the TS – rainfed; T50 – irrigation with 50% ET0; T100 – irrigation with 100% ET0; T150 – irrigation with 150% ET0.




The reference evapotranspiration totaled 1,921.24 mm at both harvests, with an average of 2.97 mm d $^{-1}$, with the highest values recorded between September and November, with an average of 3.33 mm d $^{-1}$. In 2018, the volumetric soil water content

(US) differed according to the irrigation depth applied and returned to similar values as the rains intensified at the end of November 2018, the period when irrigation ended. The U.S. differentiated again in September 2019, when irrigation was again applied (Figure 2B).

The total irrigation depth in 2018 was 69.14 mm in the T50 treatment, 217.41 mm in the T100 treatment, and 365.68 mm in the T150 treatment. During the irrigation period, a Pef of 79.13 mm was observed, which was considered the only water depth in the TS treatment. On average, the irrigation depth applied during 2018 was 1.72 mm d $^{-1}$ in the T50 treatment, 3.45 mm d $^{-1}$ in the T100 treatment, and 5.17 mm d $^{-1}$ in the T150 treatment.

In 2019, during the irrigation period (September to early December), effective rainfall of 138.21 mm occurred, and irrigation of 75.26 mm was applied in T50, with an average of 1.68 mm d $^{-1}$, whereas in T100, 150.52 mm was applied, with a daily average of 3.36 mm d $^{-1}$, and 225.78 mm in T150, with an average of 5.05 mm d $^{-1}$.

cupuaçu fruits and, consequently, the efficiency of water use (Table 2).

**Table 2** Applied water depth, average productivity values and water use efficiency of the cupuaçu trees in the 2018/2019 and 2019/2020 harvests in the municipality of Castanhal, PA.

| | **THERE (mm)** | | **P kg ha $^{-1}$** | | **USA kg ha $^{-1}$ mm $^{-1}$** | |
|---|---|---|---|---|---|---|
| Harvests | 2018/2019 | 2019/2020 | 2018/2019 | 2019/2020 | 2018/2019 | 2019/2020 |
| TS | 2,020.14 | 1,873.92 | 1,856.75c | 2,267.27c | 0.91c | 1.30d |
| T50 | 2,118.90 | 1,959.60 | 4,001.68b | 5,095.05b | 1.89b | 2.60b |
| T100 | 2,316.42 | 2,158.71 | 4,948.82a | 6,215.08a | 2.23a | 3.00a |
| T150 | 2,612.70 | 2,487.47 | 4,234.15b | 4,965.76b | 1.83b | 2.25c |
| | | ANOVA | | | | |
| | | P value | <0.0001 | <0.0001 | <0.0001 | <0.0001 |
| | | CV (%) | 8.26 | 7.43 | 8.08 | 7.23 |

Note: TS – rainfed; T50 – irrigation with 50% ET0; T100 – irrigation with 100% ET0; T150 – irrigation with 150% ET0; LA – applied water depth; P – productivity; EUA - water use efficiency; CV – coefficient of variation. Means followed by the same letters do not differ significantly from each other at the p <0.05 level on the basis of Tukey's test.

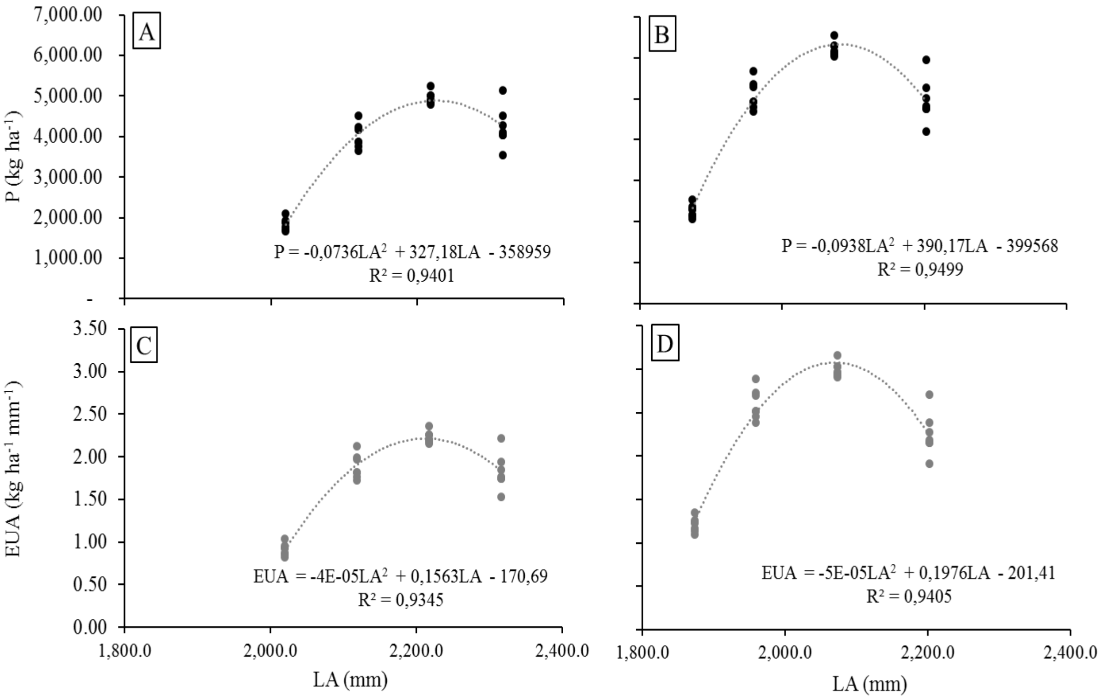
The 100% ET0 blade showed better performance for both productivity and EUA in the two harvests evaluated, whereas the TS presented lower values. The EUA varied, on average, between 1.105 kg ha $^{-1}$ mm $^{-1}$ (TS) and 2.615 kg ha $^{-1}$ mm $^{-1}$ (T100). In the 2018/2019 harvest, there was a difference between TS and T100, with values of 73% for productivity and 41% for EUA. In the 2019/2020 harvest, this difference was 63% and 56% for productivity and EUA, respectively (Table 2).

On the other hand, the results showed that the use of a water depth of 150% of ET0 did not differ statistically from the treatment with irrigation at 50% of ET0 and even promoted a decrease in productivity and water use efficiency (Table 2). Thus, the use of this water depth, which averaged 5.55 mm d $^{-1}$, caused a waste of water and economic resources and therefore should not be recommended for the irrigation of the cupuaçu tree under the experimental conditions.

The productivity and EUA response functions fit the second-order polynomial model, with a coefficient of determination above 90% (Figure 3). The maximum productivity estimated by the equations was

4,650.893 kg ha $^{-1}$ in the 2018/2019 harvest and 6,169.284 kg ha $^{-1}$ in the 2019/2020 harvest.

**Figure** 3 Cupuaçu productivity and water use efficiency under different water availability conditions (applied water depth - LA), Castanhal, PA. A and B - Productivity (P) during the 2018/2019 and 2019/2020 harvests, respectively; C and D - water use efficiency (WUE) during the 2018/2019 and 2019/2020 harvests, respectively.




The productivity observed in this study was lower than the potential described in the technical circular for the BRS-Carimbó cultivar, which is estimated at 11 t ha $^{-1}$. However, this value has no record of field observations. On the other hand, the actual productivity, which is reported in the municipal averages of the state of Pará, corresponds to 3.5 t ha $^{-1}$ (SEDAP, 2019; ALVES, 2014). These crops, which are generally in the Amazon region, do not irrigate and are intercropped with other fruit trees, as described in the research by Guimarães and Durigan (2018) and Pinho, Miller and Alfaia (2012), since farmers in the region culturally use dimensioning by adding diversity by employing other agricultural plants in their crops, even forest species, that is, adopting agroforestry systems (SAFs) (ALVES *et al*., 2018).

Therefore, although the species in question is still in the process of domestication and presents variation in production, the real productivity values are underestimated in relation to the potential productivity (ALVES *et al*., 2014). The results achieved in the irrigated treatments of this study demonstrate that irrigation is essential for increasing the production of cupuaçu fruits, since the irrigated treatments presented achievable productivity (Table 2 and Figures 3A and 3B) higher than the state average recorded for real productivity (3.5 t ha $^{-1}$).

There is clearly a great need for observations of adult cupuaçu plants, which are in full production, since research on the use of irrigation for this species is directed toward nursery plants, that is, young plants (seedlings), as in the study by Palheta *et al. (2018), who studied irrigated* cupuaçu seedlings and evaluated their performance through physiological variables, and Lozano and Fonseca (2016), who evaluated *Theobroma plants cacao* (the same genus as the cupuaçu tree) in the nursery phase under different water availability conditions in the meteorological conditions of Bahia.

With respect to the better productivity and EUA performance found for the T100 treatment, some studies state that during the flowering period in fruit orchards, irrigation should be stopped to stimulate floral emission (SANTOS *et al*., 2019). This information is widely disseminated in Pará agriculture, even justifying dryland cultivation.

However, despite the scientific basis of water stress in the flowering phase, water deficiency should not be continuous, since after the emission of flowers, which reproduce until harvest (fruits), it is essential to meet their water demand so that they can efficiently perform their metabolic and physiological processes, such as photosynthesis and transpiration (YADAV *et al*., 2020), as observed in this study, since irrigated treatments, especially T100, which meet 100% of atmospheric demand, provide greater productivity and EUA.

The results of this study are relevant, pioneering, and innovative for the use of irrigation in cupuaçu crops in eastern Amazonia, especially for agricultural practices that utilize intercropping systems. Notably, further research is needed, particularly the economic evaluation of the irrigation depths used in this study, particularly those applied in treatments 50 and 100, as well as the determination of crop yield coefficients for the species and the evaluation of fruit pulp as a function of different irrigation depths.

## 6 CONCLUSION

Irrigation promotes increased productivity and water use efficiency in adult cupuaçu trees under the climatic conditions of Castanhal, Pará, Brazilian Amazon. An irrigation depth of 100% ET0 increased the fruit yield of seven- to nine-year-old cupuaçu trees by 68% compared with that of crops without irrigation. Water use efficiency is greater in plants irrigated at depths with 100% ET0 replacement, reaching an average value of 2.615 kg ha $^{-1}$ mm $^{-1}$, whereas under conditions without irrigation, this value is 1.105 kg ha $^{-1}$ mm $^{-1}$. Therefore, an irrigation depth with 100% ET0 replacement is recommended for cupuaçu orchards.

## 7 ACKNOWLEDGMENTS

The authors would like to thank the National Council for Scientific and Technological Development (CNPq), the Coordination for the Improvement of Higher Education Personnel (CAPES), and the Amazon Foundation for the Support of Studies and Research (FAPESPA) for granting scholarships and other financial resources (FAPESPA/ICAAF 009/2017). The Federal Rural University of the Amazon (UFRA) and the Castanhal School Farm (FEC) for their logistical support, the owner of the commercial plantation for granting the study area, and the Soil–Plant-Atmosphere Interaction in the Amazon Research Group (ISPAAm).

## 8 REFERENCES

ALI, MK; KLEIN, KK Water Use Efficiency and Productivity of the Irrigation Districts in Southern Alberta. **Water Resources Management** , Dordrecht, v. 28, no. 10, p. 2751-2766, 2014. Available

at:
http://link.springer.com/10.1007/s11269-014-0634-y. Accessed on: 19 September. 2020.

ALLEN, RG; PEREIRA, LS; RAES, D.; SMITH, M. **Crop evapotranspiration** : guidelines for computing crop water requirements. Rome: FAO , v. FAO, p. 300, 1998.

ALMEIDA, MJ ; SOUSA, CM ; ROCHA, MC ; BENITES, VM ; POLIDORO, JC Deficit water replacement and organomineral fertilization on the growth and production of industrial tomato. **Irriga** , Botucatu, v. 24, n. 1, p. 69-85, 2019.

ALVARES, CA; STAPE, JL; SENTELHAS, PC; DE MORAES GONÇALVES, JL; SPAROVEK, G. Köppen's climate classification map for Brazil. **Meteorologische Zeitschrift** , Stuttgart, v. 22, n. 6, p. 711-728, 2014. Available at: http://www.schweizerbart.de/papers/metz/detail/22/82078/Koppen_s_climate_classification_map_for_Brazil?af=crossref. Accessed on: August 20, 2020.

ALVES, RM; CHAVES, SF DA S.; OLIVEIRA, RP DE; PEDROZA NETO, JL; SEBBENN, A. Canopy replacement used in the evaluation of cupuassu tree genotypes in the state of Pará. **Revista Brasileira de Fruticultura** , Jaboticabal, v. 42, n. 4, p. 110-11, 2020. Available at: http://www.scielo.br/scielo.php?script=sci_arttext&pid=S0100-29452020000401003&tlng=en. Accessed on: March 22, 2021.

ALVES, RM ; BASTOS, AJR; KEYS, SFDS; FERNANDES, JRQ Spondias mombin and Theobroma grandiflorum in agroforestry systems: productivity implications. **Brazilian Journal of Fruit Growing** , Jaboticabal, v. 40, n. 6, p. 1-8, 2018.

ALVES, RM; FILGUEIRAS, GC; HOMMA, AKO Socioeconomic aspects of cupuaçu in the Amazon: from extractivism to domestication. *In* : SANTANA, A. C *et al*.. **Market, production chains and rural development in the Amazon** . 1st ed. Belém, PA: UFRA, 2014. p. 197-223.

BELAY, SA; SCHMITTER, P.; WORQLUL, AW; STEENHUIS, T.S.; REYES, MR; TILAHUN, SA Conservation Agriculture Saves Irrigation Water in the Dry Monsoon Phase in the Ethiopian Highlands. **Water** , Basel, vol. 11, no. 10, p. 1-16, 2019. Available at: https://www.mdpi.com/2073-4441/11/10/2103. Accessed on: 24 Mar. 2022.

NUNES CLÍMACO, G.; KELLY GONÇALVES ABREU, V.; DE OLIVEIRA LEMOS, T.; LÚCIA FERNANDES PEREIRA, A. Mixed Nectar of Cupuassu (*Theobroma grandiflorum)* and Green Tea and the Effect of Preservatives and Storage on Nutritional and Sensory Characteristics. **Journal of Food and Nutrition Research** , Cagayan de Oro City , v. 7, n. 5, p. 361-369, 2019. Available at: http://pubs.sciepub.com/jfnr/7/5/5/index.html. Accessed on: March 24, 2022.

CUNHA, RLM DA; GALVÃO, JR; ALVES, RM; GOMES, VA;OLIVEIRA, FC; FERREIRA, IVL Ecophysiology of cupuaçu progeny subjected to water deficit and rehydration. **Brazilian Journal of Irrigated Agriculture** , Fortaleza, v. 12, n. 2, p. 2500-2509, 2018. Available at: http://www.inovagri.org.br/revista/index.php/rbai/article/view/766/pdf_460. Accessed on: March 22, 2021.

DAVIDSON, E.; DE ARAÚJO, A.;

ARTAXO, P.; BALCH, J. K; BROWN, I. F.; BUSTAMANTE, M. M. C; DEFRIES, R. S.; KELLER, M.; LONGO, M.; MUNGER, J. W.; WOFSY, S. C.; SCHROEDER, W.; SOARES-FILHO, B. S.; SOUZA, C. M. The Amazon basin in transition. **Nature** , São Paulo, v. 481, n. 7381, p. 321-328, 2012. Available at: http://www.nature.com/articles/nature10717. Accessed on: March 22, 2021.

DIAS, JDM; ABREU, VKG; PEREIRA, ALF; LEMOS, TDO; SANTOS, LH DOS; SILVA, VKL DA; MOTA, ASDB Development and evaluation of physicochemical characteristics and sensory acceptance of cupuaçu sweet dough. **Bulletin of the Food Processing Research Center** , Curitiba, v. 36, n. 1, p.1-10, 2019. Available at: https://revistas.ufpr.br/alimentos/article/view/45137. Accessed on: March 24, 2021.

EMBRAPA. **Brazilian Soil Classification System** . 5th ed. Brasília, DF: Revised and Expanded, 2018.

GUIMARÃES, PVP; DURIGAN, MFB Growth and development of cupuaçu fruits in an agroforestry system in the state of Roraima, Brazil. **Environment Journal** : Management and Development , Roraima, v. 11, n. 1, p. 278-294, 2018.

HAMMER, H.; HARPER, DAT; RYAN, PD PAST: Paleontological Statistics Software Package for Education and Data Analysis. **Paleontologia Electronica** , Lusby , v. 4, no. 1, p. 1-9, 2001.

INMAN-BAMBER, NG; SMITH, DM Water relations in sugarcane and response to water deficits. **Field Crops Research** , Netherlands, v. 92, n. 2-3, p. 185-202, 2005. Available at: https://linkinghub.elsevier.com/retrieve/pii/S0378429005000304. Accessed on: August 2, 2020.

LOZANO, JG; FONSECA, LPM Physiological responses of Theobroma cacao L. in the nursery stage to the availability of water in the soil. **Acta Agronómica** , Palmira, v. 65, n. 1, p. 44-50, 2016. Available at: http://www.revistas.unal.edu.co/index.php/acta_agronomica/article/view/48161. Accessed on: 21 Mar. 2021.

OLIVEIRA, ECA DE; FREIRE, FJ; OLIVEIRA, AC DE; SIMÕES NETO, DEC; CARVALHO, LA Productivity, water use efficiency and technological quality of sugarcane subjected to different water regimes. **Brazilian Agricultural Research** , Brasília, v. 45, n. 6, p. 617-625, 2011.

PALHETA, JG; SOUZA, LC DE; CUNHA, RL; ALVES, RM; BARBOSA, AVC; SOUSA, DJP DE; TEIXEIRA, JSS; CONCEIÇÃO, SS; OKUMURA, RS; NETO, CF DE O. Physiological Study of Cupuaçu [Theobroma grandiflorum (Willd. ex. Spreng.) Schum.] Tree Progenies Subjected to Water Deficiency. **Journal of Experimental Agriculture International** , Hooghly, v. 28, n. 3, p. 1-10, 2018. Available at: https://journaljeai.com/index.php/JEAI/article/view/1127. Accessed on: March 15, 2021.

PEREIRA, ALF; ABREU, VKG; RODRIGUES, S. Cupuassu - Theobroma grandiflorum. *In* : SILVA, EO; BRITO, ES; RODRIGUES, S (org.). **Exotic Fruits** . 1 ed. Massachusetts: Academic Press, 2018. p. 159- 162.

PINHO, RC; MILLER, RP; ALFAIA, SS Agroforestry and the Improvement of Soil Fertility: A View from Amazonia. **Applied and Environmental Soil Science** , London, v. 2012, p. 1-11, 2012. Available at: http://www.hindawi.com/journals/aess/2012/616383/. Accessed on: March 13, 2021.

PUGLIESE, AG; TOMAS-BARBERAN, FA; TRUCHADO, P.; GENOVESE, MI Flavonoids, Proanthocyanidins, Vitamin C, and Antioxidant Activity of Theobroma grandiflorum (Cupuassu) Pulp and Seeds. **Journal of Agricultural and Food Chemistry** , New York, v. 61, n. 11, p. 2720-2728, 2013. Available at: https://pubs.acs.org/doi/10.1021/jf304349u. Accessed on: March 22, 2021.

RADIN, B.; SCHÖNHOFEN, A.; TAZZO, I.F. Impact of rainfall quantity and frequency on soybean yield. **Agrometeoros** , Passo Fundo, v. 25, n. 1, p. 19-26, 2018.

SANTOS, IC DOS; ALMEIDA, A.-AF DE; PIROVANI, CP; COSTA, MGC; CONCEIÇÃO, AS DA; SOARES FILHO, W. DOS S.; COELHO FILHO, MA; GESTEIRA, AS Physiological, biochemical, and molecular responses to drought conditions in field-grown grafted and ungrafted citrus plants. **Environmental and Experimental Botany** , Elmsford, v. 162, p. 406-420, 2019. Available at: https://linkinghub.elsevier.com/retrieve/pii/S0098847218319488. Accessed on: September 29, 2020.

SECRETARIAT OF STATE FOR AGRICULTURAL DEVELOPMENT AND FISHERIES - SEDAP. **Cupuaçu.** Available at: <http://www.sedap.pa.gov.br/content/cupuaçu>. Accessed on: December 15, 2020.

SOUZA, A. ; SOUZA, MG ; PAMPLONA, A. ;; WOLFF, ADS **Good practices in the harvest and postharvest of cupuaçu** . Manaus: Embrapa Western Amazon, 2011. (Technical Circular, n. 36) .

SOUZA, AGC; BERNI, RF; SOUZA, MG; SOUSA, NR ; SILVA, SEL ; TAVARES, AM ; ANDRADE, JS ; BRITO, MAM ; SOARES, MSC **Good agricultural practices for cupuaçu cultivation** . Manaus: Embrapa Western Amazon, 2007. Available at: http://www.infoteca.cnptia.embrapa.br/infoteca/handle/doc/679234. Accessed on: December 15, 2020.

SOUZA, PJOP; RAMOS, TF; FIEL, L. DE CS; FARIAS, VD DA S.; SOUSA, D. DE P.; NUNES, HGGC Yield and water use efficiency of cowpea under water deficit. **Brazilian Journal of Agricultural and Environmental Engineering** , Campina Grande, v. 23, n. 2, p. 119-125, 2019. Available at: http://www.scielo.br/scielo.php?script=sci_arttext&pid=S1415-43662019000200119&tlng=en. Accessed on: March 20, 2021.

TEIXEIRA, EO; VELAME, MLA; MONTEIRO, AC ; LISBOA, SPP; SANTOS, BN; TAVARES, LB; CUNHA JUNIOR, JB; PINTO, JVN; SILVA, JVF; MARTINS, CGD; COSTA, DLP; SOUZA, PJOP Cupuaçu pulp yield under different water availability in the climatic conditions of Brazil nut plantation-PA. *In* : Barbosa Juniro, C. A (Org). **The Vicissitudes of Research and Theory in Agricultural Sciences 2** . Ponta Grossa: Atena Editora, 2020. p. 24-33.

TESTEZLAF, R. **Irrigation** : methods, systems and applications. Campinas: FEAGRI , 2017.

YADAV, A.; JAYASWAL, P.K.; VENKAT RAMAN, K.; SINGH, B.; SINGH, N.K.; USHA, K. Transcriptome analysis of flowering genes in mango (Mangifera indica L.) in relation to floral malformation. **Journal of Plant Biochemistry and Biotechnology** , New Delhi, vol. 29, no. 2, p. 193-212, 2020. Available at: https://doi.org/10.1007/s13562-019-00541-z. Accessed on: 13 Dec. 2020.