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Water stress index on sugarcane in different developmental phases

Índices de estresse de hídrico em cana-de-açúcar nas diferentes fases de desenvolvimento

Rodrigo Garcia Brunini[1*], José Eduardo Pitelli Turco[1]

[1]Universidade Estadual Paulista/UNESP, Faculdade de Ciencias Agrarias e Veterinarias/FCAV, Jaboticabal, SP, Brasil
[*]Corresponding author: rgbrunini@gmail.com
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ABSTRACT

Brazil is the world leader in the production of sugar and ethanol due to its intensive cultivation of the sugarcane crop, mainly in the Southeast region of the country. However, its expansion into other areas has gained strength in recent years and has caused significant variations in the harvest due to problems related to the climate of the region. The use of water stress indexes in the developmental phases of the crop can be an essential tool for irrigation control, preventing the negative effects of water stress on the plants. The aim of this study was to determine the ideal time to irrigate a sugarcane crop, using a water stress index found using infrared thermometry. The research was developed in an area called the "Experimental Hydrographic Basin" and employed surfaces with different slopes (0% to 40%) and solar exposures (North, South, East and West), under an induced water deficit. The analyses were performed in the field and in the laboratory. The results of this study indicate that the ideal time for irrigation differs for each phase of sugarcane development, in a range between 2.0 °C and 5.0 °C, and is more critical in the tillering phase. A surface maintained at field capacity had a lower water stress index and a higher productivity (124 Mg ha^{-1}).

Index terms: Water and soil management; water deficit; infrared thermometry; irrigation, *Saccharum officinarum* L.

RESUMO

O Brasil é lider mundial na produção de açúcar e etanol, devido ao intenso cultivo da cultura de cana-de-açúcar principalmente na região Sudeste do país. No entanto sua expansão em outras áreas vem ganhando força nos últimos anos, o que tem acarretado variações significativas nas safras devido às limitações climáticas da região. O uso de índices de estresse hídrico nas fases de desenvolvimento da cultura pode atuar como uma ferramenta essencial no manejo da irrigação, prevenindo os efeitos negativos do estresse hídrico nas plantas. Objetivou-se com este trabalho determinar o momento ideal de irrigar a cultura de cana-de-açúcar, por meio de índices de estresse hídrico utilizando-se a termometria a infravermelho. A pesquisa foi desenvolvida em uma área denominada "Bacia Hidrográfica Experimental", utilizando superfícies com diferentes declividades (0% a 40%) e exposições solares (Norte, Sul, Leste e Oeste), sob déficit hídrico induzido. As análises foram realizadas in loco e em laboratório. Os resultados indicam que o momento de irrigar difere para cada fase de desenvolvimento da cana-de-açúcar, em uma faixa entre 2,0 °C até 5,0 °C, sendo crítica a fase de perfilhamento. A superfície mantida na capacidade de campo obteve menor índice de estresse hídrico e maior produtividade (124 Mg ha^{-1}).

Termos para indexação: Manejo de água e solo; déficit hídrico; termometria a infravermelho; irrigação; *Saccharum officinarum* L.

INTRODUCTION

Plants suffer from different types of stress that result from anthropic management and/or are due to the effect of the environment itself. According to Soares and Machado (2007), a stressed plant manifests a series of physiological effects that can be linked due to modifications in the manifestation of the genes and incomplete metabolic reactions resulting in the instability of cellular development and a negative effect on the production of vegetable matter.

Croplands that are experiencing a water shortage or limitation to the crop, a condition known as a water deficit, can be considered as potential water stress areas. Water stress is a constraint that further reduces the development and the production potential of the plants and is directly related to the occurrence of short summer drought (i.e., low precipitation and high temperature and solar radiation) and a lack of irrigation management (Holanda et al., 2015).

Currently in Brazil, sugarcane expansion regions are potential areas for crop water stress, which is a condition that may limit the production of sugar and ethanol.

García-Tejero et al. (2011) and Zarco-Tejada et al. (2013) show that the main response of plants to a soil water deficit is the closure of the stomata and the reduction of leaf transpiration, a fact that leads to a gradual increase of the leaf temperature.

The temperature of the vegetative canopy is a good indicator of the plant water status, and this variable is directly proportional to the topography and slope of the land and it influences the water metabolism of the plants (Wang et al., 2010). A method known as the Crop Water Stress Index - CWSI, proposed by Idso et al. (1981) and Jackson (1982), allows the indexes of daily water stress for the crops to be found in a practical manner by means of infrared thermometry.

The investigation of water stress indexes via crop responses to various topography scenarios and sun exposure levels is a key method in the search for responses that reduce the effects of water stress in plants. Because the provision of scientific and technical information about water deficits and irrigation management is important and necessary, the aim of this research was to determine water stress indexes based on infrared thermometry for sugarcane in different development phases.

MATERIAL AND METHODS

This research was carried out in an experimental area of the Department of Rural Engineering of FCAV/UNESP, Jaboticabal Campus, SP, Brazil, located at 21°14'05" South latitude, 48°17'09" West longitude and 613 m of altitude, in a structure called the "Experimental Hydrographic Basin" (Figure 1), which has been described in detail by Turco et al. (1997).

The surfaces were filled with suitably homogenized soil of a eutrophic dark red latosol type, moderate A, kaolinite, hypoferric, clayey texture (Embrapa Solos, 2013). The climate in the region according to the Köppen classification is the Cwa type, with an average annual precipitation of 1.400 mm, an average annual temperature of 22 °C and an average relative air humidity of 70% (Peel; Finlayson; Mcmahon, 2007).

The experiment was carried out in this structure from April 8, 2015 to April 6, 2016 (encompassing the phases of tillering, growth and maturation of the crop), and ten surfaces were used to simulate lands with exposures and slopes characterized as H1 (horizontal) without a water deficit and the others under an induced, controlled water deficits designated as H2 (horizontal), 20N (20% slope, north exposure), 20S (20% slope, south exposure), 40N (40% slope, north exposure), 40S (40% slope, south

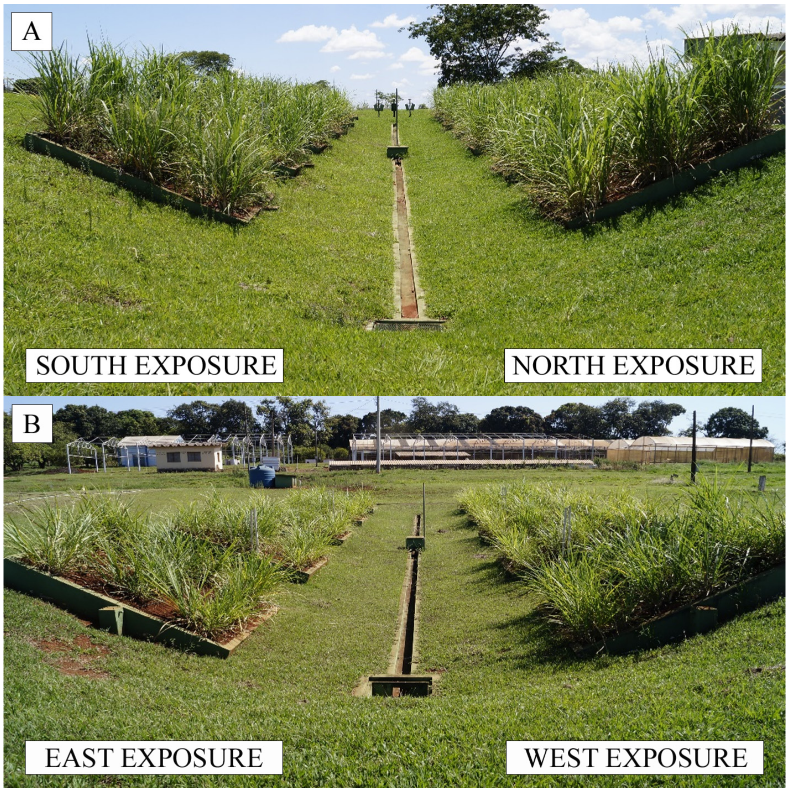

Figure 1: Experimental Hydrographic Basin, Jaboticabal-SP.
Photo: Rodrigo Garcia Brunini, 2015 (A and B).

exposure), 20E (20% slope, east exposure), 20W (20% slope, west exposure), 40E (40% slope, east exposure) and 40W (40% slope, west exposure).

The sugarcane variety RB 85-5453 was cultivated (Matsuoka et al., 1995) on all surfaces. Pre-planting procedures were carried out starting with the homogenization and preparation of the land, so that the land was in a condition to be planted, with open furrows 30 cm deep spaced at 1.4 m between the rows and fertilized. During planting, seven fresh sugarcane cuttings m^{-1} were deposited in a 30 cm furrow at a depth of five centimetres and covered, with a goal of obtaining 15-18 buds m^{-1} (Marafon, 2012).

The Davis Instruments from the Automated Weather Station provided the meteorological data, regarding the period of implantation and conduction of the experiment covering the seasons of the year and the sugarcane cultivation cycle.

Three tensiometers were installed at the centre of each surface and at 20 cm and 40 cm deep to monitor the soil water potential. The H1 surface was always maintained at field capacity with no induced water deficit, but the other surfaces (i.e., H2, 20N, 20S, 20E, 20W, 40N, 40S, 40E and 40W) were irrigated when the available water capacity of the soil (i.e., the usable reserve in mm) reached 50%. The following procedure was performed to determine when the soil reached this state.

The formula for the determination of the soil water matric potential (i.e., the critical soil moisture) is shown by Equation 1.

$$\Psi m = -12.6h + h1 + h2 \tag{1}$$

where:
Ψm – matric potential of soil water (cmwc);
h - height of the mercury column (cm);
h1- height of the mercury vat relative to the soil surface (cm);
h2 - depth of the tensiometer installation (cm).

For depths of 0.20 and 0.40 m, the soil matric potential was converted to moisture using the following mathematical expression developed by Van Genuchten (1980) and described by Dourado Neto et al. (1995) (Equation 2), which considers that at a field capacity moisture level (θcc), the soil water tension is 103.32 cm H_2O, and the current moisture (θA) is obtained daily by means of the water tension from the tensiometer readings.

$$\theta = \theta r + (\theta s - \theta r) . [\frac{1}{1 + (\alpha \ . \ \Psi m)^n}]^m \tag{2}$$

The values of the empirical constants of Equation 2 and the other physical-water characteristics of the soil area, such as average values for the layers from 0-20 and 0.20-0.40 m of depth, are shown in Table 1.

The available soil water capacity (ASWC, in mm), the water easily available in the soil (WEAS in mm) and the available soil water reserve (ASWR, mm) were determined by Equations 3, 4 and 5:

$$ASWC = (\theta fc - \theta pwp) .Z \tag{3}$$

$$WEAS = 0.5 \ . ASWC \tag{4}$$

$$ASWR = (ASWC - WEAS) \tag{5}$$

where:
θfc - soil moisture cm^3 cm^{-3} at field capacity (potential of -103.32 cm H_2O);
θpwp - soil moisture cm^3 cm^{-3} at the permanent wilting point for a matric potential of 15498.41 cm H_2O;
Z – effective depth of the crop root system (0.3-0.4 m) (Pires et al., 2001).

Table 1: Average physical-water characteristics of the Van Genuchten equation (1980), for layers from 0 - 0.20 and 0.20 - 40 m of soil depth in the experimental area.

Depth	θfc	θc	θpwp	Ds	A	N	M	θs	θr
(m)		---- (cm^3 cm^{-3}) -----		(g cm^3)	(cm^{-1})			--- (cm^3 cm^{-3}) ---	
0.00 – 0.20	0.38	0.339	0.30	1.13	0.0178	12.7127	0.1383	0.539	0.297
0.20 – 0.40	0.27	0.239	0.21	1.04	0.0182	17.7713	0.1432	0.506	0.209

θfc - soil moisture at field capacity; θc - critical soil moisture; θpwp - soil moisture at the permanent wilting point; ds - soil density; θs - saturated soil moisture; θr - soil residual moisture; A, n and m - adjustment coefficients generated by the model (Dourado Neto et al., 1995).

The Penman-Monteith method (Allen et al., 1998), corrected for each surface, was used to determine when to irrigate each surface, using the methodology adopted by Turco et al. (1997) with the use of the sugarcane coefficient (Kc) (Doorenbos; Kassam, 1994).

Drip irrigation of each surface was carried out through the installation of six hoses (one per crop line) 3.5 m in length, with drippers every 20 cm throughout the length. The set had a flow of 90 L h^{-1}. On the H1 surface, the irrigation was always carried out when the soil moisture reached the field capacity, maintaining the soil at approximately 25% moisture (Faria et al., 2012).

To evaluate the water stress index of each surface, measurements were taken between 11:00 and 13:00 according to the induced water deficit, and 10 readings were made in each plot. The temperature of the vegetation cover and the ambient air temperature were respectively measured at the same time with a FLUKE, 62 MAX model portable infrared thermometer, and a mercury thermometer with an accuracy ± 0.1 °C) when properly calibrated (Fernandes, 2010).

To calculate the CWSI, the difference between the average temperature of the vegetation cover and the air temperature was determined according to Idso et al. (1981), who proposed Equation 6:

$$CWSI = Tc - Ta \tag{6}$$

where:
CWSI – Daily Crop Water Stress Index, in °C;
Tc - temperature of the vegetation cover, in °C; and
Ta - air temperature, in °C.
A positive CWSI value indicates that a crop is under stress (Fernandes, 2010).

The plants were harvested at the end of the experiment on April 5, 2016, and all plants were weighed. The yield was calculated as the total weight per metre in three replicates. The values were estimated for one hectare, according to the methodology described by Hermann and Câmara (1999). The data were subjected to an analysis of variance using an F test, and if significant, the Tukey test followed ($p < 0.05$).

RESULTS AND DISCUSSION

Table 2 shows the amount of applied irrigation and the variation of precipitation that occurred during the experimental period in 2015 and 2016 for each treatment.

The highest amount of irrigation was applied during August, September and October (i.e., the sprouting and tillering phase of the sugarcane crop) according to the proposed method, and the lowest precipitation occurred during this period (i.e., 0.0, 24.6 and 33.0 mm of rain, respectively).

Table 2: Monthly irrigation level of each surface in each treatment and precipitation in mm during the experiment. Jaboticabal, SP, Brazil.

Date	H1	H2	20N	20S	40N	40S	20E	20W	40E	40W	Precipitation
	(mm)										
April	13.4	13.4	15.5	9.3	16.8	6.5	13.5	11.9	13.0	11.1	0.0
May	71.2	71.2	82.5	49.3	89.9	34.1	71.7	62.6	69.0	58.9	73.8
June	76.7	76.7	89.0	52.5	97.1	36.1	84.1	73.4	80.9	68.8	19.0
July	74.1	74.1	85.5	51.6	93.0	35.8	74.7	65.5	71.9	61.6	44.9
August	105.7	135.3	122.0	73.5	132.6	51.0	106.5	93.2	102.5	87.8	0.0
September	104.9	151.3	120.6	79.1	140.6	61.2	116.5	92.6	112.1	96.9	24.6
October	115.5	76.9	118.2	118.1	123.8	100.3	119.4	106.3	127.0	99.9	33.0
November	74.6	64.7	64.3	57.7	60.7	55.8	65.2	57.2	62.7	57.9	227.9
December	81.6	90.7	92.2	70.1	82.2	74.5	86.7	76.3	80.8	74.6	388.4
January	57.6	57.6	60.2	54.2	57.0	52.4	60.8	53.7	58.6	54.3	457.7
February	70.4	65.8	65.6	59.0	59.4	57.0	66.3	58.4	60.0	59.1	243.6
March	0.0	4.7	4.6	4.2	4.4	4.1	4.7	4.1	4.5	4.2	24.2
April	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total	845.5	882.2	920.3	678.5	957.7	568.8	870.0	755.3	842.9	735.2	1537.2

The horizontal surfaces H1 and H2 (Table 2) under natural conditions of sun exposure and land slope had a water demand of 845.5 and 882.2 mm. Areas that had a 40N and 20N exposure to the north sun showed the highest total irrigation demands of 957.7 and 920.3 mm, respectively, when compared to the south exposure surfaces 20S and 40S, which required irrigation amounts of 678.5 and 568.8 mm, with lower values recorded for treatments. The water demands for the east and west solar exposure areas were similar (870.0 and 842.9 mm for 20E and 40E, and 755.3 and 735.2 mm for 20W and 40W, respectively).

The total precipitation during the cultivation cycle was 1537.2 mm, which is within the expected range for the region's climate; however, as shown in Table 2, the seasonal variation of rainfall availability may affect the water requirement of a sugarcane crop, especially at the beginning of the development (i.e., the sprouting and tillering phases).

According to Jadoski et al. (2010) and De Oliveira et al. (2014), the sugarcane tillering phase is directly influenced by environmental factors such as soil moisture, light and temperature. The stress caused by the lack or excess of some of these climatic factors, such as a lack of rainfall, may lead to initial losses in the number of sprouts and tillers, have negative effects on the growth phase of the stalks and directly affect the production of the sugarcane final raw material, causing serious impacts to the sector.

According to Junior et al. (2016), in studies with sugarcane under a variable water regime, irrigation management in areas with unstable precipitation, such as sugarcane expansion regions in Brazil (North and Central West), results in favourable results for producers and is responsible for a productivity surplus of up to 65.9%.

Thus for all treatments, the soil moisture conditions due to irrigation and precipitation management (Table 2) favoured the crop development phases, having as an incisive factor in the H2, 20N, 20S, 40N, 40S, 20E, 40E, 20W and 40W treatments (i.e., periods of induced water stress and different solar exposures) in contrast with the H1 treatment, which did not suffer water stress during the study period.

Figure 2 shows the water stress index (CWSI) values for treatments of the sugarcane crop in different phases of development (i.e., tillering, growth and maturation).

The highest values of the water stress index were recorded during the tillering phase of the crop during periods of induced water stress and were approximately 6.0 °C for the H2 treatment and 6.5 °C for the 20N and 20S treatments (Figure 2A), 6.5 °C for the 40N treatment and approximately 5.9 °C for 40S (Figure 2B). The highest recorded value was 7.0 °C for 20E and 6.2 °C for 20W (Figure 2C). For 40E and 40W, the values were close to 6.5 °C and 6.4 °C, respectively (Figure 2D). In the H1 treatment (Figure 2A), which was maintained at field capacity, the highest recorded value was 1.8 °C.

The tillering phase of sugarcane is sensitive to climatic variations and the variation of water availability significantly affects the physiological processes of plants. According to Testi et al. (2008) and Trentin et al. (2011), the leaf temperature in relation to the air temperature tends to increase in sugarcane and several other crops under water stress, a phenomenon closely linked to the transpiration process.

An increase in the canopy temperature is observed with a reduction of leaf transpiration due to the higher concentration of energy in the form of latent heat. Thus, the leaf temperature becomes higher than the air temperature, which explains the behaviour of the water stress index between 1.8 to 7.0 °C for the H1, H2, 20N, 20S, 40N, 40S, 20E, 20W, 40E and 40W treatments (Figure 2 A, B, C and D) according to the water regime, the slope and solar exposures of the surfaces, which in turn directly affects the amount of solar radiation in each treatment.

Simões et al. (2014) studied the behaviour of sugarcane under water stress in the northeast region of the country and observed a significant effect of a leaf temperature increase, obtaining values up to 38.0 °C for plants experiencing a water limitation, which was approximately 10.0 °C above the ambient temperature for that region.

According to De Oliveira et al. (2014) and Silva et al. (2014), maintaining an adequate water regime during the tillering phase of sugarcane is of extreme importance for of stalk formation and development, and the production of the final raw material. Additionally, the use of water stress indexes can contribute significantly to irrigation management, providing support for a crop to reach its greatest productive potential in the field.

During the growth and maturation phases (Figure 2 A, B, C and D), the water stress index for all treatments decreased compared to the tillering phase. In Figure 2A and B (growth phase), for the treatments with an induced water deficit (20N and 40N), the highest average values occurred approximately at 3.0 °C, and the H2 treatment was also under stress at 2.0 °C, highlighting the influence of solar exposure on these treatments. For the H1 treatment at field capacity, the values were always close to 0.0 °C in the sugarcane growth and maturation phases.

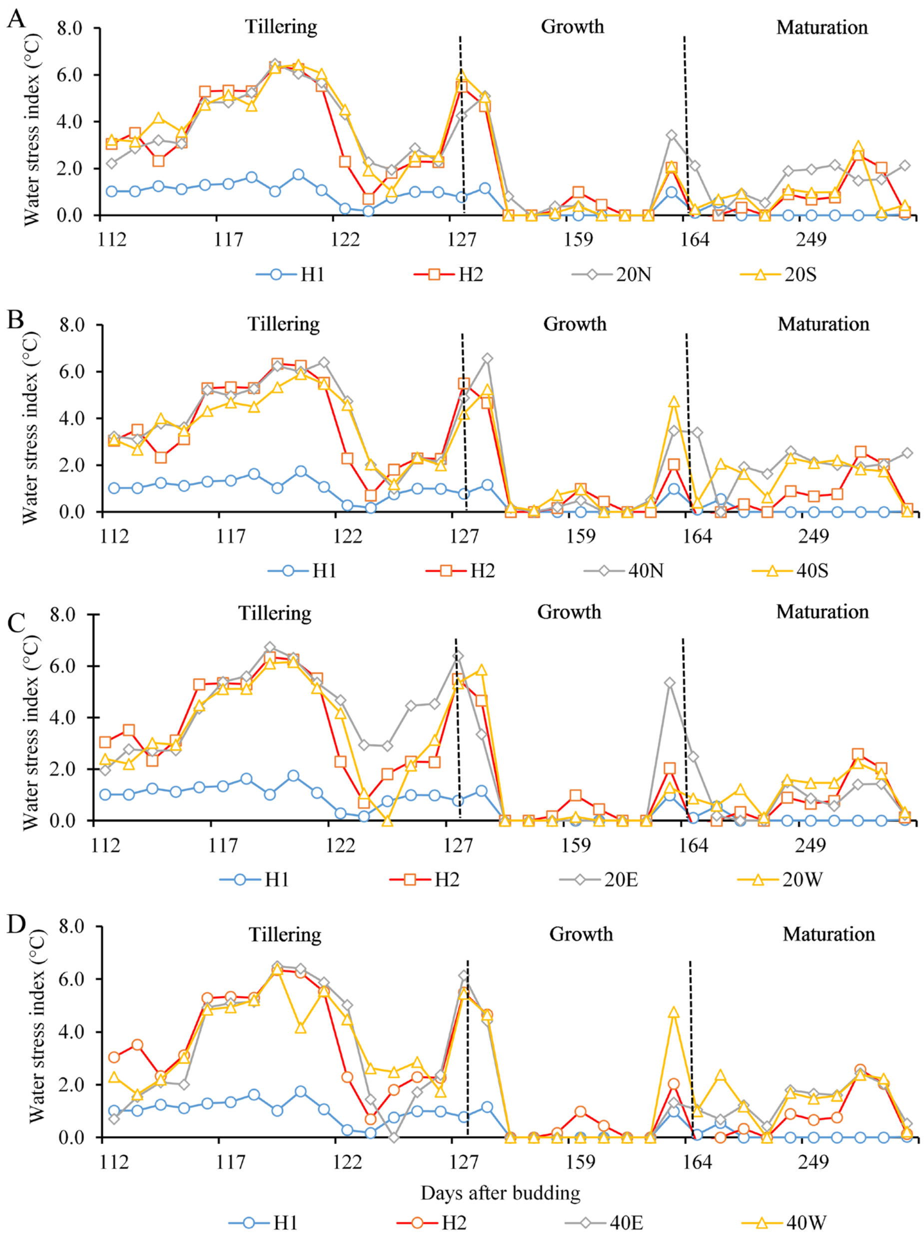

Figure 2: Water stress index, in °C, for H1, H2, 20N, 20S (A), 40N, 40S (B), 20E, 20W (C), 40E and 40W (D) treatments, in a sugarcane crop. Jaboticabal, SP, Brazil.

The decline in the water stress index is associated with a greater canopy closure by the leaves, a larger shaded area and the accumulation of reserves by the stalks. The morphology and growth structure of the crop provides the plants with a suitable "microclimate", in which smaller differences in the accumulation of solar radiation and greater support to face the water stress are present and directly affect the transpiration rate (Taiz; Zeiger, 2004).However, it is important to note that the damaging effects of the initial hydrological limitation (tillering) for treatments under water deficit are irreversible and will have a negative influence throughout the plant cycle.

The average of the water stress indexes for each development phase of the sugarcane crop in the treatments studied is shown in Table 3.

Table 3: Water stress indexes (°C) on the studied surfaces for different development phases of a sugarcane crop.

Water stress index	H1		H2		20N		20S		40N		40S		20E		20W		40E		40W	
	Temperature (°C)																			
Tillering phase*	1.2	d	5.4	c	5.1	c	6.2	b	6.3	ab	5.5	c	6.5	a	5.7	c	6.2	b	5.2	c
Growth phase**	0.3	e	1.9	c	3.3	a	0.5	e	3.4	a	1.9	c	2.4	b	0.7	e	1.2	d	2.6	b
Maturation phase***	0.0	f	0.8	e	2.0	b	1.0	de	2.2	a	2.2	a	1.4	d	1.6	c	1.7	c	1.8	bc

Averages followed by different letters differ from each other by the Tukey test ($p < 0.05$). * CV = 5.3%; **CV. = 8.9%; ***CV. = 9.2%.

In the tillering phase, the 20E treatment had the highest average water stress index (6.5 °C), followed by 40N (6.3 °C). The 20S and 40E treatments with a value of 6.2 °C did not differ from each other and were followed by the 20W, 40S, H2, 20N and 40W treatments with averages close to 5.4 °C. The H1 treatment had a lower water stress index during the period with an average of 1.2 °C.

Several authors have provided evidence that tillering is a critical phase in relation to the need of water for sugarcane cultivation. The intensity of tillers at this phase is stimulated according to the growing environment conditions; temperature, solar radiation and water availability may intensify and/or aggravate the number of tillers by mortality due to a decrease in stomatal conductance and the photosynthetic rate (Inman-Bamber; Smith, 2005, Zhao; Glaz; Comstock, 2010).

Table 3 shows that in the H2 treatment, an induced water deficit produced a high degree of stress (i.e., a CWSI of 5.4 °C) compared to H1 (1.2 °C), indicating the negative effect of a water limitation during the tillering phase. The water deficits induced in the other treatments by varying the solar exposure prove that the accumulation of radiation in the plants under water stress due to land geography maximizes the intensity of the water stress index for the cultivation of sugarcane because of the divergence of average values.

For the crop growth phase, Table 3 shows that the lowest values of the water stress index were found in H1 (0.3 °C), 20S (0.5 °C) and 20W (0.7 °C), followed by the 40E (1.2 °C) treatment and the H2 and 40S treatments, which both had a value of 1.9 °C. The highest stress indexes during the period were found for the 40N and 20N treatments, followed by the 20E and 40W treatments. During the maturation phase, the H1 treatment had a lower index (0.0 °C) whereas the 40N and 40S surfaces had the highest value (2.2 °C).

Studies evaluating the leaf temperature were carried out by Trentin et al. (2011), Vieira et al. (2014) and Brunini and Turco (2016) in a sugarcane crop and demonstrated that the treatments with a water regime in the field capacity registered canopy temperatures close to ambient temperature, indicating a lower water stress index, while in the other treatments where a water deficiency and high solar radiation were present, the canopy temperatures were higher than the air temperature, with differences close to 6.0 °C. In agreement with the maximum and average values of the recorded water stress index for the treatments under induced water deficit in the tillering phase (Figures 2A, B, C and D and Table 3).

The relation between the plant water requirements and the canopy temperature is a parameter of extreme importance to indicate when the producer should irrigate the crop (Nogueira; Silva Júnior, 2001). De Almeida Lobo et al. (2004), who worked with water stress indexes for an irrigated bean crop, concluded that the ideal time to irrigate the crop was during the breeding season and when the canopy temperatures reached 3 to 4 °C (± 0.5) above the temperature of the control plants (i.e., well-irrigated plants).

Based on the averages for the H1 and H2 treatments shown in Table 3, it is possible to state that in general, for sugarcane cultivated under such field conditions, which are most common, the tillering phase is critical for irrigation management and is the ideal time to irrigate when the canopy temperature reaches values between 2.0 and 5.0 °C relative to the environment.

According to the data in Figure 3, the usable reserve of soil water in the 0 to 0.40 m layer that was monitored corresponded to 28.5 mm. It is possible to monitor the behaviour of the water in the soil during the periods of induced water deficit (i.e., at 50% of the usable reserve) for the treatments at each stage of sugarcane development.

According to Ritchie (1972) and Santos and Carlesso (1998), the usable reserve or the evapotranspirable water can be estimated by the difference between the soil water content explored by the plant root system, between the upper limit (field capacity) and the limit of available water in the soil (the permanent wilting point).

Figure 3 shows that during the three stages of the crop development, which are tillering (117 to 128 d.a.b), growth (158 to 165 d.a.b) and maturation (248 to 254 d.a.b), the usable reserve by the treatments under a water deficit (i.e., H2, 20N, 20S, 40N, 40S, 20E, 20W, 40E and 40W) was exploited until they reached a value of 14.2 mm (i.e., 50% of the reserve), a condition considered stress. The H1 treatment was always maintained at field capacity (Allen et al., 1998, Faria et al., 2012).

Ortolani and Camargo (1987) indicate that a water limitation can cause damage to the final production of approximately 70%, evidencing the importance of planning irrigated agriculture during the development period of the plants. As the water depletion in the soil evolves, the plant capacity to absorb water decreases due to the greater energy retention by the micropores of the soil competing with the roots, thus limiting the availability of water (Bergamaschi, 1992).

Table 4 shows the maximum temperature values of the vegetative cover in the development phases of a sugarcane crop and the accumulation of global radiation during the productive cycle.

The H1 treatment had maximum temperature values close to 30.5 °C during all development phases in agreement with the scientific statement proposed by Idso et al. (1981) that plants at field capacity tend to maintain their temperature near the air temperature and have lower values of the water stress index CWSI.

The treatments under water deficit (Table 4) had greater variations in the maximum canopy temperature than H1 did during all phases of crop development due to water limitation, a decrease of leaf transpiration and an increase in the latent heat accumulation due to solar radiation in the leaves.

The ideal temperature for growth and development of a sugarcane crop is in a range close to 30.0 °C. A sudden increase of temperature affects the physiological quality of a plant, generating a loss of tillers, a decrease in the height and diameter of the stems that consequently affects the production in the field (Jadoski et al., 2010; De Oliveira et al., 2014).

For the horizontal surfaces H1 and H2, the accumulated radiation during the crop cycle was 8373 MJ m^{-2} $year^{-1}$ (Table 4). The surfaces that had the greatest accumulation of radiation were 40 N (8871 MJ m^{-2} $year^{-1}$), 20N (8792 MJ m^{-2} $year^{-1}$), 20E (8302 MJ m^{-2} $year^{-1}$) and 20W (8217 MJ m^{-2} $year^{-1}$). The 40S surface had the lowest accumulation of radiation during the cycle (6715 MJ m^{-2} $year^{-1}$). The 20S and 40W surfaces had similar radiation values (7654 and 7861 MJ m^{-2} $year^{-1}$, respectively).

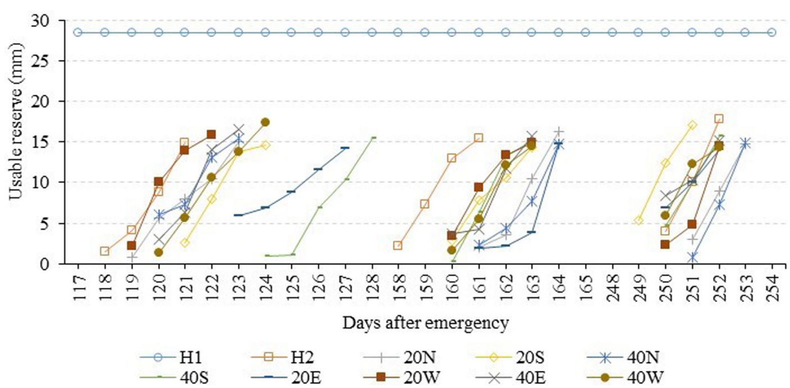

Figure 3: Average values of water available in the soil up to 0.40 m of depth during the periods of induced water stress in sugarcane for the treatments (H1, H2, 20N, 20S, 40N, 40S, 20E, 20W, 40E and 40W).

Table 4: Maximum temperature of the vegetative cover, in °C, of the treatments, in the development phases of sugarcane and the accumulated Global Solar Radiation, in MJ m^{-2} $year^{-1}$.

Development phase	H1	H2	20N	20S	40N	40S	20E	20W	40E	40W
	(°C)									
Tillering	30.7	31.7	31.9	32.9	32.5	32.7	33.0	31.7	31.7	31.3
Growth	30.5	34.5	35.8	35.9	36.4	37.1	37.8	34.1	34.4	37.2
Maturation	30.0	32.0	32.1	32.2	32.5	31.8	31.4	31.8	32.0	32.2
Accumulated radiation	(MJ. m^{-2}. $year^{-1}$)									
Total	8373	8373	8792	7654	8871	6716	8302	8217	8031	7861

André et al. (2010) and Carneiro et al. (2013) studied the balance of radiation in sugarcane in different regions in Brazil and confirmed the dependence of the albedo (reflection) on the function of the solar elevation angle. According to these authors, the angular variation of solar radiation incidence on the plants affects the balance of radiation that penetrates and is retained, thus different production scenarios that depend on the land geography influence the balance of total radiation of the crop. This fact agrees with the values shown in Table 3. In the treatments where the slope and solar exposure differ, variable amounts of solar radiation accumulate during the cycle and influence the development of the sugarcane crop.

The absence of water stress due to irrigation management can guarantee a high agronomic yield for a sugarcane crop, resulting in a high concentration of sugars in the stalks, efficient conversion of sugar and alcohol, and high productivity in the field (Da Silva et al., 2014). This was confirmed by the H1 treatment, which had a lower water stress index (1.2 °C) and a higher crop yield (124.0 Mg ha^{-1}), Figure 4 and Table 5.

A comparison of H1 with H2, which had a higher CWSI of 6.4° C (Figure 4) and a lower yield of 99.0 Mg ha^{-1} (Table 5), indicated that an induced water stress during the development phases caused a reduction of 20.1% in crop yield. This was corroborated by productivity data

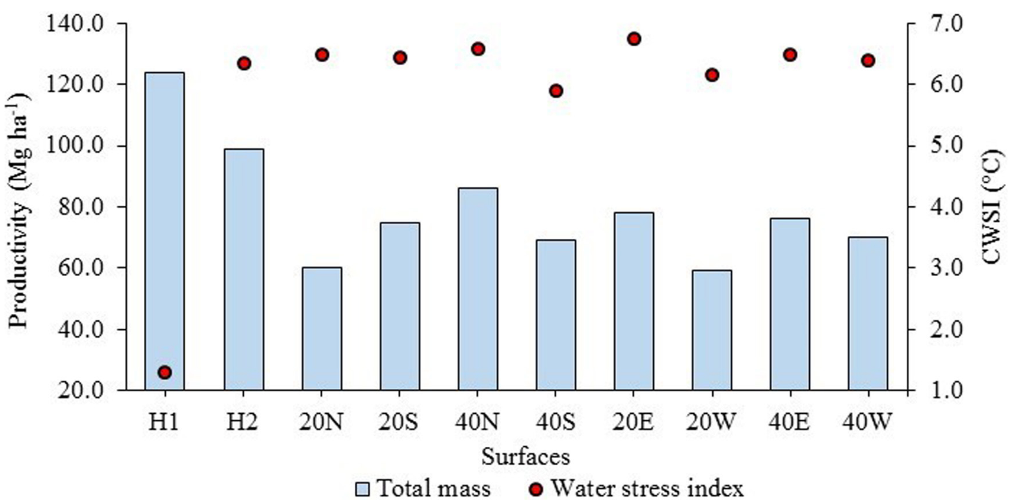

Figure 4: Sugarcane yield (Mg ha^{-1}) and the maximum CWSI (°C) for the studied surfaces.

Table 5: Average yield of sugarcane (Mg ha^{-1}).

Surfaces	Yield (Mg ha^{-1})
Slope - 0% at field capacity	124.0 a
Slope – 0% under a water deficit	99.0 b
North – 20%	60.0 f
South – 20%	75.0 d
North – 40%	86.0 c
South – 40%	69.0 e
East – 20%	78.0 d
West - 20%	59.0 f
East – 40%	76.0 d
West - 40%	70.0 e

Averages followed by different letters differ from each other by the Tukey test ($p < 0.05$). CV = 5.80%.

collected during the 2015 harvest during a period of severe water stress for the producers of the State of São Paulo by the IEA (2015) and CTC (2015) that showed losses up to 25.0% in crop yield and by Vieira et al. (2014), who observed a reduction in stalk yield of 21.5% in treatments without irrigation. De Moraes Nogueira et al. (2016) showed that treatments maintained under a water regime had better technological parameters for the production of ethanol and recoverable total sugars during the harvest than the cultivation with dry farming.

Da Costa Santos et al. (2016) discussed the productive potential of sugarcane under dry farming, which is vulnerable to periods of water stress. According to these authors, the negative effect of water limitation causes severe damage of greater than 50% in crop productivity, which agrees with the observed values for the 20N and 20W treatments (59.0 and 60 Mg ha^{-1}) (Table 5), which showed decreases of greater than 50% in yield compared to H1. The other treatments 40W and 40S had yields of approximately 70.0 Mg ha^{-1}; 40E, 20E and 20S had approximately 76.0 Mg ha^{-1}; and 40N (86.0 Mg ha^{-1}) had yield decreases between 30.1 and 43.5% respectively.

The difference between the productivity values of the treatments under an induced water deficit can be explained by environmental variables such as land topography and sun exposure, which influence the capture of solar radiation, evapotranspiration and soil moisture (Brunini; Turco, 2016).

As discussed in this paper, these morphological variables and the induced water stress for each phase of crop development are important processes in the study of water stress indexes since they support the assertion that CWSI values higher than 2.0 °C cause significant losses in final productivity (Tables 3 and 5 and Figure 4).

A comparison of the maximum CWSI of H2 (6.3 °C) to the other treatments under a water deficit (Figure 4) showed a variation throughout the data collection period - the highest values recorded during the cycle varied in a range from 5.9 °C (40S) to 6.7 °C (20E), demonstrating that the land topography and the amount of solar radiation captured in the growing area have a direct influence on the productivity of a sugarcane crop, as well as on the water stress index.

Authors such as Tilling et al. (2007), Fernandes (2010); Winterhalter et al., (2011), Maes and Steppe (2012) and Morales et al. (2015), also verified the inversely proportional relation of the canopy temperature with the productivity for soybean, bean, wheat, corn, Barbados nuts and tomato crops under the effect of water stress, and they used these data to estimate predictive irrigation models. Suárez et al. (2008) and Zarco-Tejada et al. (2013) used thermal infrared sensors in aerial vehicles to monitor olive trees and verified significant differences in the canopy temperature under a water deficit in relation to the irrigated crop, improving the CWSI technique for future studies of large areas of cultivation.

Thus, the use of water stress indexes in sugarcane cultivation, whether irrigated or under dry farming, is extremely important for monitoring the physical and technological quality of sugarcane, supporting rural producers to apply irrigation at the ideal time and avoiding losses in productivity due to the negative effects of water stress.

CONCLUSIONS

The water stress index varies for each phase of sugarcane development. The tillering phase has higher rates of water stress. Water stress indexes of 2.0 °C indicate that it is time to irrigate the sugarcane variety RB 85-85453. The exposure and the slope of the land have a direct influence on the water stress indexes for sugarcane cultivation. The H2, 20N, 20S, 40N, 40S, 20E, 20W, 40E and 40W treatments had higher water stress indexes and the lowest yield values compared to H1. The treatments that had different solar exposures in the North, South, East and West had the lowest productivity values for sugarcane compared with the horizontal treatments.

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