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TECHNOLOGICAL INFORMATION

Canonical correlation analysis applied to regulated deficit irrigation in 'Tommy Atkins' mango trees

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ABSTRACT. The objective was to identify the effect of regulated deficit irrigation on physiological, yield and root descriptors of 'Tommy Atkins' mango tree grown in a semi-arid region of Brazil. The work was carried out during two production cycles on an 11-year-old mango orchard. The design was randomized blocks with five treatments and six replications. Irrigation treatments were based on the trees' development stage: T1, irrigation supplying 100% of the crop evapotranspiration (ETc) in three production stages: fruit set stage (SI), fruit expansion stage (SII), and physiological maturation stage of the fruits (SIII); T2, 50% ETc in SI and 100% ETc in SII and SIII; T3, 100% ETc in SI and SIII and 50% ETc in SII; T4, 100% ETc in SI and SII, and 50% ETc in SIII; and T5, without irrigation in all three stages. Physiological data were measured once per stage. After harvesting the second cycle, roots were collected, following a completely randomized design, with five treatments and three replications, to determine the total root length density. Total or partial water deficit in 'Tommy Atkins' mango trees was identified by decreasing transpiration (*E*) and photosynthesis (*A*) and increasing leaf temperature (*Tleaf*). The total root length density is similar in all irrigation strategies up to 1 m horizontal distance and 0.10 m depth. Water deficit applied in the physiological maturation stage improves yield and water use efficiency.

Keywords: grouping; multivariate analysis; water deficit; semi-arid region.

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Introduction

With a production of 1.319 million tons in 2018, Brazil is one of the largest mango producing countries. Of this production, 221,913 tons were exported, which makes mango the most exported fruit in Brazil (Carvalho, Kist, & Beling, 2019). This success is mostly due to suitable soil and climate conditions coupled with the use of irrigation, which guarantees mangoes throughout the year, mainly in semi-arid regions.

Under conditions of limiting water resources and irregular rainfall in semi-arid regions, irrigation is required to obtain profitable yields. However, irrigation accounts for 50% of all the water consumption in the country (ANA, 2022). Thus, irrigation water management must be re-evaluated by further studying the feasibility of deficit irrigation strategies in mango (Zuazo et al., 2021).

Among deficit irrigation techniques, regulated deficit irrigation (RDI) and partial rootzone drying (PRD) stand out. These techniques aim to reduce the water demand of plants (evapotranspiration) by improving water productivity without decreasing or damaging yields (Sánchez-Blanco, Ortuño, Bañon & Álvarez, 2019).

Deficit irrigation techniques for mango trees grown under Brazilian semi-arid conditions have been studied (Faria, Soares, Donato, Santos, & Castro, 2016; Cotrim, Coelho-Filho, Coelho, Ramos, & Cecon, 2011; Cotrim, Coelho, Silva, Coelho-Filho, & Santos, 2017; Santos, Martinez, Donato, & Coelho, 2014a; Santos, Donato, Coelho, Cotrim-Junior, & Castro, 2016; Santos, Cotrim-Junior, Mesquita, Donato, & Coelho, 2020), as well as in other semi-arid (Darwisch & El-soufany, 2017) and subtropical environments (Levin et al., 2017; Pleguezuelo et al., 2018). All these authors used univariate statistics to interpret their results; nonetheless, this type of analysis makes it difficult to have an all-encompassing view of the effect of water deficit on all traits of agronomic importance. Conversely, multivariate statistics may be a viable alternative to pinpoint the relevant variables, thereby giving valuable insight into the biological phenomenon under study (Tavares, Valadão, Santos-Weber, & Espinosa, 2019). Therefore, using multivariate analysis can provide greater scientific support for the adoption of deficit irrigation techniques.

Canonical correlation analysis, a type of multivariate analysis, consists in creating new variates through linear combinations between the original data under study, called canonical variables (Varella, Carvalho-Pinto, Costa, & Silva, 2019). Using multivariate analysis allows us to discriminate the observed variables to group homogeneous data (Benitez, Rodrigues, Arge, Ribeiro, & Braga, 2011). For Mirzaie et al. (2014), multivariate statistical methods provide better results than univariate analyses. This is because multivariate analysis performs correlations between the analyzed variables, showing the simultaneous effect of the data, whereas univariate analysis does not show the same relationship (Varella et al., 2019).

The objective was to identify the effect of regulated deficit irrigation on physiological descriptors, yield and root of 'Tommy Atkins' mango trees grown in a semi-arid region of Brazil using the canonical correlation analysis.

Material and methods

Experimental site

The experiment was carried out on an experimental orchard located in Ceraíma Irrigated Perimeter, in the municipality of Guanambi, Bahia State, Brazil (14º13'30" S, 42º46'53" W, 525 m of altitude). The region has an average annual precipitation of 680 mm and an average annual temperature of 25.6°C. The climate is hot and dry semi-arid with rainy season concentrated from November to March. The soil has been classified as medium-textured Eutrophic *Neossolo Flúvico* with high activity clay (Santos et al., 2018), which corresponds to a Fluvisols (IUSS Working Group WRB, 2015) or an Fluvents (Soil Survey Staff, 2014).

The study was performed for two crop cycles (2010 and 2011) on 11- to 12-year-old 'Tommy Atkins' mango trees. Regulated deficit irrigation (RDI) was applied from the beginning of flowering to fruit maturation. Figure 1 shows daily values of mean air temperature, mean relative humidity, rainfall and wind speed measured during the experimental period.

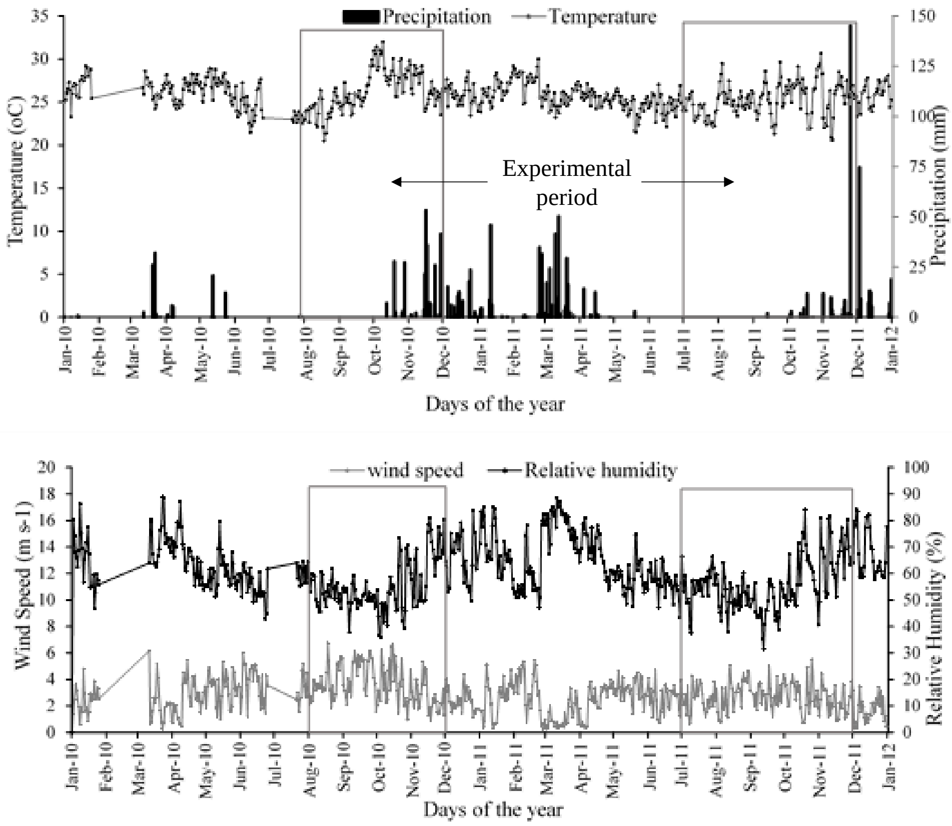

Figure 1. Daily values of mean air temperature (A), wind speed (B), precipitation (C) and relative humidity (D) for the years 2010 and 2011 in the experimental orchard.

Five treatments were arranged in randomized blocks and replicated six times. Each experimental unit consisted of one tree. The trees were spaced 8 x 8 m apart. One microsprinkler with flow rate of 56 L h^{-1} and operating pressure of 200 kPa was installed per plant, at 0.5 m from the trunk.

Crop practices and irrigation scheduling

Trees were managed following common practices for mango grown in the region. Following the harvest, each plant was fertilized with 500 g of monoammonium phosphate (MAP), 200 g of ammonium sulfate, 150 g of potassium chloride, and 20 kg of chicken manure. Before the beginning of the experiment, the trees were irrigated daily until the appearance of two vegetative flushes per branch. Thereafter, a growth regulator (Paclobutrazol) was applied to the trees and irrigation was interrupted. When the trees exhibited terminal branch epinasty (Mouco & Albuquerque, 2005), calcium nitrate was applied to leaves to stop bud dormancy and induce uniform flowering. After that, irrigation treatments were applied at the production phase, which comprises three stages.

Stage I (SI) is from flowering to fruit set, about 65 days after flowering (DAF). Stage II (SII) corresponds to the period of expansion of fruits, approximately 95 DAF. Stage III (SIII) corresponds to growth and physiological maturation of fruits, which occurs about 120 DAF. Treatments were applied during the three stages: T1, irrigation supplying 100% of ETc (crop evapotranspiration) in the three stages; T2, 50% ETc in SI and 100% ETc in SII and SIII; T3, 100% of ETc in SI and SIII and 50% of ETc in SII; T4, 100% ETc in SI and SII and 50% ETc in SIII; and T5, without irrigation in all stages.

Irrigation scheduling was based on crop evapotranspiration, which is a product of reference evapotranspiration (ETo) and crop coefficient (Kc). Reference evapotranspiration was calculated daily using the standard FAO method, Penman-Monteith (Allen, Pereira, Raes, & Smith, 1998), using data from an automatic weather station installed near the orchard. Crop coefficients ranged from 0.45 to 0.87, as used by Cotrim et al. (2011) and Santos, Martinez, Donato, and Coelho (2014b). Irrigation water came from a tubular well with electrical conductivity between 0.62 and 1.32 dS m^{-1}.

In the first cycle, irrigation began at 10 DAF and ended at 115 DAF (SII). As for the second cycle, irrigation ended at 136 DAF (SIII). Afterwards there were no more irrigation events because the rains met the water demand of the trees. The irrigation run time was calculated using the equation proposed by Goodwin and Boland (2002). Location coefficient (Kl) was obtained using the Fereres method, according to Bernardo, Soares, and Mantovani (2006).

Analyzed variables

During each development stage and in all treatments, the following data were collected: transpiration rate (*E*), photosynthesis (*A*), stomatal conductance (*gs*), internal CO_2 concentration (*Ci*), leaf temperature (*Tleaf*), and photosynthetically active radiation incident on the leaf (*Qleaf*). In the first cycle, data were collected between 10:00 and 11:00 am, and in the second cycle, between 1:00 pm and 2:00 pm, using an infrared gas analyzer (IRGA), model LC PRO (ADC Bioscientific Ltd, Great Amwell, England).

Yield was evaluated according to individual fruit weights, as these were separated every 100 g into nine weight classes: yield for 100 g fruits (Y100); yield for 200 g fruits (Y200); yield for 300 g fruits (Y300); yield for 400 g fruits (Y400); yield for 500 g fruits (Y500); yield for 600 g fruits (Y600); yield for 700 g fruits (Y700); yield for 800 g fruits (Y800); and total yield (Ytotal). Water use efficiency (WUE) was the ratio between yield and gross irrigation water depth plus precipitation. Instantaneous water use efficiency (*A*/*E*) was the ratio between photosynthesis and transpiration.

In the second cycle, after harvesting, the roots were sampled following a completely randomized design, with five treatments and three replications and one plant per experimental unit. The length and diameter of the roots were determined for all treatments and the root length density (RLD) was the ratio between the total root length and the soil volume occupied by the roots.

Samples were collected at four depths (0.10, 0.35, 0.60, and 0.85 m) and five distances from the trunk. These five distances were split into two groups. The first group comprised roots collected at 0.5-m- and 1.0-m-away from the trunk. Roots collected at 1.5-m-, 2.0-m- and 2.5-m-away from the trunk formed the second group. The volume of each sample used to obtain the RLD was 500 cm^3 (10.00 x 10.00 x 5.00 cm).

After sampling the roots, the samples were placed in plastic bags and taken to a laboratory to wash the soil off the roots. Afterwards, the samples were separated according to their position in the soil profile and scanned into a computer. The files were converted to TIFF (Tagged Image File Format) and analyzed using Rootedge application (Kaspar & Ewing, 1997) to determine length and diameter of the roots. Root length density was calculated using the methodology described by Santos et al. (2014a). Then, all root lengths were added up to obtain the total root length density (TRLD).

Data analysis

Physiological, yield and total root length density data were analyzed by multivariate statistics. To obtain the multivariate analysis of variance, the 'manova' function of the 'stats' package was used. Canonical variables were studied using the 'candisc' package. A split-plot in time arrangement was used, with the year assigned to the subplot. Data on water use efficiency were tested by univariate analysis, in a split-plot arrangement, with the RDI treatments in the plot and the crop cycle in the subplot. Then, Tukey test was performed at a 5% significance level using Sisvar software. The graphs were created using Microsoft Excel®.

Results and discussion

Physiological data

By the analysis of canonical variables (Table 1), the physiological data most associated with the first and second canonical variable in stage I were leaf temperature (*Tleaf*), internal CO_2 concentration (*Ci*), stomatal conductance (*gs*), photosynthesis (*A*), and transpiration (*E*). In stage II, the variables were leaf temperature (*Tleaf*), photosynthetically active radiation incident on the leaf (*Qleaf*), instantaneous water use efficiency (*A/E*), transpiration (*E*) and photosynthesis (*A*). In stage III, they were transpiration (*E*), stomatal conductance (*gs*), photosynthesis (*A*), leaf temperature (*Tleaf*), and instantaneous water use efficiency (*A/E*).

Table 1. Correlations between the first and second canonical variables (V_1 and V_1) with photosynthetically active radiation incident on the leaf (*Qleaf*), leaf temperature (*Tleaf*), internal CO_2 concentration (*Ci*), transpiration (*E*), stomatal conductance (*gs*), photosynthesis (*A*), and instantaneous water use efficiency (*A/E*) in the three stages of development.

Variable	Stage I		Stage II		Stage III	
	V_1	V_2	V_1	V_2	V_1	V_2
Q_{leaf}	-0.4578	-0.2142	0.9022	0.2251	0.4417	-0.5105
T_{leaf}	-0.9169	0.3009	0.9716	0.1669	0.6051	-0.5681
Ci	0.6897	0.1168	-0.5408	-0.2641	0.3627	-0.4800
E	-0.2814	-0.7164	0.2480	0.8081	0.8848	0.0468
Gs	-0.1085	-0.8028	-0.5487	0.4252	0.7820	0.2242
A	-0.2159	-0.8146	-0.3312	0.6734	0.6322	0.5562
A/E	0.0955	0.1150	-0.6944	0.0813	-0.1639	0.7844

The differences in physiological data associated with the first two canonical variables (Table 1) were due to the different irrigation regimes applied to the crop, which promote changes in the trees' metabolism, causing some physiological components to be expressed more significantly. Leaf temperature (*Tleaf*), transpiration (*E*) and photosynthesis (*A*) are important for the study of dissimilarity on the effects of RDI in the three production stages of the mango tree. Through these physiological data, it is possible to identify the water levels in the plant because incident solar radiation, air temperature, soil moisture, and, especially, the development stage of the plant directly affect its water status. Therefore, these processes depend on soil-water-plant-atmosphere interactions.

For Schaffer, Andersen, and Crane (1994), transpiration is a good indicator of water availability in mango trees. When the plant is in an environment with adequate water supply, transpiration rates are generally high. When soil moisture decreases, transpiration rates decrease due to stomatal closure, a strategy used by the plant to reduce water loss (Salisbury & Ross 1992). Therefore, another variable of great importance for the study of water relations is stomatal conductance (*gs*), which was associated to define the dissimilarity of the data in stages I and III (Table 1).

Stomatal conductance is a mechanism for controlling gas exchange in plants, so the lower the water level in the soil, the lower the stomatal conductance to reduce water loss by the plant. Thus, the low water availability in the soil reduces stomatal conductance and transpiration, thereby reducing photosynthesis rates (Silva, Santos, Lira, Santana, & Silva-Junior 2010). These reductions due to water deficit influence turgor, thus impairing cell growth (Taiz, Zeiger, Moller, & Murphy, 2017).

The relationship between the canonical variable 1 (V_1) and the canonical variable 2 (V_2), referring to the physiological parameters from the initial flowering stage to the fruit set (stage I), for the two cycles under study, showed that 62.33% of the variation was explained by the V_1 axis and 20.53% by the V_2 axis. The two variables together explain 82.86% of the total variation in the data, allowing the study of graphical dispersion (Figure 2).

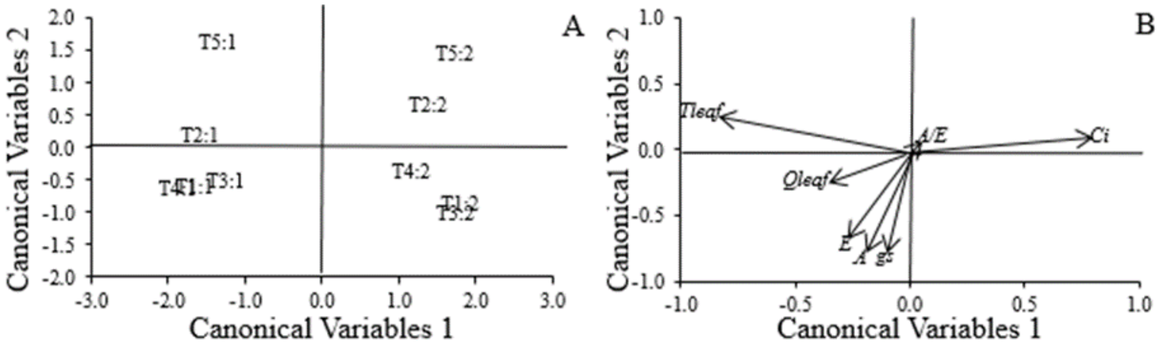

Figure 2. Dispersion of scores: treatments from the first (T1:1, T2:1, T3:1, T4:1 T5:1) (A) and second (T1:2, T2:2, T3:2, T4:2 and T5:2) (B) cycles concerning the physiological data of photosynthetically active radiation incident on the leaf (*Qleaf*), leaf temperature (*Tleaf*), internal CO_2 concentration (*Ci*), transpiration (*E*), stomatal conductance (*gs*), photosynthesis (*A*), and instantaneous water use efficiency (*A/E*), sampled from the beginning of flowering until the fruit set of 'Tommy Atkins' mango tree.

The multivariate test indicated differences between the two crop cycles (Figure 2): the first cycle was positioned on the left, exhibiting negative values for V_1. Meanwhile, the second crop cycle expressed positive values for the same variables and was on the right. Rain-fed plants (T5:1 and T5:2) showed positive values for V_2, diverging only in V_1, which was responsible for dividing the data.

Mango trees without irrigation in the second cycle (T5:2) showed low transpiration rates (*E*), stomatal conductance (*gs*), photosynthetically active radiation incident on the leaf (*Qleaf*), and photosynthesis (*A*), and increased internal CO_2 concentration (*Ci*) and instantaneous water use efficiency (*A/E*). Plants from treatments 1, 3 and 4 of the second evaluation cycle (T1:2, T3:2 and T4:2), without deficit in stage I, showed similar results and differed from plants from treatments 2 and 5 (T2:2 and T5:2). The 50% reduction of ETc in this stage for T2:2 plants increased the instantaneous water use efficiency (*A/E*) and the internal CO_2 concentration (*Ci*).

In the first cycle, plants under treatments 1, 3 and 4 (T1:1, T3:1 and T4:1) had high rates of photosynthetically active radiation incident on the leaf (*Qleaf*), transpiration (*E*) and stomatal conductance (*gs*) and photosynthesis (*A*), and low internal CO_2 concentration (*Ci*) and instantaneous water use efficiency (*A/E*). The mango trees under treatment 2 in the first cycle (T2:1) had high leaf temperature values (*Tleaf*), as a result of the partial water deficit in the first stage (SI).

The differences in positioning of the treatments in the two cycles, one on the left (cycle 1) and the other on the right (cycle 2) (Figure 2), were due to the time of reading the physiological variables because such measurements are time-point (Santos et al. 2014b; 2016) and influence the result. For Salisbury and Ross (1992), as a crop adaptation, plants grown under water deficit conditions (T5:2) (Figure 2) reduce their transpiration to prevent water loss. Conversely, irrigated plants generally have higher transpiration rates. Satisfactory water conditions explain the high transpiration rates in treatments 1, 3 and 4 (T1:1, T3:1 and T4:1).

The behavior of the scores associated with the physiological data for the fruit expansion stage (stage II) in the two evaluation cycles can be seen in Figure 3. The first two canonical variables, V_1 and V_2, correspond, respectively, to 86.65% and 8.89%, which represents 95.54% of the data variability.

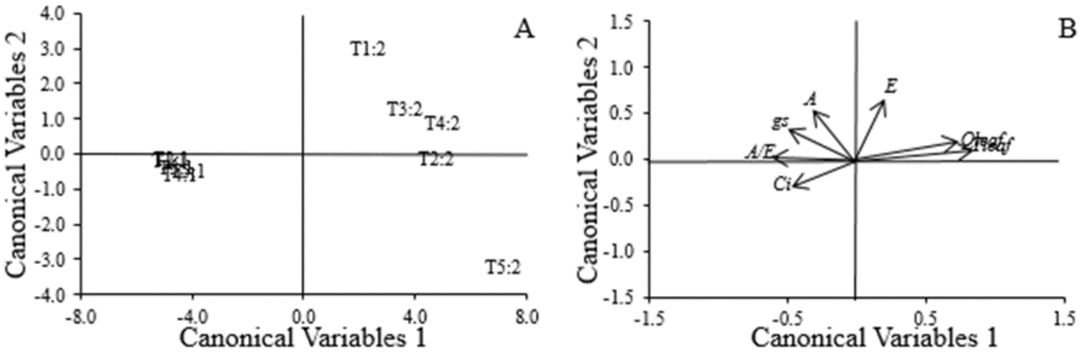

Figure 3. Dispersion of scores: treatments from the first (T1:1, T2:1, T3:1, T4:1, and T5:1) (A) and second (T1:2, T2:2, T3:2, T4:2, and T5:2) (B) cycles concerning the physiological data of photosynthetically active radiation incident on the leaf (*Qleaf*), leaf temperature (*Tleaf*), internal CO_2 concentration (*Ci*), transpiration (*E*), stomatal conductance (*gs*), photosynthesis (*A*), and instantaneous water use efficiency (*A/E*), sampled in the expansion stage of 'Tommy Atkins' mango fruits.

The fruit expansion stage showed the same behavior as that in stage I, separating those from the evaluation cycles (Figure 3). In the second cycle, in the fruit expansion stage, fully irrigated plants (T1:2) reached high values of transpiration (*E*) and low levels of internal CO_2 concentration (*Ci*) in the leaves.

Plants under treatments 3 and 4 in the second cycle (T3:2 and T4:2) expressed high values of photosynthetically active radiation incident on the leaf (*Qleaf*) and leaf temperature (*Tleaf*) and low rates for internal CO_2 concentration (*Ci*). Mango trees under treatment 2 in the second cycle (T2:2) showed low stomatal conductance (*gs*), photosynthesis (*A*) and instantaneous water use efficiency (*A/E*).

All treatments from the first evaluation cycle were close to each other, which provided the plants with low values of transpiration (*E*), photosynthetically active radiation incident on the leaf (*Qleaf*) and leaf temperature (*Tleaf*). On the other hand, it showed high values for the internal CO_2 concentration (*Ci*).

Available soil moisture establishes a comfort zone for the plant, which, in turn, increases transpiration rates (Salisbury & Roos, 1992) as well as RuBisCO carboxylation efficiency (Taiz et al., 2017). This result occurred in plants in stage II of the second cycle (Figure 3). According to Silva, Souza, Leone, Souza, and Tanaka (2012), leaf temperature of irrigated plants tends to be lower than that of rain-fed plants, as the loss of latent heat is the main form of cooling (Taiz et al., 2017). In this work, a different result was obtained for the plants from T4:2 (Figure 3), which had full irrigation at this stage.

In the first cycle, it is not possible to observe differences, as plants are 11 years old and the orchard went through a period in which no crop practices and irrigation were carried out, which might have affected the results. The plants expressed differences under each deficit condition.

Figure 4 shows two-dimensional scatter plots of the scores related to V_1 and V_2 of the physiological parameters measured at fruit growth and physiological maturation stage (stage III). The first two canonical variables explain 92.51% of the data behavior. V_1 explains 67.57% of the variation, while V_2 explains 24.94%. In all stages of development of the mango trees, the sensitivity of the analysis of canonical variables was verified, separating the two study cycles. However, in stage III, the side on the graph changed, as the first cycle is on the positive side of V_1 and the second cycle is on the negative side.

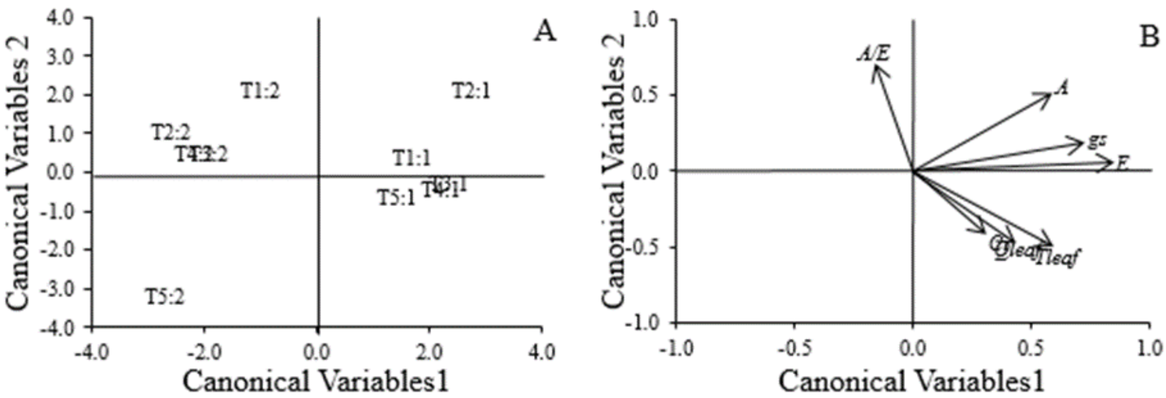

Figure 4. Dispersion of scores: treatments from the first (T1:1, T2:1, T3:1, T4:1, and T5:1) (A) and second (T1:2, T2:2, T3:2, T4:2, and T5:2) (B) cycles concerning the physiological data of photosynthetically active radiation incident on the leaf (*Qleaf*), leaf temperature (*Tleaf*), internal CO_2 concentration (*Ci*), transpiration (*E*), stomatal conductance (*gs*), photosynthesis (*A*), and instantaneous water use efficiency (*A/E*), sampled in the growth and physiological maturation stage of 'Tommy Atkins' mango tree.

In the first production cycle, trees under the treatments 2, 3, and 4 (T2:1, T3:1, and T4:1) expressed high values for stomatal conductance (*gs*) and transpiration (*E*). These rates might be explained by the presence of soil moisture at adequate levels. Trees grown under treatment 1 (T1:1) showed high photosynthesis rates, while plants under treatment 5 (T5:1) had higher values for leaf temperature (*Tleaf*), internal CO_2 concentration (*Ci*), and photosynthetically active radiation incident on the leaf (*Qleaf*) (Figure 4).

Trees under treatments 2, 3 and 4 applied in the second cycle (T2:2, T3:2, and T4:2) grouped together and showed low values of photosynthetically active radiation incident on the leaf (*Qleaf*), internal CO_2 concentration (*Ci*) and leaf temperature (*Tleaf*). These physiological data differed from those of rain-fed (T5:2) and fully irrigated (T1:2) trees. The T1:2 treatment, despite causing differences in the variables, led to results close to those of the grouping. Mango trees under T5:2 showed lower transpiration (*E*), photosynthesis (*A*), stomatal conductance (*gs*) and instantaneous water use efficiency (*A/E*) and were different from those of the other treatments. Trees under T1:2 and T5:2 expressed different physiological results than those of RDI-treated trees.

In stage III, it rained on the area; as the measurements are time-point, the rainfall influenced the results; therefore, the graph in Figure 4 had to be modified. Moreover, it could be due to the fact that stage III is considered the stage where ‘Tommy Atkins’ tree is least sensitive to drought, according to studies carried out by Santos, Martinez, and Donato (2013) and Cotrim et al. (2011; 2017).

The high values of photosynthetic rates recorded in fully irrigated plants revealed that soil moisture was at satisfactory levels. On the other hand, under water deficit conditions, ‘Tommy Atkins’ mango trees have mainly higher leaf temperature values than those of fully irrigated plants (Silva et al., 2012).

The rainy season (Figure 4) raises soil water levels, but this increase in moisture was not enough, for example, to increase stomatal conductance of T5 plants (without irrigation), caused by the closure of the stomata due to history of water deficit suffered by mango. The use of this stomatal closure strategy occurs due to a signal coming from the roots at a time of water deficit, promoting the synthesis abscisic acid (ABA), which is translocated to the leaves via xylem and promotes stomata closure (Taiz et al., 2017). Although it prevents plants from losing water by reducing transpiration, stomatal closure reduces photosynthesis.

Yield as to mean fruit weight

In the dispersion of treatments and yields by weight of fruits as a function of scores and placement of the eigenvectors of the first two canonical variables, the first explaining 68.07% of the data and the second 18.71%, together explaining 86.77% of total data variance (Figure 5).

Trees under the treatments 1 and 2 of the second production cycle (T1:2 and T2:2) (Figure 5) expressed better responses because the fruit yield classes of 500, 600, 700, and 800 g, as well as total yield (Y500, Y600, Y700, Y800, and Ytotal), were the most relevant variables for these treatments. The mango trees under treatment 2 (T2:2), despite the reduction in water in the fruit set stage, reached significant yield values in the higher weight classes.

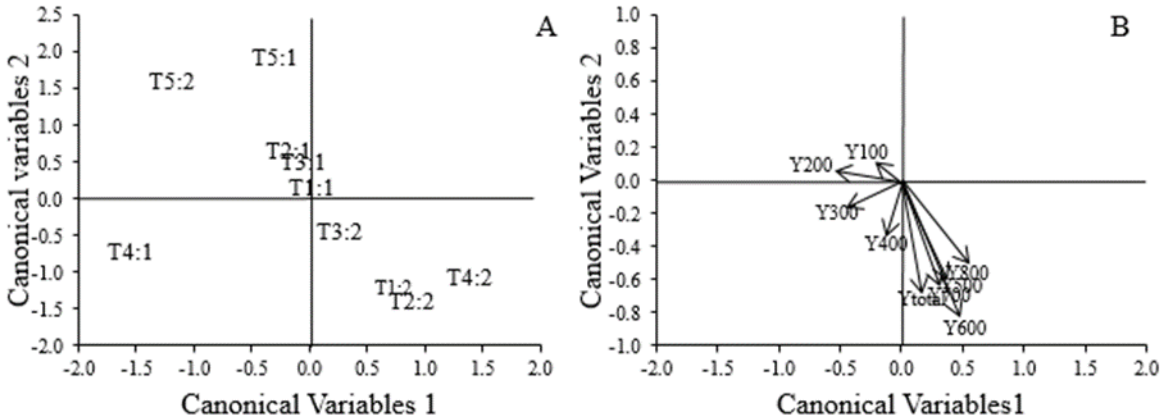

Figure 5. Dispersion of scores: (A) for treatments from the first cycle (T1:1, T2:1, T3:1, T4:1, and T5:1) and from the second cycle (T1:2, T2:2, T3: 2, T4:2, and T5:2) concerning yield data grouped every 100 g in nine classes (Y100, Y200, Y300, Y400, Y500, Y600, Y700, Y800, and Ytotal) for each treatment.

The grouping of weights of Y500, Y600, Y700, Y800, and Ytotal was also responsible for the good performance of plants from treatments 4 and 3 in the second cycle (T4:2 and T3:2). However, trees from treatment 4 of the first cycle (T4:1) are isolated in one of the quadrants of Figure 5, as it had negative values for V_1, thus showing lower fruit weights for Y500, Y600, Y700, Y800, and Ytotal.

Plants of treatments T5:1 and T5:2 showed a high value for V_2, while Y500, Y600, Y700, Y800, and Ytotal expressed a negative correlation for this variable; therefore, they are inversely proportional as this high correlation value represents low yield in these classes. In this case, the plants of T5:1 and T5:2 had more fruits weighing 100, 200, and 300 g. Mango trees under T2:1, T3:1, and T1:1 revealed more significant amounts in all specific fruit weight class.

Plants under treatment 2 (T2:2) (Figure 5) reached significant high yields in the higher weight classes, which differs from the results reported by Santos et al. (2013), who found that a 50% reduction in ETc in stage I significantly reduces yield compared to full irrigation. Mangoes under treatments 4 and 3 in the second cycle (T4:2 and T3:2) had results similar to those found by Santos, Neves, Silva, and Donato (2015), who identified that the deficit in the fruit expansion and physiological maturation stages did not show a reduction in yield.

Furthermore, in the assessment by Santos et al. (2014b) on the yield of the 'Tommy Atkins' mango tree, stage III yielded fruits belonging to weight classes that are more desirable in foreign markets.

Plants with deficit in stage III of the first cycle (T4:1) (Figure 5) had a significant amount of fruits in 300- and 400-g weight classes. This result is similar to that found by Cotrim et al. (2011; 2017), who reported the average fruit weight of 'Tommy Atkins' mango tree of around 400 g. Trees with water deficit in all stages (T5:1 and T5:2) produce fruits with lower weights. The stress induced by water deficit increases the drop of fruits in the treatments, resulting in a lower number of fruits (Levin et al., 2017). This fact was also evidenced in the study on the use of RDI in 'Tommy Atkins' mango conducted by Cotrim et al. (2011), who reported lower yield for the rain-fed treatment, while fully irrigated plants had higher yields.

Root length density

Figure 6 shows the dispersion of scores for each treatment as to total root length density (TRLD), distance from the trunk and depth of the root system, as a function of scores and placement on diagrams of the eigenvectors. The first canonical variable explains 56.92% of the data and the second variable explains 30.78%, and the two canonical variables can explain 87.70% of the total variation of the data, so it is possible to evaluate the graphical dispersion. Plants under all treatments show different TRLD distribution (Figure 6). However, the roots up to 1 m horizontally and at a depth of 0.10 m were present in all treatments almost equally.

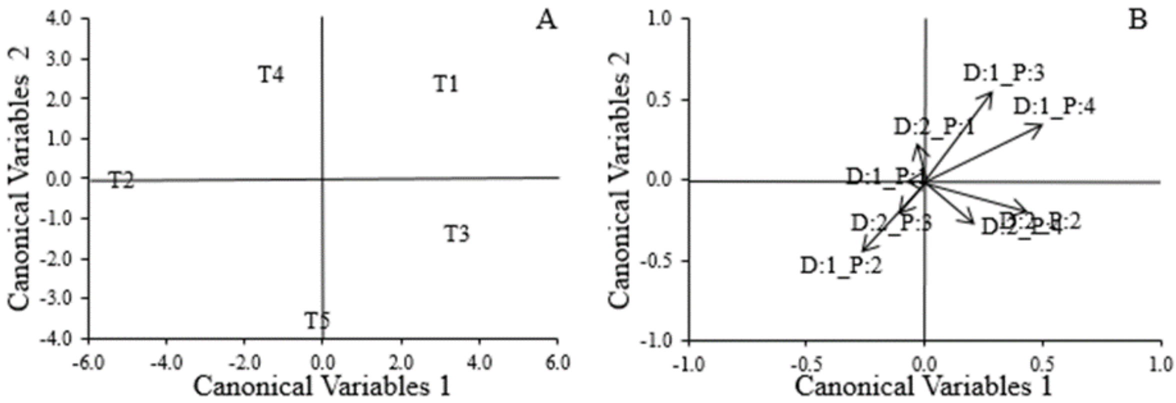

Figure 6. Dispersion of scores: (A) for the five treatments (T1, T2, T3, T4, and T5) (B) as a function of the total root length density, divided into two groups of distance Dt1 (0.5 and 1.0 m) and Dt 2 (1.5; 2.0, and 2.5 m) and at four depths Dp1 (0.10 m), Dp2 (0.35 m), Dp3 (0.60 m) and Dp4 (0.80 m) sampled on the orchard of 'Tommy Atkins' mango trees.

Mango trees from treatments 1 and 3 (T1 and T3) had a high value for canonical variable 1 and plants from treatment 1 (T1) had a high value for canonical variable 2, but plants from treatment 3 (T3) had low value for canonical variable 2. Therefore, fully irrigated trees (T1) in all stages of cultivation had more roots in group 1 (0.5 m at 1.0 m away from the trunk) and at depth of 0.6 m.

Mango trees under treatment 3 (T3) had more roots in group 2 (1.5, 2.0, and 2.5 m away from the trunk) and at depths of 0.35 and 0.85 m. Plants from treatment 2 did not form clusters at any distance from the trunk and depth, showing root distribution in all positions. Under treatment 4 (T4), the plants had more superficial roots, at a depth of 0.10 m, and with roots up to 2.5 m away from the trunk. The roots of the plants from treatment 5 (T5) (without irrigation) showed a more horizontal distribution, reaching up to 2.5 m away from the trunk, but at depth of 0.35 m.

Root distribution also influences fruit yield because both density and length of the roots determine water and nutrient uptake by plants (Azevedo, Chopart, & Medina, 2011), which are necessary to physiological processes of fruit development. The formation of the root system depends on the volume of water that the plant receives and the irrigation scheduling. Additionally, the roots grow towards wet soil and, when roots are in areas with adequate moisture levels, they start increasing in thickness.

Bojappa and Singh (1974), cited by Choudhury and Soares (1992), observed, using radioactive techniques, root activity of mango trees at 1.2 m away from the trunk and 0.15 m deep. Similarly, Santos et al. (2014a) reported a higher concentration of roots between 0.5 and 1.5 m away from the trunk and with a depth of 0.10 to 0.85 m. These results are close to those found in this work (Figure 6).

Some studies have shown that a depth of 0.6 m is where the highest concentrations of mango tree's absorptive roots are found. In the work by Coelho, Oliveira, Araujo, Vasconcelos, and Lima (2001), they determined the distribution of the root system of 'Tommy Atkins' mango tree under different levels of irrigation, using microsprinklers, and found that the region with the highest concentration of roots is at a depth of 0.6 m. The authors also report that for irrigation scheduling based on the water content in the soil, the sensors must be installed at a horizontal distance up to 1.75 m and a depth of up to 0.6 m. Therefore, fully irrigated plants showed lower biomass allocation in roots as they are always in a region with adequate soil water availability.

Plants under treatment 3 underwent water deficit in the fruit set stage, thus invested more in roots to meet their needs, modifying the source-sink relationship; therefore, these trees did not yield a significant amount of fruit in any weight class (Figure 6).

Yield and water use efficiency

When analyzing yield and WUE using univariate statistics, no interaction between irrigation strategy and cycle was observed for these variables. However, there were independent effects of irrigation strategy and cycle.

Fruit yield of 'Tommy Atkins' mango changed according to the irrigation management strategy (Table 2), and the second evaluation cycle reached higher yield values at 5% significance level (Figure 7). Plants from treatment 4 (RDI applied in the maturation stage) had higher yields than plants from treatment 2 (RDI in stage I), while rain-fed plants had lower yields.

Table 2. Yield (t ha^{-1}) and water use efficiency (WUE) (kg ha^{-1} mm^{-1}) for the different treatments.

Variable	T1	T2	T3	T4	T5	CV (%)
Yield	20.97 ab	14.37 b	17.33 ab	24.19 a	5.10 c	40.03
WUE	30.17 ab	23.65 ab	27.73 ab	36.72 a	16.65 b	49.31

Means followed by the same letter in the row do not differ significantly from each other by the Tukey test at 5% significance level.

Under full irrigation and RDI conditions, WUE for 'Tommy Atkins' is similar; however, under dry conditions, the plants have lower WUE. For the 'cycle' factor, regardless of the water availability condition, WUE was higher in the second evaluation cycle (Figure 7).

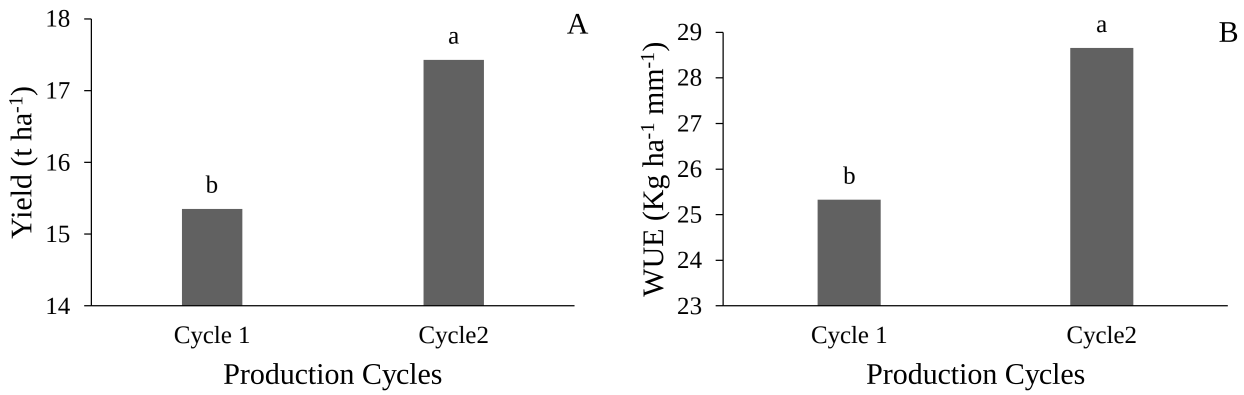

Figure 7. (A) Yield and (B) water use efficiency (WUE) in two production cycles. Means followed by the same letter in the row do not differ significantly from each other based on Tukey test at 5% significance level. The coefficients of variation for yield and WUE as shown in Figure 7 above are 21.79 and 20.31%, respectively.

Cycles influenced yield and WUE, and the second cycle had a significantly higher value when compared to the first cycle. The percentage increments were 11.94% for yield and 11.64% for WUE.

Mango trees under treatment 4 had higher yields, a result similar to that found by Santos et al. (2014b; 2016), who concluded that a 50% reduction in ETc in the third stage provides better results, because stage III is less sensitive to water deficit compared to the fruit set stage. Rain-fed trees (T5) (Table 2) reached low levels, due to the absence of water during all stages of fruit development, and this probably caused interference in the rate of nutrient uptake and growth inhibition, which caused a reduction in photosynthesis rates and lower yields (Taiz et al., 2017); consequently, WUE was also the lowest. WUE is a ratio between fruit yield and the amount of water the plants received, as the amount of rainfall was considered when calculating WUE.

Conclusion

Total or partial water deficit in the 'Tommy Atkins' mango tree can be identified by the reduction of transpiration (*E*) and photosynthesis (*A*) and by the increase in leaf temperature (*Tleaf*). Regulated deficit irrigation, when applied in the physiological maturation stage, results in greater yield and water use efficiency. Conversely, reducing the amount of water should not be performed in the fruit set stage of 'Tommy Atkins' mango tree. Total yield was higher in treatment 4 (100% ETc in SI and SII and 50% ETc in SIII), allowing a 13.32% increase in yield using a 50% reduction in ETc in stage III compared to full irrigation. Total root length density has a similar distribution up to 1 m horizontal distance and 0.10 m depth in all irrigation strategies. Even plants that suffer water deficit showed this behavior because this strip is easily absorbing rainwater.

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