

Thermal imaging to assess the crop water status of melon plants under tropical semi-arid climate

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Research Article

Keywords: Cucumis melo L., dryland, irrigation management, leaf temperature, water stress.

Posted Date: April 12th, 2021

DOI: <https://doi.org/10.21203/rs.3.rs-289496/v1>

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Abstract

Deficit irrigation (DI) strategies and soil cover are highly effective to improve the the water productivity in semi-arid regions. However, the effective monitoring of plant water status under DI strategies becomes crucial. The main objective of this study was to evaluate the use of thermal images to estimate the water status of melon plants cultivated in soil with and without mulching under different irrigation regimes. The experience was carried out from October to December 2018. The study was carried out in a randomized block design, in a split plot arrangement. Plots were composed by soil cover (with and without mulching with plant material), and subplots by 5 irrigation regimes (120, 100, 80, 60 and 40% of crop evapotranspiration-ETc), with five replicates. The following variables were evaluated: canopy temperature (T_{canopy}), leaf water potential (Ψ_{leaf}), air temperature (T_{air}), soil moisture, crop yield and the thermal index (ΔT), this being defined as the difference between T_{canopy} and T_{air} . ΔT showed high correlations with crop yield and crop water consumption, evidencing that thermography is an efficient tool to identify the water status of melon plants and could be employed for a proper irrigation scheduling under the tropical semi-arid scenarios. Moreover, the use of thermal images also allowed the identification of beneficial effects of soil cover on leaf water status and crop yield, mainly under moderate DI. The obtained results also demonstrate that mulching is essential to increase melon yield and water productivity in tropical regions.

1. Introduction

Melon (*Cucumis melo* L.) belongs to the Cucurbitaceae family and is one of the most appreciated fruits by consumers (FAO, 2016). Worldwide, 148,189,457 tons of the fruit are produced (FAO, 2018), with Asia holding approximately 75.5% of the planted area and 82.31% of the global production. The largest exporters are China (64.3%), Turkey (3.9%), Iran (3.7%), Egypt (1.9%), Brazil (1.8%), and the USA (1.8%) (Nguyen et al., 2019).

In Brazil, melon production is concentrated in the Northeast region, where the climate favors its cultivation under irrigation. The region accounts for over 95% of the national production, represented mainly by the states of Ceará and Rio Grande do Norte (Celin et al., 2017). The main melon-producing regions have semi-arid characteristics, which provide the best climate conditions for the crop. However, these regions are prone to drought and water shortage is a critical issue to sustainable agriculture. Thus, improving the water productivity in irrigation by seeking new management strategies is needed to support continued agricultural production (Gondim et al. 2011).

Deficit irrigation strategies (DI) are highly effective to improve the water management and to ensure the development of agriculture in semi-arid regions. These strategies save water without significantly impacting crop yield and have a positive impact on fruit quality (Ortuno et al., 2010; Fernández et al., 2013; Gómez-del-Campo, 2013; Padilla-Díaz et al., 2015). However, the effective monitoring of water status in the plant over its cultivation cycle becomes crucial (Poblete-Echeverría et al., 2016; Fernández, 2014).

Many researchers have studied different physiological parameters of plants to monitor crop water status (Fuentes et al., 2005; Tilling et al., 2007; Han et al., 2018). According to Jones (2004), measuring directly these parameters in the plant is more precise and has been broadly used instead of measuring soil water status. However, efficient water management depends on reliable tools to assess the water status of crops and their spatial and temporal variation. The traditional field measuring method for leaf temperature and leaf water potential involves direct contact with the leaf tissues and the use of equipment that is difficult to handle (Klein et al., 2013). Therefore, some authors have been successful in performing this measurement using thermal images, which are able to indicate and detect the effect of water stress in crops (Ullah et al., 2012; Pereira et al., 2015; Cohen et al., 2012; Gerhards et al., 2016).

Thermography is a potential tool used to estimate the canopy temperature, which can be used as an indicator of water stress. The use of thermal cameras, when combined with automated image analysis, becomes very accurate, being able to measure the relative temperature instead of the real temperature (Meron et al 2013). Another application of thermography is the simulation using models from experimental measurements to estimate stomatal conductance and water stress under sub-optimal weather conditions (Maes et al., 2011). It is important to observe that one of the limitations of thermography was the high cost of the thermal cameras. However, new devices with high precision and low costs have increased the possibility of applying this technique (Costa et al., 2013; Fuentes et al., 2012, García-Tejero et al., 2018b) For example, thermal imaging camera connected to smartphone is a potential promising tool to accelerate the monitoring of crop-water status under field conditions (García-Tejero et al., 2018a).

Moreover, imaging techniques with infrared thermography are able to detect minimal changes in temperature. Thus, these techniques are being widely used in precision agriculture, with several applications, such as the measurement of leaf temperature and the identification of disease attack in the plants (Lindenthal et al. 2005; Pineda et al. 2018). In this sense, changes in leaf temperature can be the result of environmental and meteorological factors, as well as damages caused by plant diseases. For example, the infection by pathogens affects water status, and hence, transpiration rate and cuticular and stomatal conductance of plants are changed, resulting in significant variations in leaf temperature. Studies with cucumber, for example, demonstrated that leaf temperatures of plants infected with powdery mildew and mildew were about 4.5°C higher than those of healthy plant (Wang et al., 2012; Wen et al., 2019).

Thus, the objective of this study was to analyze the feasibility of using thermal images to estimate the water status of melon plants under tropical semi-arid climate. To assess the accuracy of this technique, measurements were performed at different times throughout the crop cycle under different water regimes and on soil with and without mulching.

2. Material And Methods

2.1. Experimental site and plant material

The experiment was carried out between July and September 2018 in the experimental area of the Federal Institute of Education, Science and Technology of Ceará – IFCE, in the city of Sobral (03°41'10"S, 40°20'59" W, altitude 69 m), Ceará, Brazil. According to the Köppen classification, the local climate is BSw'h', hot and semi-arid, with 2,563 h of annual sunlight, mean air temperature of 28.3°C, and mean relative humidity of 68%. The dry season lasts 7 to 8 months and the rainy season is concentrated from January to May, with an average annual rainfall of 854 mm (INMET, 2018). The soil of the four areas was classified as Arenosols, according to World Reference Base for Soil Resources (FAO, 2015). Chemical and physical characteristics of the soil samples collected at 0-20cm soil layer are shown in Table 1.

Seeds of yellow melon (*Cucumis melo* L.), hybrid Goldex F1, were sown in polystyrene trays with 128 cells each, using cattle manure and washed sand at 1:1 ratio as substrate. After emergence, the seedlings were kept for about seven days in the trays, a period needed for the development of two true leaves, and after transplanted to the field.

2.2. Experimental design and treatments

A randomized complete block design with a split plot arrangement was used, with five replicates per irrigation regime. The plots were composed by soil cover (with and without mulching with plant material) and subplots were formed by 5 irrigation regimes. The planting spacing was 2.0 x 0.5 m, and each subplot had 10 useful plants.

The mulching was performed with dry leaf carnauba (*Copernicia prunifera* L.) residue, keeping a 3.0 cm layer around the melon plants. This is a by-product from carnauba wax, very abundant material in the region. Silva et. al. (2014) reported the following chemical composition of this leaf residue: N = 27.13 g kg⁻¹, P = 1.46 g kg⁻¹, K = 5.41 g kg⁻¹, Ca = 4.98 g kg⁻¹, Mg = 2.88 g kg⁻¹, Na = 1.4 g kg⁻¹, B = 50.54 mg kg⁻¹, Fe = 47.78 mg kg⁻¹, Cu = 0.59 mg kg⁻¹, Mn = 2.07 mg kg⁻¹, and Zn = 0.56 mg kg⁻¹. The five irrigation regimes were defined as a percentage of the crop evapotranspiration (ET_C) as follows: (IR₁, 120%; IR₂, 100%; IR₃, 80%; IR₄, 60%; and IR₅, 40% of ET_C).

2.3. Crop fertilization and Irrigation

Nutritional requirements of the crop were supplied by 140 kg ha⁻¹ N, 300 kg ha⁻¹ K₂O, and 240 kg ha⁻¹ P₂O₅. Top dressing was performed via daily fertigation using a venturi system.

A drip irrigation system was employed with PCJ - CNL self-compensating in-line button drippers at mean pressure of 150 kPa and nominal flow of 4.2 L h⁻¹, with one dripper per plant. Drippers were previously evaluated in laboratory conditions, using Christiansen's uniformity coefficient (CUC), proposed by Christiansen (1942), and the distribution uniformity coefficient (DUC), which presented values of 91 and 84%, respectively.

The amount of water applied was daily determined, by ET_C estimations by means of reference evapotranspiration and crops coefficients (Allen et al. 1998). Reference evapotranspiration (ET₀) was estimated by direct readings of the daily evaporation in a Class-A pan tank installed next to the

experimental area, adopting a tank coefficient (K_p) of 0.72, according to local climate conditions. The crop coefficients (K_c) used were 0.50, 0.80, 1.05, and 0.75, as recommended by Doorenbos and Kassam (1994) and Doorenbos and Pruitt (1997), corresponding to the periods of vegetative growth, flowering, fruit production, and fruit maturation, respectively. The soil cover factor for located irrigation was calculated using a ruler to measure the dimensions of the melon plant branches in the cross-section of the planting rows by dividing the value of row spacing. The amount of water applied in each irrigation treatment throughout the plant cycle was 386.69, 322.24, 257.79, 193.34 and 128.89 mm, respectively for IR_1 , IR_2 , IR_3 , IR_4 , and IR_5 .

2.4. Soil moisture measurements

Soil moisture was determined in samples collected at the 0–20 cm soil layer at 15, 30, 45 and 60 days after transplanting (DAT). The determination of soil moisture ($g\ g^{-1}$) was performed in three replicates for each treatment, using the gravimetric method (Jarrell et al., 1999).

2.5. Leaf water potential

Leaf water potential (Ψ_{leaf}) was measured at 15, 30, 45 and 60 DAT, at 5 a.m. (predawn), according to Scholander et al. (1965), using a pressure camera (Model 3115, SOILMOISTURE). The third leaf, counted from the apex of the stem (i.e., the youngest mature leaf) was chosen for the measurement. Three replicates for each treatment were used.

2.6. Canopy temperature and thermal index

Canopy temperature (T_{canopy}) was measured using a FLIR I40 thermal camera, at the same dates used for measure soil moisture and leaf water potential. The device instantaneously identifies temperature with thermal sensitivity of $0.06^\circ C$ (thermal image resolution: 80×60 ; multi-spectral image resolution: 320×240). Thermal images were captured between 0.50 and 1.0 m away from the plants. The images were acquired manually with the camera on a tripod for better image adjustment. All images were captured between 8 and 9 a.m. (Brazilian Time, GMT - 3), and treated in the software FLIR QuickReport. For the quantification of the average temperature of the canopy (T_{canopy}), three images of each plant were captured from a total of three plants per treatment. Air temperature (T_{air}) was monitored using a HOBO U12-012 thermohygrometer with a data logger installed next to the experimental area. Data on T_{canopy} and T_{air} were used to calculate the thermal index $\Delta(T_{canopy} - T_{air})$, according to Jackson et al (1981).

2.7. Crop yield

Crop productivity was determined in each experimental unit by extrapolating the values for $t\ ha^{-1}$. Only fruits with commercial characteristics were counted, eliminating all fruits that showed defects. The fruits were sorted and classified manually.

2.8. Statistical analyses

The data were submitted to analysis of variance (F test), Tukey's test ($p \leq 0.05$) and regression analysis. The models were chosen based on the significance of the regression coefficients by the F test ($p \leq 0.05$)

and the highest value of determination coefficient (R^2). Statistical analyzes were performed using the software SISVAR (Ferreira, 2014).

3. Results And Discussions

3.1. Changes in canopy temperature, leaf water potential, and soil moisture during the phenological crop cycle

Figure 1 shows the mean values T_{canopy} , Ψ_{leaf} , and soil moisture measured at 15, 30, 45, and 60 DAT in soil with and without mulching. Figure 1A and 1B show an increase in T_{canopy} up to 45 DAT, followed by a decrease, except in treatments with 120% of ETC. Since the melon plant progressively increases water consumption over its phenological cycle, it is likely the most irrigation regimes do not meet the water requirements of the crop, particularly in the period of greatest demand. This assumption is based on increases in T_{canopy} which usually occurs when soil water availability is low and stomatal conductance decrease. According to Dejonge et al. (2015), T_{canopy} increases when solar radiation is absorbed, but the plant is cooled when this energy is used for leaf transpiration.

In general, T_{canopy} decreased when the water availability was elevated. When the plant was under well-watered conditions, T_{canopy} remained at values between 18 and 20° C and with small changes throughout the crop cycle (Fig. 1A, B). These results are similar to those obtained in other crops (Leinonen and Jones, 2004; Berni et al., 2009; Bellvert et al., 2016; Poblete-Echeverría et al., 2016), where water status was also estimated in plants using thermal information. Likewise, in other works there are reports of significant correlations between thermal information and physiological variables related to plant water status (Jones, 1999; López et al., 2012; Fuentes et al., 2014; Osroosh et al., 2016)

In general, higher T_{canopy} values occurred in treatments IR₄ and IR₅. This can be related to the greater water restriction imposed by these treatments during the melon crop cycle. Under these conditions, the plant closes the stomata and reduces the transpiration, which increases the canopy temperature (Lisar et al., 2012). In works by García-Tejero et al. (2018) with almonds, Pou et al. (2014) with grapevine, and Stuckens et al. (2011) in a citrus orchard, using thermography, it was observed that plants subjected to water restriction conditions had higher canopy temperatures. However, variations in meteorological variables can also directly influence the canopy temperature data (Maes and Steppe, 2012; Costa et al., 2013).

Plants growing in soil without mulching showed mean values of T_{canopy} 1.3 to 3.6°C higher than those observed in the treatments with soil cover. It is likely that mulching led to lower evaporation and, consequently, higher amount of water remains available to plants. The use of mulching resulted in soil water conservation (Fig. 1E, F), as demonstrated in other studies (Baumhardt et al., 2013; Jin et al. 2016; Kang et al. 2017; Liang et al. 2017; Yao et al. 2017), and helped plants to maintain lower canopy temperature (Ponge et al. 2013; Ni et al. 2019). This technique also contributes to increase crop yields

and water use efficiency, as demonstrated in a study carried out in semiarid regions of China (Wang et al., 2016).

The mean values of Ψ_{leaf} in IR₁ and IR₂ were - 0.079 and - 0.090 MPa, respectively, indicating that water supply was adequate in these treatments, with plants showing a good water status in the leaves. However, IR₃, IR₄, and IR₅ tended to decrease Ψ_{leaf} , especially at 45 DAT (Fig. 1C, D), the most critical moment in the melon cycle, with flowering and early fruit production (Miranda et al. 1999). These results indicate that water deficit intensifies in this period, mostly in treatments without mulching and that also showed lower soil moisture (Fig. 1E, F). According to some authors (Gonzalez-Dugo et al., 2014; García-Tejero et al., 2016; Bellvert et al., 2014), Ψ_{leaf} is a good indicator of the leaf water status. It is particularly important to indicate variations and water stress levels of plants under poor irrigation or different soil management (for example, soil cover), as showed in the present study (Fig. 1).

3.2. Crop yield, thermal index parameters and soil cover relationship

Thermal index was not affected by soil cover in treatment with the highest DI (60% less water, IR₅) at all evaluations (Fig. 2). This treatment also showed the highest and positive values of thermal index, indicating significant effects in the leaf water status. On the other hand, the results were statistically identical for soil cover considering the treatments with high irrigation depth (IR₁ and IR₂) at 15, 30, and 60 DAT, but the values were always negative, suggesting improvements in the crop water status (Fig. 2A, B, and D). However, the best contributions of the mulching was observed for treatments with moderate DI (up to 40% less water, IR₃ and IR₄), when plants showed lower thermal indexes at all evaluations, when comparing with those values observed in plants grown in soil without mulching. It can be stated that soil cover is efficient to maintain soil moisture values for a longer period, reducing the risk of water stress for the crops ((Jin et al. 2016; Wang et al. 2016; Dong et al., 2017). Our results showed the importance of mulching to ensure soil water availability at the moment of highest demand, even with high irrigation depth (100%), and for treatments with moderate DI (mainly up to 20%), helping plants to maintain the leaf water status, as showed by thermal image and leaf water potential analyses (Fig. 1).

Many authors consider that thermal index, $\Delta(T_{\text{canopy}} - T_{\text{air}})$, is more recommended to estimate the crop water stress using thermometric images due to its feasibility (García-Tejero et al., 2011; Costa et al., 2018; García-Tejero et al., 2018b). Urban et al. (2017) reported temperature differences up to 9°C between plants grown in dry and moist soil. Our results also indicated significant differences in the thermal index between irrigation regime treatments and between treatments with and without soil cover (Fig. 2). The use of mulching also led to better plant development conditions (Daryanto et al., 2017) and increased water use efficiency through lower water loss by evaporation, which leads to a greater volume of water stored for longer period (Wang et al., 2008; Zegada-Lizarazu and Berliner, 2011; Li et al., 2013).

Thermal index showed negative correlation with soil moisture (Fig. 3A) and with crop evapotranspiration (Fig. 3B). This implies that under ideal soil moisture conditions, there is high transpiration rates in the whole plant, markedly increasing crop evapotranspiration and reducing the temperature of the canopy (Schirrmann, et al., 2015; Tanaka et al., 2015; Schirrmann et al., 2016). On the other hand, low soil

moisture does not only affect the plant water relations by reducing the leaf water content and cell turgor, but also affects stomatal conductance, reducing leaf transpiration, raising canopy temperature and limiting carbon assimilation rates (Lisar et al., 2012).

Figure 3C shows the variation in $\Delta(T_{\text{canopy}} - T_{\text{air}})$ as a function of Ψ_{leaf} , which also exhibited a downward linear trend. Positive thermal index values occurred at lower Ψ_{leaf} , showing that water restriction made the T_{canopy} higher than the air temperature. These results indicate that under these conditions, melon leaves present lower transpiration rates and, consequently, T_{canopy} increases, evidencing that the crop is experiencing a certain water stress. Similar results were also observed by Ballester et al. (2013).

Figure 3D shows that when thermal index is closed to -3.2°C , crop yield reach values around 44.0 t ha^{-1} . However, when $\Delta(T_{\text{canopy}} - T_{\text{air}})$ reaches values around 0.0°C , productivity decreases to 34.0 ton ha^{-1} . Comparing crop yields obtained with the highest and lowest $\Delta(T_{\text{canopy}} - T_{\text{air}})$ values, a difference of 30.47 t ha^{-1} is observed, corresponding to 69% production loss. That is, when the thermal indexes were higher, the melon productivity decreased significantly. Reduction in the productivity under high canopy temperatures supports the comments by Lisar et. (2012) and DeJonge et al. (2015).

The thermal images presented in Tables 2 and 3 also show the impacts of the treatments on the thermal index and melon yield. In treatment with mulching (Table 2), images of plants under no DI (IR_1 and IR_2) presented values of ΔT lower than -3.3°C , with yield around of 44.0 t ha^{-1} . On the other hand, plants under low irrigation depths (IR_4 and IR_5), thermal index was higher in all observations, and the yield reached only 24.78 and 13.20 t ha^{-1} , respectively. These results showed that the use of infrared thermal images aided in recognizing the differences in the water availability for full and DI treatments, as was also demonstrated for vineyard and olive orchards (Grant et al. 2007; Costa et al. 2010; Bellvert et al., 2016; Poblete-Echeverría et al., 2016; García-Tejero et al. 2018).

On the other hand, in treatments without mulching (Table 3) the thermal index ranged from -3.0°C under full irrigation to $+3.8^{\circ}\text{C}$ for the most stressed treatment. Comparing data of Tables 2 and 3 it is possible to observe that plants cultivated in the soil with mulching showed better physiological performance and higher productions. Yao et al. (2017) and (Ni et al., 2019) state that the use of soil cover resulted in lower canopy temperature and favored the assimilation of nutrients, root development, water retention and soil aeration. Our results demonstrate that the analysis of thermometric images accurately demonstrates the positive impact of this technique, showing clear differences between treatments with and without soil cover. This beneficial effects of soil cover, confirmed also by thermal images, have been reported by other authors (Pereira et al., 2015; García-Tejero et al., 2016; Egea et al., 2017).

Our results showed that mulching was efficient to reduce thermal index and increase productivity, especially in the treatment with moderate water stress. For treatments with 20 and 40% of DI, there were increases of 30.6 and 52% in crop yield in plots with mulching, compared to plots without mulching. For the treatment without water deficit (100% of ET_c) there was also a beneficial effect of soil cover, with an

increase of about 24% in crop yield. Possibly, this treatment presented a deficit in the stage of greater water consumption, as evidenced by data of leaf water potential and canopy temperature, especially in soil without mulching (Fig. 1). The use of a non-regional crop coefficient explains, at least in part, this water deficit evidenced in this treatment. On the other hand, the treatment with application of 120% of the ETC showed no differences between the treatments with and without mulching, indicating that an additional 20% of water was necessary to meet the demand of the crop grown without soil cover.

4. Conclusions

Thermal index $\Delta(T_{\text{canopy}} - T_{\text{air}})$ showed high correlation with crop yield, leaf water potential and crop water consumption, demonstrating that thermal images are enough efficient to identify the water status of melon plants and may be employed as a irrigation management strategy under tropical semi-arid climate.

The use thermal images also allowed the identification of beneficial effects of soil cover on leaf water status and crop yield, especially under moderate deficit irrigation. The results also demonstrate that mulching is essential to increase the productivity and water use efficiency in the cultivation of melon in semi-arid tropical regions.

Declarations

Authors declare that the melon used in the experiment was the F1 goldex hybrid, purchased from the company Top Seed. I also inform you that the field study was in compliance with Brazilian law.

Declaration of Competing Interest: Authors declare that they have no conflict of interest

Acknowledgements

Acknowledgments are due to the 'Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq)', 'Instituto Federal de Educação, Ciência e Tecnologia do Estado do Ceará (Campus Sobral)', and 'Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES), Brazil, for the financial support for this research.

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Tables

Due to technical limitations the tables are available as a download in the Supplementary Files.

Figures

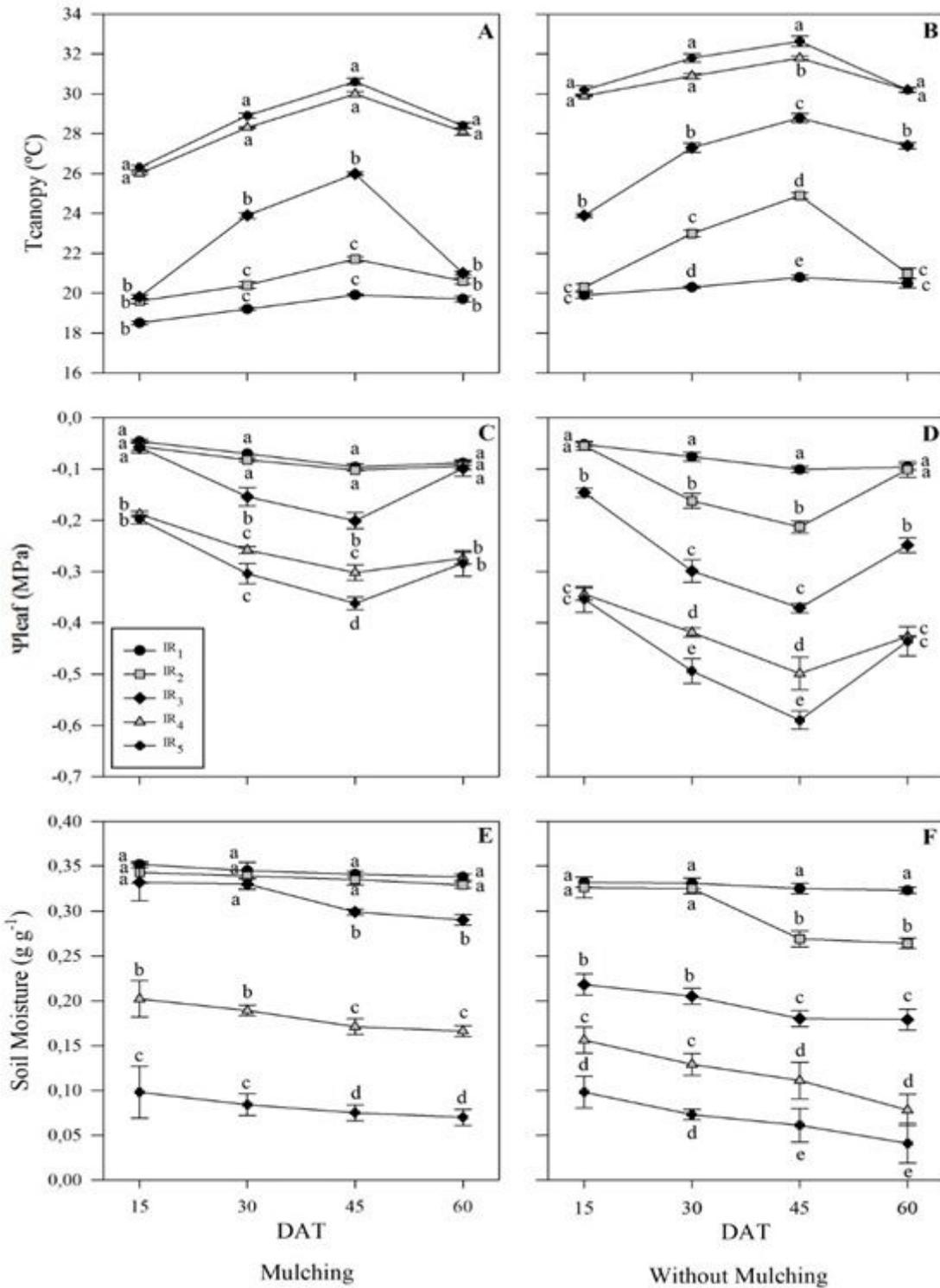


Figure 1

Variations in mean canopy temperature-Tcanopy (A and B), leaf water potential- Ψ_{leaf} (C and D), and soil moisture (E and F) at 15, 30, 45, and 60 days after transplant (DAT) under different irrigation regimes (IR1 120, IR2 100, IR3 80, IR4 60, and IR5 40% of ETC) in soil with (A, C, and E) and without mulching (B, D, and F). Means followed by the same letter, for irrigation treatments at each measurement date, do not differ by Tukey's test (p < 0.05). Vertical bars represent errors of the means.

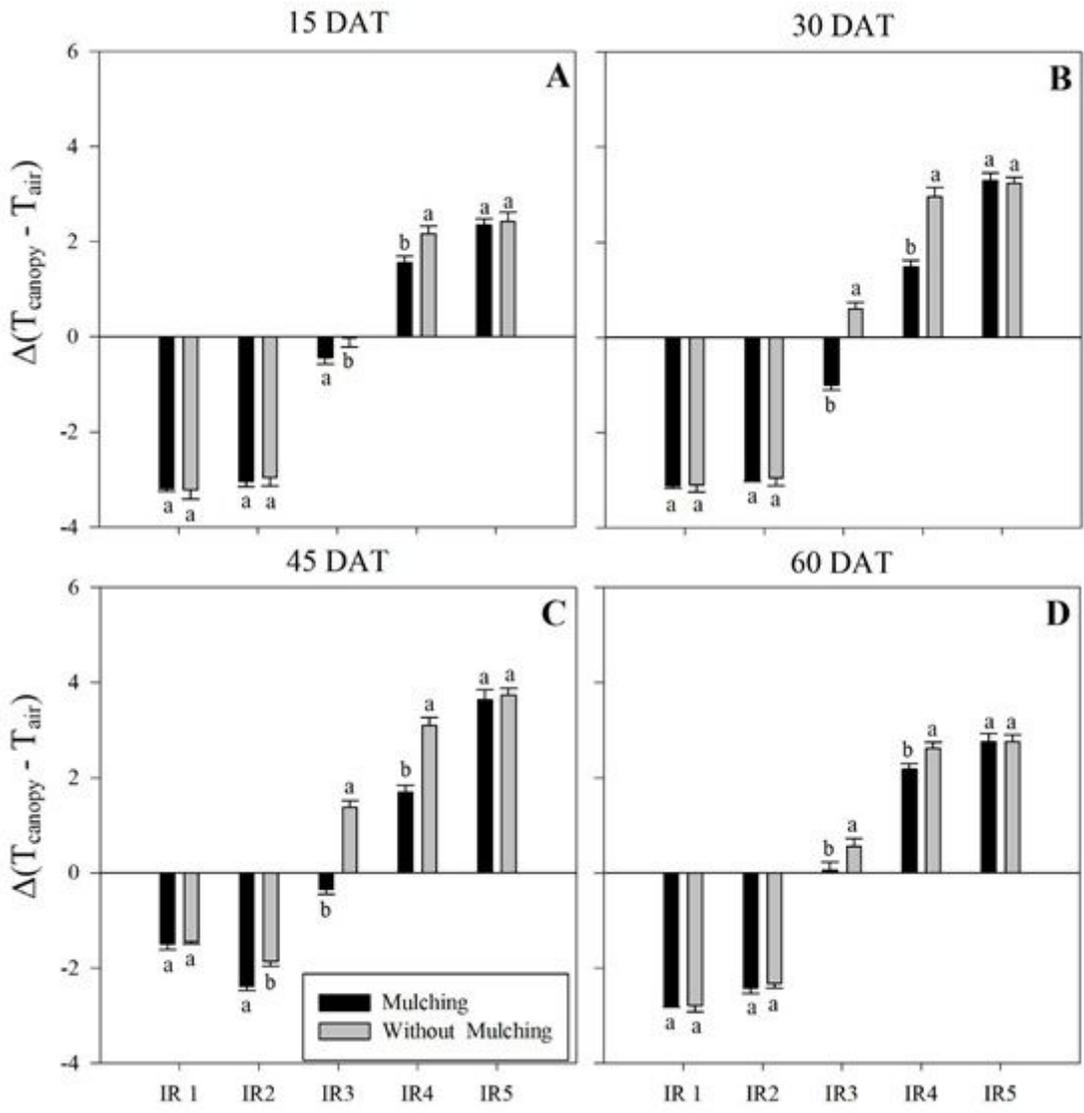


Figure 2

Means of thermal index $\Delta(T_{\text{canopy}} - T_{\text{air}})$ as a function of irrigation regimes and soil cover (with and without of mulching) at 15 (A), 30 (B), 45 (C), and 60 days after transplant (DAT) at different irrigation regimes (IR1 120, IR2 100, IR3 80, IR4 60, and IR5 40% of E_{Tc}). Means followed by the same letter, for mulching treatments at each irrigation regime, do not differ by Tukey's test ($p < 0.05$). Vertical bars represent errors of the means.

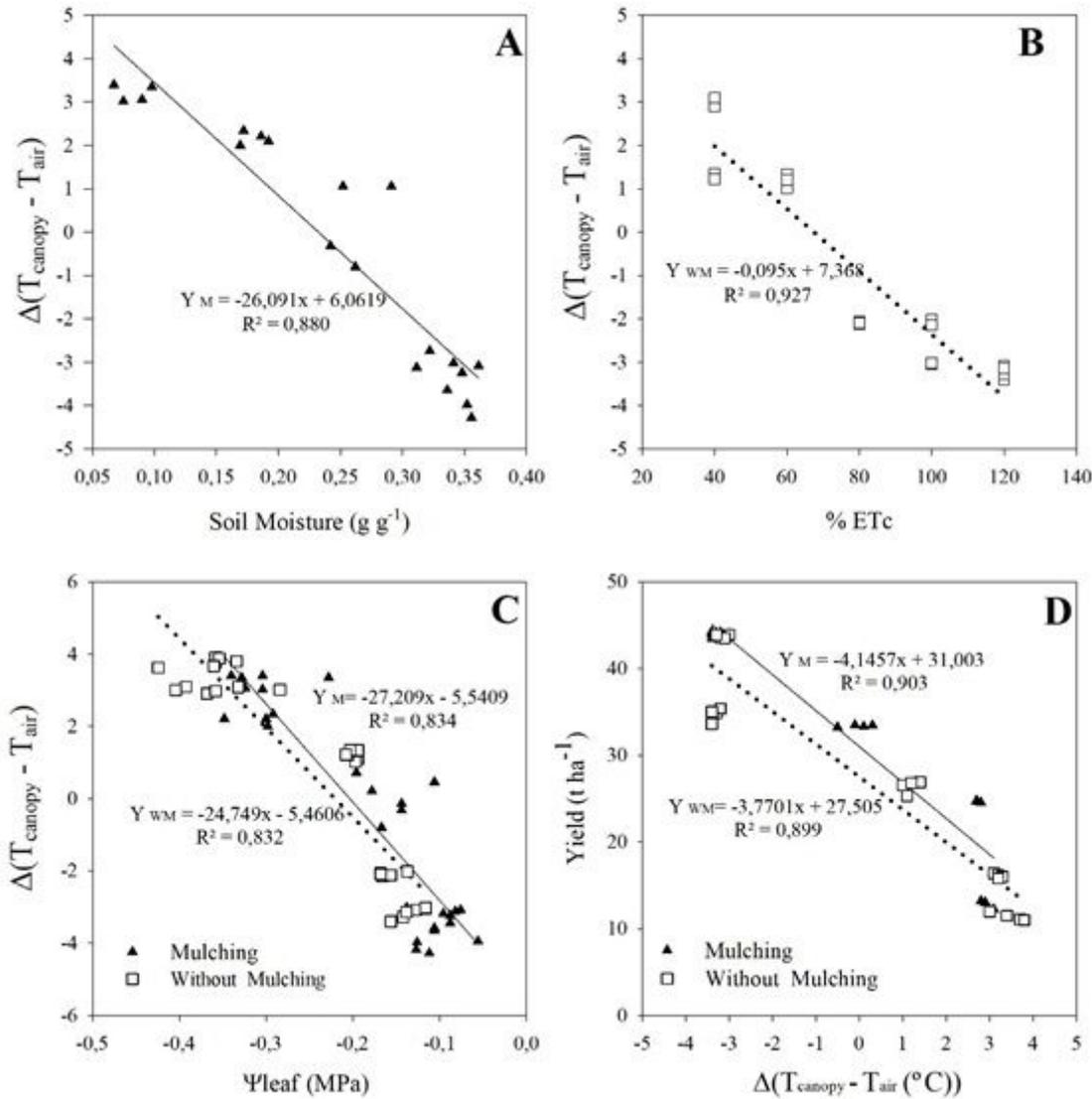


Figure 3

Relationships between thermal index $\Delta(T_{\text{canopy}} - T_{\text{air}})$ and soil moisture (A), thermal index and crop evapotranspiration-ETc (B), thermal index and leaf water potential (C), and crop productivity and thermal index (D).

Supplementary Files

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