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# Performance of the AquaCrop model in the climate risk analysis and yield prediction of cowpea (*Vigna Unguiculatta* L. Walp)

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**Abstract**

The present work evaluated the Aquacrop model as a tool for climate risk analysis and yield prediction of cowpea, cultivated in a dystrophic yellow oxisol. The model was previously calibrated and validated for two harvests, in order to simulate the biomass and yield of cowpea, considering four applied water blades over its reproductive period. The good achieved results prove the model's efficiency for this kind of simulation. After validation, the yield simulation of cowpea based on the meteorological data (2003 to 2014), soil and crop management of 12 harvests was performed. Two scenarios were given: the potential yield without water restrictions; and the actual yield, considering to pluvial availability conditions of the inserted series. The results suggested that the optimum sowing dates are between April 1st and 20th, in which there was a low yield loss (< 10 %) considering the potential yield, high probability (> 90 %) of achieving high yields (above 1300 kg ha$^{-1}$) and a low risk of getting crop harvesting in the rainy period. After all, the model proved to be a feasible tool for predicting cowpea yield in the region and also over regions with similar characteristics.

**Keywords**: agricultural modeling; optimal sowing window; water deficit; yield; yield decrease.
**Abbreviation:** Avg_average; AWC_Available Water Content; AY_Simulated Actual Yield; B_biomass; BGM_Beginning of Grain Maturation; CC_Canopy Cover; DAS_Days After Sowing; DEF_Soil Water Deficit; DSSAT_Decision Support System for Agrotechnology Transfer; Ea_Application Efficiency; EF_Model Efficiency; EMBRAPA_Brazilian Agricultural Research Corporation; $ET_C$_Crop Evapotranspiration; $ET_0$_Reference Evapotranspiration; FAO_Food and Agriculture Organization of the United Nations; FC_Field Capacity; GD_Gross Difference; I_Irrigation; IB_ Gross Depth; INMET_ National Institute of Meteorology; Kc_Crop Coefficient; LAI_Leaf Area Index; Oi_observed yield; OSW_Optimum Sowing Window; Pi_Simulated Yield; PRP_Precipitation; PY_Simulated Potential Yield; RAW_Readily Available Water; RD_Relative Difference; RH_Relative Humidity; SD_Sowing Dates; SR_Solar Radiation; VCW_Volumetric Content of Water; Y_Yield; YD_Yield Decrease.

## Introduction

Cowpea is produced worldwide and Brazil is the third place in the producer's world ranking, behind only Nigeria and Niger (Freire Filho et al., 2011). This culture usually is planted in developing countries, where it is associated with the generation of employment and income in these regions (Farias et al., 2017). In the north of Brazil specifically in the state of Pará, it is mainly produced in the northeast of the state, but despite large investments in the production chain, it has shown low yield (788 kg ha$^{-1}$) when compared to other producing regions, such as the Central West region (1200 kg ha$^{-1}$) (Ruas, 2017).
A huge part of this productive limitation is due to climatic variability that affects the yield and restrict its planting only to the rainy season, making it almost unusable in the following semester because of the water necessity by the crop during essential stages (reproductive phase) and by the lack of precipitations in this period (Fernandes et al., 2015), which happens in most of regions of Pará and especially the northeast (Lopes et al., 2013).
On the other hand, the occurrence of large amounts of precipitation during the grains physiological maturation stage can also affect the final yield and quality, due to the environment conducive for diseases and to the accelerating process of deterioration of the crop's grains (Diniz et al., 2013).
This explains why precipitation is the main climatic risk factor for agricultural production (Ferreira and Rao, 2011), because the climatic dynamics in northern region of the

country (Inter Tropical Convergence Zone, El Niño and La Niña and etc.) favors a wide interannual and seasonal variation of rainy seasons in this region (Li et al., 2011). All this combined with the lack of knowledge about the weather and the increase in the probability of greater climatic adversity have worried grain producers and researchers in the area, because studies show that interannual climatic variabilities tend to increase causing disturbances in the world agricultural context (Ray et al., 2015).

Thus, tools capable of assisting the best choice of strategies to be adopted in planting and harvesting can be a great solution to anticipate and reduce risks quickly and maximize yields (Lima Filho et al., 2013). Currently, there are crop models (CERES, CROPGRO) that are able to simulate the development of a crop according to the local edaphoclimatic conditions, crop characteristics, soil characteristics, management adopted and as well as assist in management and planning of practices to be used (Sentelhas et al., 2015).

Among the models, the AquaCrop model from FAO is highlighted (Food and Agriculture Organization of the United Nations) which has been widely used in several crops, such as corn (Paredes et al., 2014), barley (Tavakoli et al., 2015) and pea (Paredes and Torres, 2016). The AquaCrop model was developed from studies and simplifications of relationships according to the soil-plant-atmosphere system, performing its simulations through information on climate, soil, cultivar and management practices adopted (Raes et al., 2017).

Due to its practicality and robustness, together with the lack of studies of this nature to help the productive chain, the AquaCrop model was used as a tool for climatic risk analysis and yield prediction of cowpea in the climatic and soil conditions of Castanhal's city, after the model calibration (2013) and validation (2014) to simulate the biomass and yield. This municipality is located in the northeast of Pará, and also the main production pole of cowpea in the state of Pará.

**Results and discussions**

***Climate variability***

The annual production variability of cowpea (Ruas, 2017) is due to biotic factors, such as pests, and the most influent ones, factors of abiotic origin, such as the great climatic variability of producing regions, especially radiation, temperature and precipitation (Farias et al., 2015, Teixeira et al., 2015, Souza et al., 2017). These variables are of great importance for agricultural production and any change directly affects the planting and management to be adopted (Minuzzi et al., 2015).

The municipality of Castanhal is located in an Ami climatic zone according to Koppen, and it has a rainy period from January to May, representing 70 % of the total annual PRP, and a dry period from August to December, representing only 16 % of total annual PRP (Souza et al., 2017). In this study (Fig. 1), the rainy trimester was from February to April, with March (330.35 mm) being the wettest month. These characteristics directly imply in the choice of sowing date of cowpea in Pará, occurring in this quarter (Freire Filho et al., 2011).

On the other hand, the dry period was from September to November (PRP < 45 mm), and this period was considered the most critical in the region (Farias et al., 2017), with November (33 mm) being the driest month. The monthly air temperatures (Tavg) presented high values (≈ 26.5 °C) and it did not suffer large variations during the year, with values of maximum (Tmax) and minimum (Tmin) average air temperatures ranging from 34.0 °C (November) to 18.0 °C (March), respectively.

The SR (solar radiation) parameter, which is very important for the cultivation of cowpea, also does not show large variations throughout the year, being above 15 MJ $m^{-2}$ $dia^{-1}$ and reaching its highest values during the dry period of the region, more precisely during September (19.23 MJ $m^{-2}$ $dia^{-1}$).

Therefore, PRP is the one that best defines the climate of the region, since variables such as Tavg and SR do not show large seasonal variations (Lima et al., 2016; Souza et al., 2017). Thus, in addition to obtaining high yields, the rainy season will be considered in the evaluation of sowing window choice in the region, since PRP should be avoided during cowpea harvest (Freire Filho et al., 2011).

***Biomass and yield on the experiment versus water deficit***

There was a significant effect ($p < 0.05$) in the interaction between treatments (T1 to T4) and the variables considered, except for the experimental year of 2013 (in treatments T2 and T3) that did not present significant differences for yield (Table 1). On the other hand, cowpea under optimum conditions (T1) could reach a total biomass of 538.45 kg $ha^{-1}$ (2013) at the end of the reproductive phase over this period; there was a water deficit (T4) of 23 and 36 mm, for 2013 and 2014, respectively. This deficiency caused a reduction of ≈ 28 % in biomass and ≈ 40 % in cowpea yield when compared to T1 treatment. Therefore, the water deficit during the reproductive phase of cowpea causes a loss in biomass production and thereby in the final yield, mainly due to the lack of water during the grain filling phase.

This is also evidenced in other studies who also verified that the water deficit caused a decrease in the stomatal conductance of cowpea. Such condition caused a decrease of the final yield by up to 72 % in the treatments that were not irrigated (Souza et al., 2017). This proves that the deficit during the reproductive phase can be a determinant in the production of cowpea in the region.

***Simulation of the yield by AquaCrop model***

Paredes and Torres (2016) state that to obtain good results in the simulations by the model, it is necessary to have a coherence between the values obtained in the field and the simulated values, since they indicate that the parameterization of the culture to the model was performed positively and this depends on several parameters related to soil, water and culture.

When comparing AquaCrop to other models (DSSAT, for example), some authors affirm that it obtains better simulations, since its parameterization procedures and their standard values are described in detail by FAO and in this way help in the process of adjustments in the model that you are looking for (Pereira et al., 2015). In the present study, the use of water by the crop in the simplest way possible through the use of a smaller number of parameters (Raes et al., 2017).

**Table 1.** Mean values of biomass (kg ha$^{-1}$), yield (ton ha$^{-1}$) and water deficit (mm) imposed by the treatments adopted, during the vegetative phase in 2013 and 2014.

| Year | Treatments | Deficiency | Biomass | Yield |
|---|---|---|---|---|
| **2013** | T1 | 0 | 538.45 a | 1319.97 a |
| | T2 | 6 | 473.77 b | 1222.16 b |
| | T3 | 14 | 450.79 c | 1188.49 b |
| | T4 | 23 | 397.71 d | 817.94 c |
| **2014** | T1 | 1.4 | *63.77 x 10$^{-5}$ a | 1569.18 a |
| | T2 | 9 | *71.25 x 10$^{-5}$ b | 1233.54 b |
| | T3 | 21 | *73.22 x 10$^{-5}$ c | 1002.26 c |
| | T4 | 36 | *76.14 x 10$^{-5}$ d | 792.34 d |

Different letters represent that there was a significant difference between the means in the column, by the Tukey test ($p < 0.05$). The deficiency values were calculated for an Available Water Content (AWC) of the 45 mm. *Biomass values transformed as a function of the equation, x = 0.33 / original value, suggested by the Box-Cox method for data normalization.

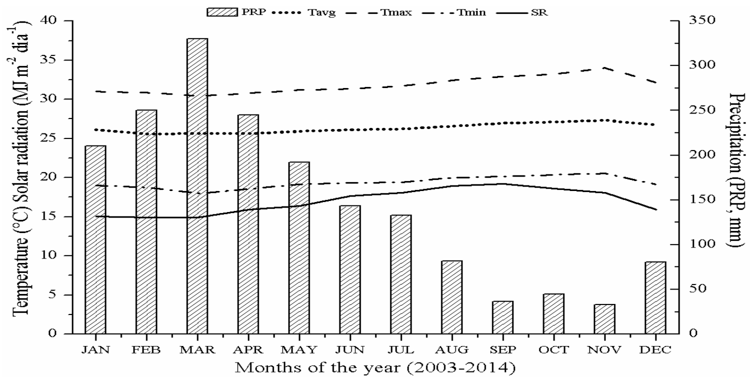


**Fig. 1.** Climatic variability of Castanhal (2003 - 2014).

**Table 2.** Average deficiency (DEF) during vegetative (VEG) and reproductive (REP) phases of cowpea, simulated by AquaCrop model for different sowing dates (SD) (1st, 10th and 20th days) and precipitation (PRP) occurring 10 days after the beginning of grain maturation (BGM), over the period from 2003 to 2014.

| | SD | JAN | FEB | MAR | APR | MAY | JUN | JUL | AUG | SEP | OCT | NOV | DEC |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| DEF VEG (mm) | 1 | 10.45 ±17.68 | 5.28 ±15.65 | 2.34 ±15.13 | 1.22 ±10,09 | 2.21 ±14.62 | 14.12 ±13.07 | 18.13 ±12.68 | 41.16 ±7.38 | 67.03 ±4.85 | 66.48 ±6.55 | 74.31 ±4.86 | 38.15 ±8.56 |
| | 10 | 8.54 ±11.92 | 4.65 ±15.90 | 1.06 ±14.08 | 0.89 ±11.12 | 5.89 ±15.42 | 17.14 ±12.47 | 22.84 ±11.88 | 45.41 ±8.19 | 59.73 ±7.14 | 65.51 ±6.77 | 52.00 ±6.92 | 23.44 ±7.87 |
| | 20 | 7.45 ±13.61 | 3.92 ±16.04 | 1.00 ±16.84 | 0.56 ±6.86 | 8.78 ±12.21 | 18.43 ±10.00 | 30.79 ±9.30 | 50.18 ±8.56 | 67.58 ±5.52 | 72.10 ±6.46 | 34.24 ±20.10 | 12.31 ±9.41 |
| DEF REP (mm) | 1 | 8.56 ±14.78 | 2.83 ±12.56 | 0.86 ±3.78 | 2.89 ±6.89 | 9.98 ±12.89 | 21.13 ±14.78 | 22.15 ±13.45 | 38.91 ±8.78 | 42.18 ±7.45 | 45.16 ±4.89 | 34.15 ±2.89 | 23.16 ±9.15 |
| | 10 | 7.45 ±10.67 | 1.98 ±7.87 | 1.76 ±4.87 | 3.76 ±5.78 | 13.76 ±15.86 | 24.15 ±13.67 | 27.89 ±12.34 | 35.41 ±9.65 | 39.73 ±12.89 | 41.72 ±7.45 | 30.17 ±7.89 | 22.18 ±10.24 |
| | 20 | 5.78 ±14.89 | 1.75 ±3.89 | 1.65 ±1.34 | 2.78 ±5.34 | 18.57 ±10.09 | 26.18 ±9.87 | 36.17 ±8.89 | 41.71 ±7.23 | 57.45 ±19.01 | 56.64 ±8.55 | 28.19 ±10.04 | 20.67 ±14.17 |
| PRP 10 BGM (mm) | 1 | 80.17 ±14.69 | 79.58 ±26.47 | 84.42 ±17.87 | 35.14 ±11.60 | 36.92 ±18.60 | 27.42 ±20.20 | 27.08 ±21.36 | 20.00 ±14.38 | 17.00 ±19.79 | 26.25 ±25.23 | 36.27 ±21.71 | 46.45 ±14.78 |
| | 10 | 87.33 ±34.41 | 76.25 ±18.30 | 68.00 ±25.50 | 30.87 ±17.74 | 32.13 ±15.03 | 29.08 ±27.04 | 11.83 ±10.88 | 17.42 ±16.05 | 14.08 ±17.28 | 28.92 ±36.26 | 43.36 ±23.14 | 86.82 ±14.78 |
| | 20 | 96.83 ±25.93 | 82.75 ±23.85 | 69.12 ±19.50 | 20.00 ±25.96 | 19.20 ±10.96 | 25.92 ±19.14 | 11.50 ±8.39 | 8.75 ±11.98 | 8.33 ±12.49 | 22.92 ±19.44 | 55.82 ±36.33 | 71.82 ±14.78 |

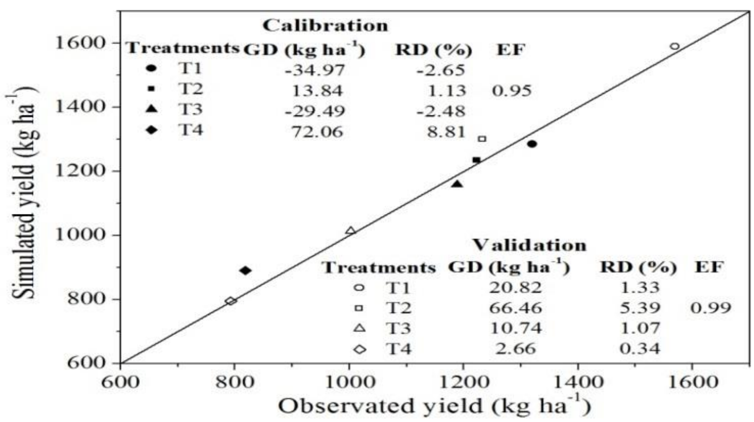


**Fig 2.** Comparison between the observed and simulated values of cowpea yield during the validation and calibration stage in different treatments adopted.

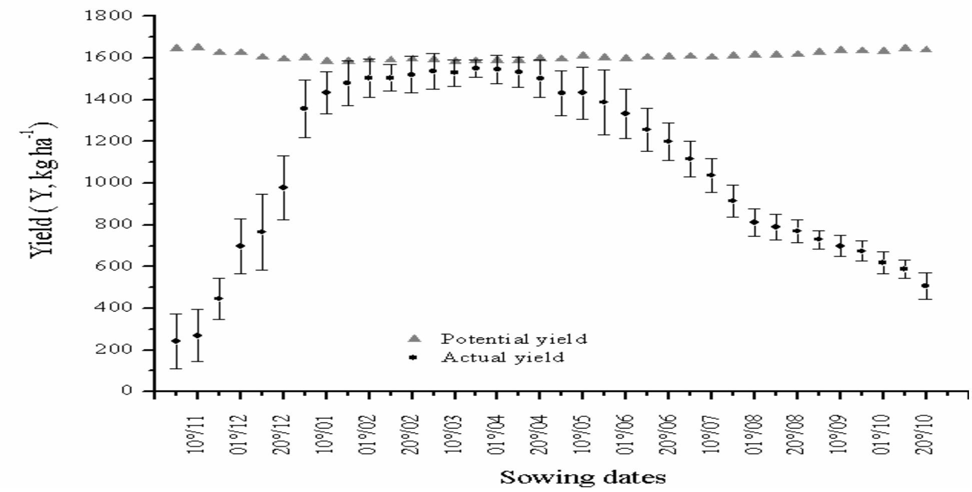


**Fig 3.** Cowpeas yield (Y) simulated by the AquaCrop model for two conditions, potential (PY) and actual (AY).

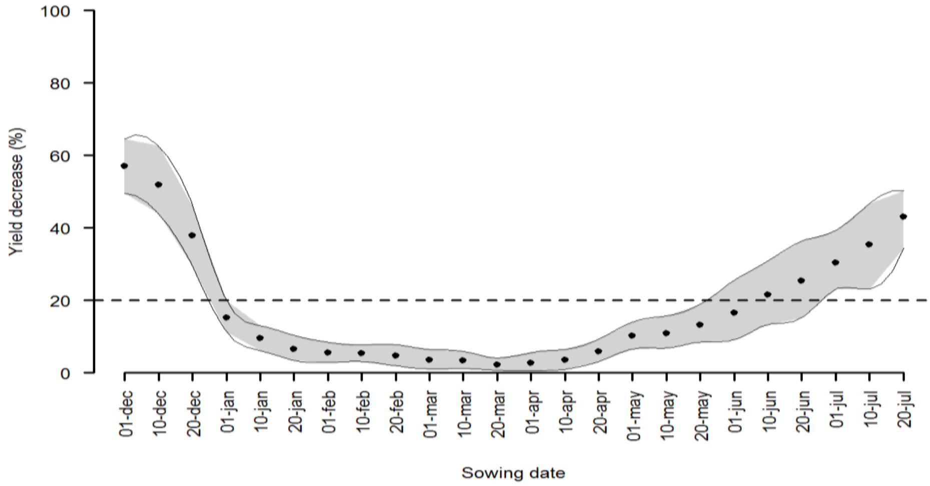


**Fig 4.** Yield decrease (YD) by sowing date, associated to a 95% confidence interval calculated by the bootstrap technique.

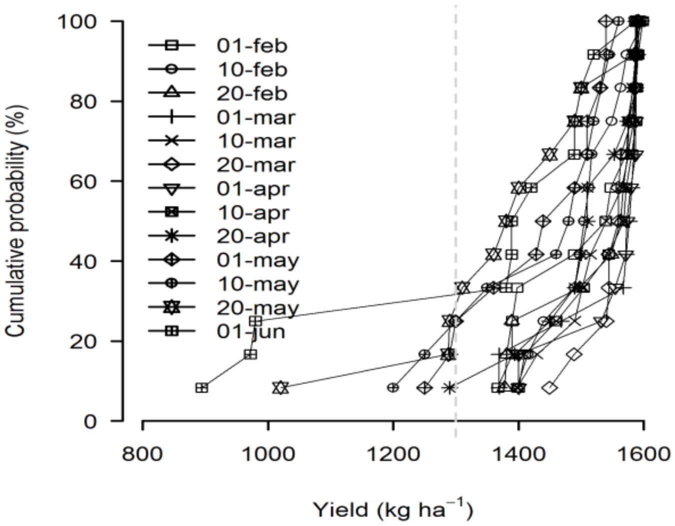


**Fig 5.** Probability of yield (kg ha$^{-1}$) for sowing dates that presented YD < 20 % (from February 1st to June 1st). The dashed line is the yield of 1300 kg ha$^{-1}$.

In general, the model showed good efficiency (EF) in the simulation of yield (Y) for cowpea, in both steps and for all treatments adopted (Fig. 2). During 2013 (calibration), the EF value was 0.95, due to the overestimation of yield in the T4 treatment (RD = 8.81 %). However, during validation (2014), the model was more efficient (EF = 0.99) in the simulation of Y, due to the low differences (RD of 0.34 to 5.39 %) between observed and simulated values. These results showed that AquaCrop model demonstrates a good efficiency for predicting the cowpea yield in the region.

Similar results were obtained in a study with a more complex model and it reinforces that AquaCrop model can be used in the region to predict yields and to proper management of cowpea to obtain high yields. Oliveira et al. (2012) used the CROPGRO-Dry model for three bean cultivars in Viçosa, state of Minas Gerais, and they obtained concordance between the simulated and observed values, varying from 0.88 to 0.99, during the calibration and validation steps, respectively.

### *Yield prediction of cowpea*

The simulated potential yield (PY) of cowpea showed a small variation (1584 to 1651 kg ha$^{-1}$). It presented the highest values for sowing occurred between September 1st and November 10th (Fig. 3). On the other hand, the actual simulated yield (AY) presented greater variation, from 242 to 1590 kg ha$^{-1}$, due to PRP variation throughout the year.

The results evidenced a good period for sowing cowpea in Castanhal with an optimal sowing window (OSW) between January 10th and May 20th, when a decrease in the standard deviations of actual yield (AY) is observed which approximates of the average potential yield (PY) (1610 kg ha$^{-1}$).

During a OSW, the cowpea presented high yields (AY > 1300 kg ha$^{-1}$), above the average yield in the state (788 kg ha$^{-1}$) (Ruas, 2017), while the sowing outside OSW showed large variations of AY (242 to 1357 kg ha$^{-1}$), due to the lack of PRP in this period, causing water deficit during vegetative phase of cowpea (> 14.12 mm ± 13.07) (Table 2).

The water deficit during this phase causes a reduction in the development rate of the canopy that intercepts less SR, which reduces its stomatal conductance, reducing its capacity to perform photosynthesis and accumulate biomass, consequently, that means, it produces a negative effect on the crop development affecting directly in the final yield (Fernandes et al., 2015; Souza et al., 2017).

The yield simulations results demonstrate that PRP represents the true limiting factor for its production in the study region. This fact has been evidenced several times in studies in the north (Farias et al., 2017; Souza et al., 2017), northeast (Lima Filho et al., 2013; Fernandes et al., 2015) and midwest (Oliveira et al., 2012) which lead to the climatic risks of agricultural production in Brazil.

### *Yield decrease and climate risk analysis*

The relationship between AY and PY, also called average yield decrease (YD, %) with an acceptable value of 20 % of PY (Lima Filho et al., 2013), was also analyzed in Castanhal. The YD was lower than 18 % (PY loss of 290 kg ha$^{-1}$) over the period from January 1st to June 1st, in more than 95 % of the simulations (Fig. 4). There was an increase in YD for previous and later sowing. For example, in the sowing of July 20th, the value reached 45 % (loss of 724 kg ha$^{-1}$ of PY) and on December 1st, the value reached 58 % of YD (loss of 934 kg ha$^{-1}$ of PY), which are high in response to the water deficit occurred during the vegetative and/or reproductive phase.

The dates after the graphs were not analyzed, because as the dry period of the region begins, the YD is quite high, since there is no way to establish the cowpea (Table 2) and produce high yields due to lack of water in this period, as observed by Lima Filho et al. (2013) and by Souza et al. (2017).

The AquaCrop model was sensitive to the environmental variations of Castanhal, even in the YD < 20 % period (January 1st to June 1st) there was a great variation in the probability of reaching high yields of the cowpea (Y > 1300 kg ha$^{-1}$) (Fig. 5). In the sowing that occurred between February 1st and April 10th, there was 100 % of probability of obtaining high yields. In simulations starting on April 20th, there was a probability of over 90 %, and for later dates, since May 1st, high yields are obtained with only 75 % of probability, according to the simulations of the model.

Studies have shown that the PRP occurrence during grain harvest favors the appearance of fungal diseases, and depending on the period of these rains, it increases the severity of diseases, which can decrease the final yield and its quality (Lima Filho et al., 2013; Castro et al., 2016). Thus, the sowing of January was not considered, once the harvest of its crop coincided with the rainy season of Castanhal (Table 2), with the wettest month (March) and it is worth noting that the model does not perform this type of analysis.

Thus, the results show that the period from April 1st to 20th would be the most recommended for cowpea cultivation in Castanhal, once it had a low YD (YD < 10 %), high probabilities (90 % above 1300 kg ha$^{-1}$) to reach high yields and lower PRP possibilities during harvesting.

This study confirms the efficiency of models use, such as the study of Lima Filho et al. (2013) which evaluated the YD of cowpea with CROPGRO in the municipality of Cruz das Almas, without the use of probabilities in their analysis. They identified that the best season for sowing in Bahia was from middle to end of the rainy season, to avoid the PRP in the BRS Guariba crop. Freire Filho et al. (2011) indicate for the Brazilian Northeast and for varieties of cowpea, which have a cycle of 71 to 90 days that the sowing should be done from the middle of the rainy season of each region avoiding the harvest during rainy periods, because it would increase the probability of grains rotting.

This demonstrates that AquaCrop model can be used as yield prediction tool. In addition, it may be used in other crops as long as it has information about soil, climate and culture to be simulated. However, the model potentiality is only achieved if it is used correctly, understanding its operation, limitations and possibilities.

## Materials and methods

### *Experimental site and culture management*

The field experiment was conducted in an area of 2.5 ha within the school farm of the Federal Rural University of Amazonia (UFRA) (01.32° S, 47.96° W, 41 m of altitude), in the municipality of Castanhal, during the years of 2013 and 2014. The soil in the area is dystrophic yellow oxisol (Lima et al., 2016) and its textures physical (undisturbed sample) and chemical characteristics (deformed sample) were obtained through samples collected in the area before planting.

During the experiments, an automatic meteorological station was installed to monitor some variables in the field, such as the volumetric content of water in the soil (VCW, $cm^3$ $cm^{-3}$), the temperature (Tavg, °C), the air relative humidity (RH, %), the solar radiation (SR, MJ $m^{-2}$ $dia^{-1}$), the precipitation (PRP, mm), etc. The averages were recorded and stored every 10 minutes by a CR10X model datalogger (Campbell Scientific Inc.). In addition, data from a climatic series from 2003 to 2014 were used in model simulations of yields. The data were collected in an automatic station located in the municipality of Castanhal and approximately 3 km from the study area, belonging to the National Institute of Meteorology (INMET).

The BR3-Tracuateua cultivar was used which has a cycle of 60 to 70 days, because it has tolerance to high temperatures and water deficit, being the most recommended and used by the productive regions of the state (Freire Filho et al., 2009). The seeding occurred mechanically with a distance of 0.50 m between the lines and an average of 10 plants in a linear meter, totaling 200,000 plants per hectare and it was carried out on October 1 and September 9 in the years of 2013 and 2014, respectively at the year of ending financial support for the experiment.

The analyses were carried out by the soil analysis laboratory of the Brazilian Agricultural Research Company (EMBRAPA), which indicates a sandy loam texture composed by 73% of sand, 14% of silt and 13% of clay (Ramos et al., 2016). Fertilization was also suggested by the same laboratory for cowpea cultivation, which was divided and carried out before and 30 days after sowing (DAS), during the first year, 0-60-45 kg $ha^{-1}$ of NPK and 0-40-45 kg $ha^{-1}$ of NPK or the second year.

***Experimental design and treatments***

The experimental design was a randomized block design with 6 replicates and 4 treatments, in order to submit the cowpea to different levels of water availability. These treatments consisted in the daily application of irrigation (drip irrigation) slides computed from crop evapotranspiration ($ET_C$) during reproductive phase of cowpea, since this phase is considered the most sensitive to water deficit (Carvalho et al., 2014; Souza et al., 2017). In the treatment 1 (T1), 100 % of the water lost by $ET_C$ was replaced, the treatment 2 (T2) restored 50 % of $ET_C$, the treatment 3 (T3) restored 25 % of $ET_C$ and the treatment 4 (T4, control) there was no replenishment through irrigation, as it is used by farmers in the region.

During the vegetative phase, all treatments received the same amount of water (100 % of $ET_C$'s replacement) in order to keep them in the field capacity (FC). The calculation of $ET_C$ (mm $dia^{-1}$) was performed using the following expression:

$$\mathrm{ET_C} = (\mathrm{Kc} \times \mathrm{ET_0}) \qquad (1)$$

Where, $ET_0$ is the reference evapotranspiration (mm $dia^{-1}$), estimated by the Penman Montheith method and Kc (dimensionless) is the crop coefficient suggested by Bastos (Farias et al., 2017).

The watering shift was daily in 2013 and every two days in 2014, maintaining the treatments in the FC (0.22 $cm^3$ $cm^{-3}$) to guarantee the loss of water only by ETC and also that the analyzes occurred due to the decrease of this replacement and not for the deficit of several days.

The net water depth or Irrigation depths (I, mm), applied in the different treatments, were calculated by the ratio between the gross depth (IB, mm) and the application efficiency (Ea, decimal) of the irrigation system. Further details on the experiment can be found in Farias et al. (2017).

***Crop data***

The crop development was daily monitored, from its emergence until the end of the cowpea cycle. In order to do it, the scale of Gepts and Fernández (Souza et al., 2017) was used, in which 10 plants were observed in a line of 1 meter, exclusively for this monitoring. The growth measures were collected from the 15th and 9th DAS in 2013 and 2014, respectively and on a weekly scale, by selecting two 20-meter lines in each treatment. Five plants were taken by each treatment (0.5 m linear), considering the experimental design adopted for each block (6 repetitions). Their organs were separated into samples of stem, petiole, leaf, discs, peduncle, flower, pod and grain (when present).

The yield was carried out when 90% of the plants were in stage R9 (66th and 63rd DAS, in 2013 and 2014, respectively). Three linear lines of 2 meters were selected, exclusively for yield analysis in each treatment. Thereby, the edges of the treatments were not considered in any analysis. Thus, any border effects were avoided. Grains and pods were collected and counted. All these samples were weighed with a precision scale (0.001 g) to obtain the fresh weight of each sample and weight of 1000 grains (when they existed). Then, they were taken to aerated greenhouses at 70 °C until constant dry weight (72 hours) of the total dry matter (MSt) (Biomass above the soil, t ha-1), and then again weighed.

The leaf area index (LAI, $cm^2$ $cm^{-2}$) was determined by the disc method, in which three leaf discs of 0.01 m radius were removed in each plant, for this calculation, through leaf dry matter samples (MSf ) (Farias et al., 2017).

***Statistical analysis***

Statistical analyzes were carried out using the Assistat software, version 7.7. Firstly, the *Kolmogorov-Smirnov* normality test was applied, in order to verify if the data of the dependent variables, yield, and biomass, follow a normal distribution at the significance level of 5 % (α) (Silva and Azevedo, 2016).

The biomass data of 2014 did not present a normal distribution. Thus a transformation in the data was performed through the Box-Cox tool, which suggests the best equation for it (λ = - 0.33, suggested equation), guaranteeing the normality required for further analysis. Therefore, the inverse transformation was carried out = 0.33 / B value for this transformation. On the other hand, the B and Y data values presented a normal distribution according to the results from the variance analysis. Then, their transformation was not necessary.

After that, Tukey's test was applied at a level of $p < 0.05$ for each year, aiming to demonstrate that the water deficit during the reproductive phase of cowpea influences the loss of biomass and yield in the region.

***AquaCrop model***

The AquaCrop model was developed by the FAO (Land and Water Division) in 2009, including a version called AquaCrop-GIS which can be integrated with ArcGIS software (Raes et al., 2017), and more recently an open source version (Foster et al., 2017). This study used the 5.0 version that was designed to offer a balance between simplicity and robustness, presenting great precision in its output results relating to water uses by the culture (Steduto et al., 2012). The model considers the water effects on incomes of diverse cultures incorporated to the application through its modules and the user can insert new cultures by the essential parameters for their simulation (Raes et al., 2015).
The AquaCrop uses a relatively small number of crop parameters when compared to other models, which makes it widely used in researches that aims to understand the effects of water deficit on crop yield and biomass production (Tavakoli et al., 2015). It also allows the best use of water management to obtain a gain in the yield and management of water resources used in agriculture (Paredes et al., 2014).
The model simulates crop yield (Y, kg $ha^{-1}$) and biomass production (B, t $ha^{-1}$) as a function of canopy cover (CC, %) differently from other models that used LAI. In this study, the CC was obtained by LAI's derivation from an exponential function of temporal degradation of the crop that is given by the extinction coefficient of the canopy (α, dimensionless), according to details described by Paredes and Torres (2016).
The model inputs consisted of daily climatic data of series from 2003 to 2014, coming from an automatic meteorological station; from the average annual $CO_2$ concentration in the atmosphere, of the model itself; the soil data from soil analysis of the experimental area; the culture data that were obtained during the experiments; and the irrigation data from the daily liquid blades used in the treatments.
The generation of irrigation schedule was based on time criteria used in the experiments (fixed range, permissible depletion expressed in mm or % of readily available water (RAW)) and depth criteria (refilling at field capacity (FC) or using a fixed net application expressed in mm or % of RAW). Raes et al. (2015) described more details about the information required by the model.

***Calibration and validation***

To calibrate and validate the model was used yield data of cowpea in two harvests (2013 and 2014). During the calibration (2013) the model parameters were adjusted until the responses approached the observed values. In the validation (2014) the results obtained were compared using as statistic criteria the Nash and Sultcliffe efficiency of the model, the gross (GD) and relative (RD) difference, this last expressed as percentage:

$$\mathrm{GD} = (\mathrm{Pi} - \mathrm{Oi}) \quad (2)$$

$$\mathrm{RD} = \frac{(\mathrm{Pi} - \mathrm{Oi})}{\mathrm{Oi}} \quad (3)$$

Where, Pi is the simulated yield (kg $ha^{-1}$) by the model and Oi is the observed yield (kg $ha^{-1}$) (Paredes and Torres, 2016).

***Yield prediction by model and yield decrease***

After the model validation, the simulations of cowpea yield were performed through its seasonal module, scheduling 36 sowing dates performed on the 1st, 10th and 20th day of each month, beginning in November and ending in October for each of the 12 years (2003-2014) inserted, totaling 432 performance simulations. All the practices adopted were related to those used by producers of the region and the area studied, such as cultivar, spacing, fertilization, and irrigation system.
Two scenarios were adopted: (1) Potential scenario, where the automatic irrigation function of the model was activated, when RAW dropped by 60 %; and (2) Actual scenario, where the irrigation function was deactivated, leaving the crop subject to pluvial availability conditions (Oliveira et al., 2012).
Thus, the yield decrease (YD, %) of cowpea was obtained by:

$$\mathrm{YD} = \left[1 - \left(\frac{\mathrm{AY}}{\mathrm{PY}}\right)\right] \times 100 \quad (4)$$

Where AY is the simulated actual yield (kg $ha^{-1}$) and PY is the simulated potential yield (kg $ha^{-1}$) (Lima Filho et al., 2013). In addition, the 95 % confidence interval was calculated by resampling, using the bootstrap in R software. In this analysis, the software is programmed to generate 1000 resampling with replacement, constructing an empirical distribution and determining 2.5 % and 97.5 % percentiles used to obtain the band with 95 % probability of occurrence of the value, more details in Efron and Tibshirani (1993).
The normal soil water balance (Thornthwaite and Mather method) suggested by Pereira (2005), was used to aid in supplementary irrigation strategies, in sowing window choice, in the water use by the crop in the studied area, and in the calculation of the balance components (DEF (Deficiency, mm), AWC (Available Water Content, 45 mm), Str (Storage, mm)) analyzed in this study, similar to the work of Souza et al. (2017).

**Conclusion**

The AquaCrop model can be used to simulate the yield of cowpea in the region, once it showed sensitivity to the management conditions and the precipitation variability from the municipality of Castanhal in the state of Pará. The yield forecasts are reliable, due to the high-efficiency values attributed during their validation, which contributes to the predictability of the model. This was even stronger when compared to the results of other models already tested with this methodology.
The model is also able to aid in future studies in the agility to produce information that is determinant in management practices, decision-making, and water use by cowpea culture, aiming to improve the yield in the region. The model has great potential for its use in the state of Pará and for other cultures.

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