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CANOPY TEMPERATURES AND ACCUMULATED DEGREE DAYS ON COTTON PLANTS UNDER WATER DEFICIT

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1 ABSTRACT

Canopy temperature is one of the best integrators of plant health and has been successfully used for irrigation scheduling. Therefore, the objective of this study was to evaluate the canopy temperature of cotton plants under water stress at different stages of the crop cycle and to determine the accumulated degree days based on canopy temperature. It was applied water deficit periods of 15 days at the following phenological stages: First Square, First Flower, Peak Bloom and Opening Bolls and control treatment. Canopy temperature was obtained using SmartCrop® wireless infrared temperature sensors. The results showed higher canopy temperatures during water deficit periods. For water deficit periods, canopy temperature values were always above the optimum temperature for cotton metabolism. As a result of the stress caused by water deficit, cotton yield was significantly reduced, with the higher yield loses recorded when applied deficit occurred during flowering stages (beginning and peak). Accumulated degree days also varied according to water stress, with a shortened phenological cycle for treatments with water deficit in comparison to the control without stress. The period for fiber thickening was also influenced by the variation in canopy temperature due to water stress, which may reflect decline in fiber quality.

Keywords: Irrigation; Phenological cycle; Stress; Environmental conditions; Infrared thermometry.

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2 RESUMO

A temperatura do dossel é um dos melhores assimiladores da saúde das plantas e tem sido usada com sucesso para manejo da irrigação. O objetivo deste estudo foi avaliar a temperatura do dossel do algodoeiro sob déficit hídrico em diferentes estágios fenológicos e determinar os graus dia acumulados a partir da temperatura do dossel. Foram aplicados períodos de déficit hídrico de 15 dias nos seguintes estádios fenológicos: Botão floral, Início do florescimento, Pico do florescimento e Abertura do Capulhos, além da testemunha. A temperatura do dossel foi obtida usando sensores sem fio de temperatura infravermelho SmartCrop®. Os resultados mostraram maiores temperaturas do dossel durante o déficit hídrico, quando comparados a testemunha. Para os períodos de déficit hídrico a temperatura do dossel esteve sempre acima da temperatura ótima para o metabolismo do algodoeiro. Devido ao déficit hídrico, a produtividade do algodoeiro foi significantemente reduzida, com os piores resultados para o déficit durante o florescimento (início e pico). Os graus dia acumulados variaram em função do estresse hídrico, com as plantas completando seu ciclo mais precocemente. O período de espessamento das fibras foi influenciado pela variação na temperatura do dossel devido ao estresse hídrico, podendo refletir em declínio da qualidade da fibra.

Palavras-chave: Irrigação, Ciclo fenológico, Estresse, Condições ambientais, Termometria por infravermelho.

3 INTRODUCTION

Canopy temperature is one of the best integrators of plant health and a direct measure of the energy being released by the plant. Therefore, continuously monitoring canopy temperature using infrared wireless sensors can provide real-time information on crop water status, water use and metabolic functions.

Bockhold et al. (2011) found that canopy temperature can be used to quantify the water stress of plants, since plants in non-stressed conditions efficiently transpire maintaining plant's temperature within internal optimum ranges. Stomatic closure in a stressed plant will suppress transpiration, thus raising leaf temperature (LARCHER, 2000). According to Amani; Fischer and Reynolds (1996), for a given genotype, canopy temperature is a function of several environmental factors, mainly plant water status, air temperature, relative humidity and solar radiation. Canopy temperature can also provide a more reliable measurement of the accumulation of thermal units, or accumulated degree days (ADD), which is another important parameter to be evaluated, because crop development is a reflection of the environmental factors during the growing season, and yield is the accumulated result of plant metabolism throughout the season. Therefore, weather conditions are determinant to crop yield since the temperature progression from planting until harvest is the major driver of crop growth and development (MAHAN et al., 2014).

Continuous canopy temperature monitoring is a reliable way to determine ADD in cotton, especially under water stress conditions, because air temperature does not reflect the plant physiological and metabolic changes, such as stomatal closure and lower transpiration (REDDALL et al., 2007; MAHAN et al., 2014). Peng; Krieg and Hicks (1989) reported that the use of ADD for cotton were more reliable when working under adequate water availability conditions.

This factor could be corrected by working with the canopy temperature instead of the air temperature for the ADD values. Kimball et al. (2012) concluded that the calculation of cumulative degree days for wheat cultivation based on canopy temperature was useful in assessing the effects of the ambient temperature variation, and that it improved the data when compared to irrigated and rainfed treatments. Thus, the objective of this work was to evaluate the use of canopy temperature for water stress assessment in different stages of cotton crop cycle, calculating accumulated degree days under the same conditions.

4 MATERIAL AND METHODS

4.1 Location

The experiment was conducted from June to November of 2016, at the Experimental station of EMPARN - Agricultural Research Company of Rio Grande do Norte state, located in Apodi town, with central coordinates: 5º 37' 19"S and 37º 49' 06"W and altitude of 132 m.

The climate of the region is characterized as semi-arid and hot tropical, with predominance of BSw'h' type, according to Köppen's climatic classification. The rainy season is in the summer (late December until April). Soil of experimental area was classified as eutrophic Cambisols (EMBRAPA, 2013), and the texture is sandy-clay, with 49% of sand, 45% of clay and 6% of silt. Fertilization was conducted based on a soil fertility analysis and it was performed according to technical recommendations for cotton (Table 1).

Table 1. Soil chemical characteristics of experimental area in Apodi, RN, at 0-40 cm depth.

Year	pH water	OM ($g\ kg^{-1}$)	P ($mg\ kg^{-1}$)	Na^+	K^+	Ca^{2+}	Mg^{2+} ($cmol_c\ dm^{-3}$)	H + Al	CEC	BS
2014	6.20	16.4	10.7	0.4	1.6	34.8	10.0	23.1	69.9	46.8

4.2 Cotton cultivar and agronomic data

Cotton BRS 368RF cultivar, genetically modified with resistance to glyphosate herbicide was used for this study. The study was carried out under no-tillage system (NTS) and without cotton thinning practices. A mechanized seeder with three lines was used for planting. For weeds, diseases and insect pest control, phytosanitary treatments were carried out when the first symptoms appeared but consistently across all treatments. Agronomic and irrigation data are presented in Table 2.

Table 2. Agronomic data and irrigation parameters during the cotton cycle

Variables	
Planting date	06/07/2016
Row spacing	0.8 m
Plant density	8 -12 plants m^{-1}
Fertilization at planting	150 kg ha^{-1} of P_2O_5 and 30 kg of N (MAP* form)*
Top dressing	150 kg of N ha^{-1}(Urea)
Last irrigation	28/10/2016 (105 DAE)
Harvest date	21/11/2016
Crop cycle period	127 days
Total rainfall during the growing cycle	0.0 mm

* MAP – Monoammonium Phosphate

4.3 Treatments and Experimental Design

A randomized complete block design with four replications was used for this study. Each experimental plot consisted of four 6.0-m rows spaced at 0.8 m between rows. Each plot of 4.8 m^2, had as useful area the 2 central rows, excluding 1.0 m from each border.

Treatments consisted of four periods of water deficit including First Square (FS), First Flower (FL), Peak Bloom (PB), Opening Bolls (OB) and control treatment without water deficit (ETc). Water replacement based on crop evapotranspiration was determined using Penman-Monteith FAO 56 method, with equation (1):

$$D_{gross} = ETc/Af \qquad (1)$$

where:
D_{gross}– Gross irrigation depth, mm
ETc – Crop evapotranspiration, mm
Af – Application efficiency, decimal

The crop evapotranspiration (ETc) is given in Equation 2:

$$ETc = ET_0 \times Kc \qquad (2)$$

where:
ET_0 - Reference Evapotranspiration based on Penman-Monteith methodology (ALLEN et al., 1998)
Kc - Crop coefficient for cotton, estimated by the number of days after emergence (BEZERRA et al., 2010).

$$Kc = -0{,}00006.DAE^2 + 0{,}011.DAE + 0.5703 \qquad (3)$$

where:
DAE - Days after emergence

A fixed conventional sprinkler system with 12 x 15 m spacing was used to perform irrigations, with application intensity of 9 mm h^{-1} for Christiansen uniformity coefficient (CUC) and irrigation efficiency (considering wind and losses by evaporation) equal to 85 and 63%, respectively. Irrigations were carried out every three days, depending on the soil water storage capacity, in order to keep the available soil water content above 40%.

Treatments with water deficit consisted of 15 days period without irrigation in the predetermined stage (Table 3). After this period, plants were irrigated normally, according to ETc model.

Table 3. Water deficit period in each treatment.

Treatment	Start of water suppression	Period of Water deficit (DAE)	Irrigation Depth (mm)
First Square (FS)	Beginning with the first flower bud in at least 10% of the plants	35 – 51	673
First Flower (FL)	Opening of first flower in at least 10% of the plants	52 – 63	675
Peak Bloom (PB)	Boll loading. At least 10% of plants heavily fruited where first bolls were completely full	64 – 80	632
Opening Boll (OB)*	Opening of bolls in at least 10% of the plants	From 90	718
Control (full ETc)	Without deficit irrigation during all crop cycle.		780

* This treatment did not receive further irrigations, because it has happened just before removal of irrigation. DAE: Days after emergence

4.4 Canopy Temperature and Accumulated Degree Days

Canopy temperature was monitored throughout the growing season using wireless infrared thermometers (IRT) Smartcrop® System (Smartfield Inc., Lubbock, Texas, USA, http://www.smartfield.com/). The SmartCrop® system was previously described by Mahan and Yeater (2008) and Mahan et al. (2010). The SmartCrop® system uses a combination of wireless IRT sensors installed in the field, and a remote base station installed on the edge of the field for continuous data collection. One SmartCrop® sensor was installed in each plot, positioned 20 cm above the crop canopy, with a viewing angle of approximately 60 °. Sensors height was adjusted weekly following plant growth to maintain the pattern of measurements taken at 20 cm above the canopy.

Each SmartCrop® sensor has a field of view of a 1:1 ratio, thus allowing an area observation of 20 cm diameter based on the 20 cm height above the canopy. Data were collected with intervals of 1 minute, and an average was calculated every 15 minutes. After that, data were sent every hour via mobile data link for storage and subsequent analysis. Canopy temperature collection started at 46 DAE. Measuring plant canopy temperature earlier and on smaller plants, would have caused exposed soil to interfere in the reliability of the data.

Accumulated degree days (ADD) were calculated both by the average canopy temperature and by the average air temperature, measured at 2 m above canopy by the SmartCrop® base station. A base temperature of 15.6 °C was used for ADD calculations, as it is considered the lowest temperature for cotton growth (REBA; TEAGUE; VORIES, 2014). The ADD values were calculated with equation 4:

$$GDA = \sum (T_a - 15{,}6°C) \quad (4)$$

where:
Ta –Average Temperature, °C;

4.5 Harvest

Cotton harvest was performed manually and yields calculated on a per plot basis.

4.6 Data Analysis

All data were subjected to Analysis of Variance (ANOVA) analysis and Tukey mean treatment separation at $p \leq 0.01$ and $p \leq 0.05$ by Sisvar 5.3 software (FERREIRA, 2011).

5 RESULTS AND DISCUSSION

5.1 Canopy Temperature

Canopy temperature increased in treatments with water stress (Table 4). This is consistent with previous published reports and it is believed to be of the result of stomata closure and, therefore, a decrease of plant transpiration. According to Keener and Kircher (1983), when leaf water availability is reduced, transpiration decreases and the plant loses its ability to cool its tissues.

The average canopy temperature during the evaluation period (46 to 108 DAE), even for treatments subjected to water stress, were within the optimum range for cotton physiological functions and biochemical characteristics, which is 28°C, according to Wanjura; Upchurch and Mahan (1995) and Mahan et al. (2005). Bockhold et al. (2011) found similar values, equal to 28.5°C for well-irrigated cotton, which did not differ from water stress treatments. However, Mahan et al. (2014) found values of 23.1°C for the well-irrigated cotton and 25.7°C for rainfed cotton under water stress.

There are two reasons for these results. The first one is that only 15 days of water stress into the entire evaluated period for canopy average temperature was so short, attenuating their effects. The second and probably predominant factor is that these average values took into account the night temperature, which is less sensitive to water stress (MAHAN; YOUNG; PAYTON, 2012).

Thus, in order to thoroughly evaluate the results, nocturnal temperature data were excluded, and the canopy average temperature was calculated just for the daytime period (6 am to 6 pm) (Table 4).

Table 4. Cotton canopy temperature and yield for four water deficit treatments from 46 to 108 DAE.

	Treatment	Canopy Average Temperature (°C)	Diurnal Average Temperature (°C)	Cotton Yield (kg ha^{-1})
	Control Full ETc	26.9a	29.9a	6281a
Water Deficit (15 days)	First Square (FS)	28.2b	31.2ab	3768b
	First Flower (FL)	28.3b	32.2ab	1668b
	Peak Bloom (PB)	28.1b	31.8b	2250b
	Opening Bolls (OB)	27.8ab	30.2ab	6087a

* Averages followed by the same lowercase letter in the column do not differ among themselves by the Tukey test at 5% of probability.

The control (ETc) presented the lowest canopy temperature during the daytime period, (29.9°C) and close to the reported physiological optimum of ~28°C (BURKE; MAHAN; HATWELD, 1988). On the other hand, average temperature was above 30°C for treatments with water stress in some stage of the phenological cycle. The highest average canopy temperature was observed when water deficit started at the beginning of flowering period (32.2°C), and it was well above the optimum temperature to control transpiration on cotton leaves (BURKE; MAHAN; HATWELD, 1988). These results are in agreement to those previously found by Pettigrew (2004). First Flower treatment also had the lowest yield and 73% lower than the control (ETc) (Table 4).

According to Pinto et al. (2010) and Gutierrez et al. (2010), environmental conditions of water stress showed negative correlation between canopy temperature and yield.

Figure 1. Diurnal average temperature of canopy at 46 DAE for each treatment with water deficit. Stress is indicated when temperatures exceed 32°C.

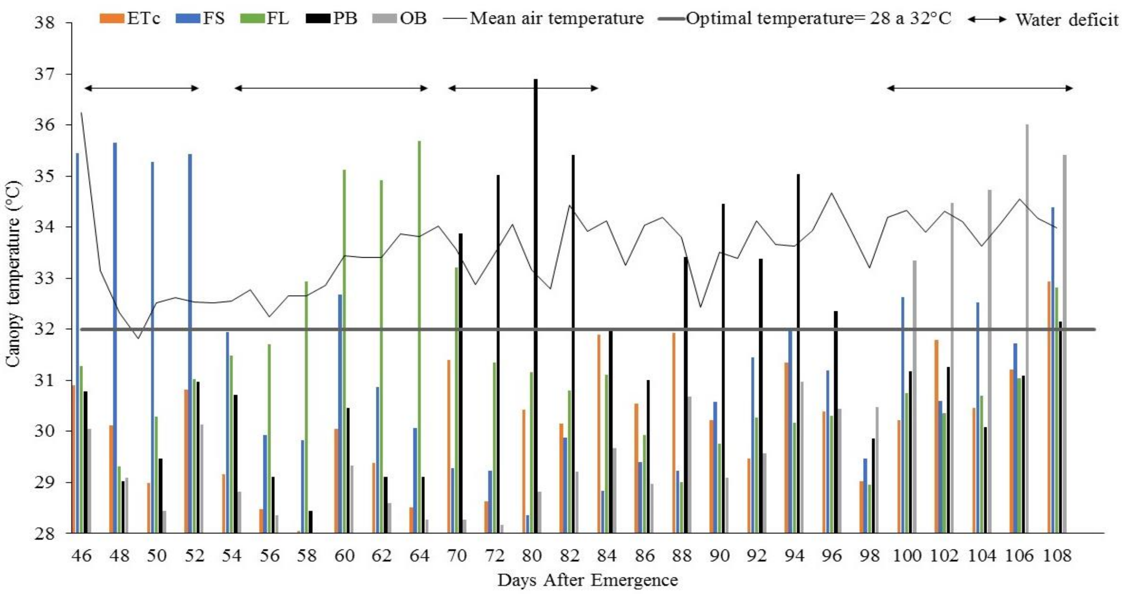


Figure 1 shows the variation of the diurnal average canopy temperature and diurnal air temperature, where we can observe the moments in which the plants were under water stress, represented by the canopy temperature above 32°C, which is the upper acceptable range for growth. During the water stress period, canopy temperature for each treatment reached values around 35°C, well above the upper range of optimum temperature for cotton metabolism and an indicator of plant stress. Wiggins et al. (2014) found average values of daytime canopy temperature equal to 32.6°C and 30.0°C for water-stressed and well-irrigated cotton, respectively, corroborating the values obtained in the present study.

There were significant differences in cotton yield among treatments (Table 4), with the greatest losses on yield due to water deficit resulting during the flowering stages. The high sensitivity of cotton during flowers development is because, even with moderate increases in temperatures above 32°C, numerous processes such as pollen development and fertilization are inhibited (SNIDER et al., 2011). Thus, considering that the success of fertilization is a basic requirement for seed production, small increases in temperature above the optimum can decline cotton yield as a result of the limitations in the amount of fiber per seed (PETTIGREW, 2008).

In comparison, the control (i.e., full ETc treatment), which was well irrigated throughout the cotton cycle, did not record canopy temperatures above 32°C during the evaluation period, demonstrating that the plant was being supplied with enough water to avoid significant stress and yield loss.

Once normal irrigation resumed, canopy temperature for the different treatments stayed within the optimum temperature range. However, canopy temperature for those treatments with water deficit during the stages of fruit filling (i.e., PB and OB), were still higher than the optimum canopy temperature upper range. This was also visually corroborated by the defoliation that occurred in this treatment due to the water stress.

Comparing both canopy and air temperatures, it was observed that canopy temperatures for well-irrigated control treatment (ETc) were always below those of the air temperature, while for treatments with water deficit, canopy temperatures were above the air temperature, but just for the period where plants were under water stress. Canopy temperature for the well-irrigated control treatment (ETc) was in average 3.5 °C lower than that of the air temperature. Burke and Upchurch (1989) found that cotton plants cool their leaves up to 10°C below air temperature by the use of transpiration, whereas Nobel et al. (1999) reported reductions up to 6°C.

Figure 1 and Table 5 show average values of the daytime canopy temperature during the stress period. It is observed that in all water stress periods, independently of the phenological stage, daytime canopy temperature was 5.8; 4.0; 3.7 and 2.6 °C higher than the canopy temperature of the well-irrigated control for FS, FL, PB and OB treatments, respectively.

After the start of opening bolls (OB treatment), despite an increase in canopy temperature above the optimum canopy temperature and also above the upper range limit value of 32°C, plants did not suffer a significant loss in yield compared to the control treatment (Table 4). These results demonstrate that at this stage of development, irrigation could probably be shortened or terminated, and accounted for a total of 62 mm of water savings when compared to the control (Table 2).

The value of canopy temperature is once again confirmed and demonstrated as a simple way to schedule irrigation in cotton, especially for automation of irrigation systems within a precision agriculture setting, as cited by Evett et al. (2002), Sadler et al. (2002) and Peters and

Evet (2008). In addition, canopy temperature provides direct information of the plant's water status, compared to other technologies that offer indirect measures of plant stress such as soil moisture and/or meteorological data. Additionally, the continuous measurement of canopy temperature (i.e, every 15 minutes), provides an excellent resolution of crop condition during all physiological stages of development (MAHAN; YOUNG; PAYTON, 2012).

From a research perspective, this tool can also be very useful for selection of water stress resistant cultivars in plant breeding programs, facilitating the screening in field conditions of a large number of cultivars quickly and accurately. Mason and Singh (2014) reported that canopy temperature is a useful tool for the phenotypic selection of water stress tolerant genotypes because it integrates many physiological responses with a simple low cost and fast measurement.

Table 5. Daytime average canopy temperature during the water deficit period.

Treatment	Period of water deficit (Days After Emergence)	Daytime canopy average temperature during the water stress period (°C)	
		Treatments	Control Treatment (ETc)
First Square (FS)	35 – 51	35.3B	29.5A
First Flower (FL)	52 – 63	33.3B	29.3A
Peak Bloom (PB)	64 – 80	33.9B	30.2A
Open Boll (OB)	From 90	33.2A	30.6A

* Averages followed by a capital letter within a row are not significantly different by the t-test.

5.2 Accumulated degree days (ADD)

The ADD values ranged from 1329 (ETc) to 1403 (PB), the value obtained by air temperature was 1364 (Table 6). This difference led to variations in the crop cycle, modifying the timing to application of defoliants and desiccants (70% of open canopies) (EMBRAPA, 2014). Davidonis et al. (2004) and Yeates; Constable and McCumstie (2010) also reported that cotton development is affected by temperature. Then, the new arrangement for defoliants application followed the same order of the crop cycle finalization, which in turn was assigned by the greatest accumulation of degree days, that was: PB, FS, FL, OB, and ETc.

Table 6. Variation in the accumulation of heat units (Accumulated degree days) resulting from different water deficit treatments based on canopy and air temperatures.

	Treatment	Accumulated degree days
	Air Temperature	1364
	ETc	1329
Water Deficit	First Square (FS)	1398
Water Deficit	First Flower (FL)	1392
Water Deficit	Peak Bloom (PB)	1403
Water Deficit	Open Boll (OB)	1377

Up to 46 DAE, all treatments had the same pattern in ADD accumulation, since ADD were calculated based on air temperature (Figure 2). After 46 DAE, when the canopy temperature began to be monitored, variations in ADD among treatments were observed, being the lowest values always for the control ETc treatment (Figure 2).

This demonstrates and confirms that water stress in cotton induces variations in ADD as previously reported by Mahan et al. (2014). Thus, the use of ADD to monitor the cotton phenological cycle based just on air temperature, can lead to errors, since this parameter is not able to translate the water stress suffered by the plants.

Peng; Krieg and Hicks (1989) and Mahan et al. (2014) observed that the use of ADD in cotton is more useful in well managed irrigation areas and less useful in areas where water deficit occurs. Therefore, under such water stress conditions, determination of ADD based on canopy temperature is a more adequate tool to determine phenological stages of development.

Figure 2. Accumulated heat units (accumulated degree days) during growing season for water deficit treatments from canopy temperature and air temperature (45 days after emergence was the first temperature canopy collected data).

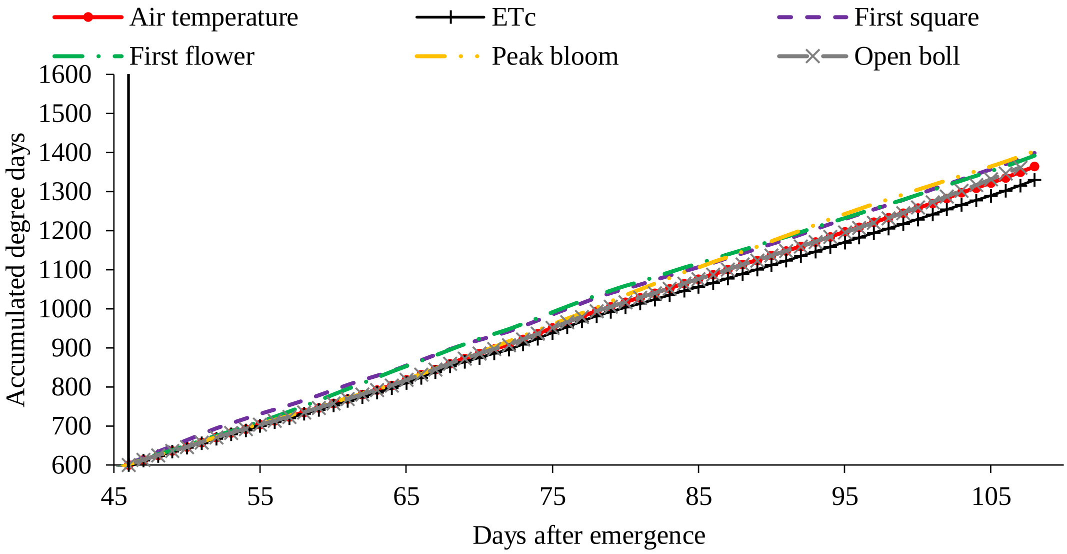


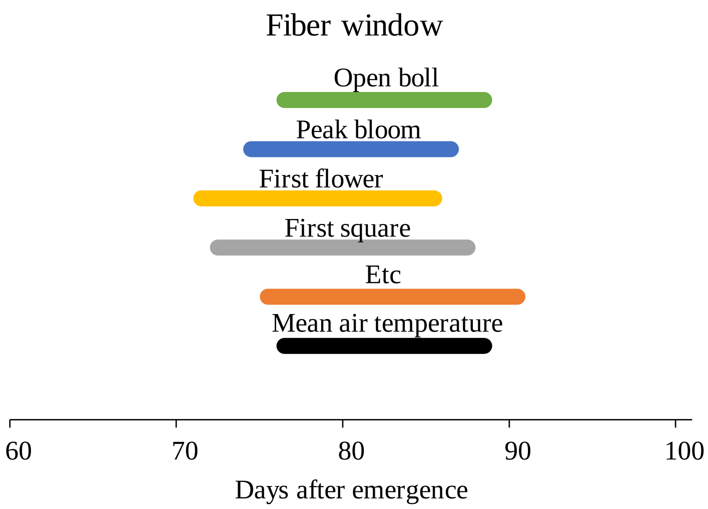
Figure 3 shows the variation of the period for fiber thickening in function of the ADD for different treatments studied. Bange et al. (2010) found that cotton fiber thickening period occurs in the interval between 926 and 1112 ADD, and during this period the temperature caused better effect on the micronaire of the fiber.

The beginning of the period varied between 71 and 76 DAE for water deficit to FL and PB treatments, respectively. The end of period ranged from 85 to 90 DAE for FL and control treatments (ETc), respectively (Figure 3). For the air temperature, the beginning and end of the fiber thickening period were 76 and 88 DAE, respectively.

The duration of the fiber thickening period also varied between 13 and 16 days, with the shortest periods (13 days), referring to the PB and OB treatments. Mahan et al. (2014) found variations in the fiber thickening period between 14 and 33 days, with the lowest values also being found for treatments with water stress. This shortening in the fiber thickening period, can lead to micronaire problems (HAIGLER et al., 1991; ROBERTS et al., 1992), degrading fiber quality, which shows the importance of avoiding water stress at this stage.

Canopy temperature can also be a useful tool for predicting the effects of environmental conditions throughout the growing season on fiber quality parameters such as micronaire, as well as the prediction of time to harvest and desiccant applications (WANJURA; NEWTON, 1981).

Figure 3. Variation in the beginning, during, and at the final of the fiber thickening period as a function of applied water deficit treatments, with accumulated degree days based on the canopy and air temperatures.



As discussed previously, calculation of ADD to monitor the fiber thickening period based on air temperature should not be considered reliable because of the variability induced by water stress. Thus, the calculation of ADD based on canopy temperature can improve data quality and allow for a better standardization of the results, offering suitable data for use, that can support overall crop management and irrigation.

6 CONCLUSIONS

Canopy temperature for cotton was significantly influenced by water stress at all stages of the crop cycle;

The most critical stage to water stress in cotton was during flowering, with the highest reductions in yield;

Canopy temperature proved to be a useful tool to evaluate the water status of the cotton plants under irrigation conditions;

Accumulated degree days based on canopy temperature varied according to water stress;

Accumulated degree days calculated based on the canopy temperature is a useful tool to monitor crop cycle under water stress conditions;

Canopy temperature can be used to improve the cotton irrigation management and in selection programs of cultivars resistant to water stress.

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