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Fruit yield and gas exchange of Tahiti lime at different irrigation depths in the Amazon[1]

Produtividade e trocas gasosas do limão Tahiti em diferentes lâminas de irrigação na Amazônia

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HIGHLIGHTS:

Irrigation increases the yield and growth of Tahiti lime fruits in the Eastern Amazon.
The fruit yield to February is positively correlated with the average soil moisture in October and November.
The second annual flowering of Tahiti lime in the Eastern Amazon is reduced by irrigation.

ABSTRACT: Tahiti lime is a species of great economic importance worldwide. In Brazil, production is concentrated in the states of São Paulo and Pará, where it is usually grafted onto the Rangpur lime. This study aimed to analyze the effects of different irrigation depths on the fruit yield, phenology, and gas exchange of Tahiti lime trees grafted onto Swingle citrumelo. Irrigation was performed during the first year at four different irrigation depths in a random block design with five blocks and four treatments to maintain the soil matric potential in the following ranges: T_1: below -50 kPa, T_2: from -30 to -50 kPa, T_3: from -10 to -30 kPa, and T_4: above -10 kPa. The flowering, carbon assimilation rate (A), stomatal conductance (g_s), transpiration (E), and fruit yield were measured. Fruits were harvested earlier in the most irrigated treatment, T_4, and the yield increased from 2.22 to 6.89 kg per plant from T_1 to T_4. The average fruit weight escalated from 78.6 to 96.1 g from T_1 to T_4, and carbon assimilation increased from 6.89 to 9.51 μmol CO_2 m^{-2} s^{-1} from T_1 to T_4.

Key words: citriculture, water management, water resources, sustainability

RESUMO: A lima ácida Tahiti é uma espécie de grande importância econômica em todo o mundo. Em território brasileiro, a produção concentra-se nos estados de São Paulo e Pará, onde geralmente é enxertada em limão-cravo. Este estudo tem como objetivo analisar o efeito de diferentes lâminas de irrigação na produção de frutos, fenologia e trocas gasosas de lima ácida Tahiti enxertada em citrumelo Swingle. A irrigação foi realizada durante o primeiro ano, com quatro lâminas de irrigação diferentes em um delineamento de blocos ao acaso com 5 blocos e 4 tratamentos, para manter o potencial matricial do solo nas seguintes faixas: T_1: abaixo de -50 kPa, T_2: de -30 a -50 kPa , T_3: de -10 a -30 kPa e T_4: acima de -10 kPa. Foram medidos florescimento, taxa de assimilação de carbono (A), condutância estomática (g_s), transpiração (E) e produção de frutos. Os frutos foram colhidos mais cedo no tratamento mais irrigado, T4, e a produtividade aumentou de 2,22 para 6,89 kg por planta de T_1 para T_4. O peso médio dos frutos aumentou de 78,6 para 96,1 g de T_1 para T_4. A assimilação de carbono aumentou de 6,89 para 9,51 μmol CO_2 m^{-2} s^{-1} de T_1 para T_4.

Palavras-chave: citricultura, manejo da água, recursos hídricos, sustentabilidade

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Introduction

Tahiti lime is a hybrid citrus species that is largely produced in Brazil and other Latin American countries (FAOSTAT, 2022). The fruit yield of Tahiti lime ranges between 3,165 and 36,559 kg ha^{-1} among the Brazilian states (SIDRA, 2022). The state of Pará is the second largest producer in the country, with an annual production of 105,000 tons and an average yield of 19,645 kg ha^{-1}. The fruit harvest is concentrated between December and April (Barbara et al., 2021).

The physical characteristics of citrus fruits, such as weight and size, are impaired by water deficiency in the early phases of fruit development (Bremer Neto et al., 2013; Chen et al., 2022). Trees generally obtain a fruit yield between 51.5 and 169.8 kg per tree without irrigation, and between 54.1 and 194.5 kg per tree in the sixth year after planting with irrigation (Espinoza-Núñez et al., 2011). The fruit yield is significantly influenced by the choice of rootstock and the presence or absence of irrigation (Espinoza-Núñez et al., 2011). Planting density is also a determining factor (Ladaniya et al., 2020).

Citrus species close their stomata in response to water deficit, dry air, and salinity stress (Ribeiro & Machado, 2007; Silva et al., 2018), which can prevent major damage to plants and significant yield losses, while decreasing the carbon assimilation rate (Wagner et al., 2021).

This study aimed to analyze the effects of different irrigation depths on fruit yield, phenology, and gas exchange of Tahiti lime trees grafted onto Swingle citrumelo under tropical rainforest climate conditions in the Eastern Amazon, using a planting density higher than that normally used in the region.

Material and Methods

The experiment was conducted in an irrigated Tahiti lime orchard in the municipality of Capitão Poço, in the Eastern Brazilian Amazon (Figures 1A and B). According to Köppen's climate classification, the climate of the region is Am (Alvares, 2013). The orchard is 71 m above sea level. It was planted in 2014, and the experiment was performed between June 2020 and May 2021, when the orchard was between six and seven years old.

The orchard was 250 m wide (along the north-south axis) and 500 m long (along the east-west axis). It was divided into two irrigation sectors of 250 × 250 m each, and the rows of trees followed an east-west direction. The spacing between plants in the same row was 2.0 m, the distance between rows of plants was 6.8 m, and the average tree height was 3.9 ± 0.2 m. Swingle citrumelo was used as the rootstock; however, Rangpur lime is more often used in the region (Stenzel & Neves, 2004). Swingle citrumelo was used due to its resistance to foot rot caused by *Phytophthora* spp. (Dewdney & Johnson, 2021), which is one of the most prevalent diseases in citrus orchards in the studied region. The trees were pruned each year at the beginning of June.

The treatments consisted of different irrigation depths between August and mid-November 2020. Irrigation was performed using a drip irrigation system, with one drip hose per row, a flow rate of 2.0 L h^{-1} per emitter, and 0.55 m of spacing between emitters, which resulted in 3.63 emitters per plant. Irrigation was performed once daily during the above-mentioned months. Each irrigation event had a duration of 9.35 hours; therefore, 68 L of water was supplied for each plant during each irrigation period. The average reference evapotranspiration (Allen et al., 1998) was between 4.0 and 6.0 mm per day, and between 4.0 and 5.0 mm per day during the dry season of 2021. The crop coefficient of citrus trees is reported to range between 0.67 and 0.96 (Jamshidi et al., 2020), or 0.68 when reference evapotranspiration is greater than 4.0 mm per day (Marin et al., 2019).

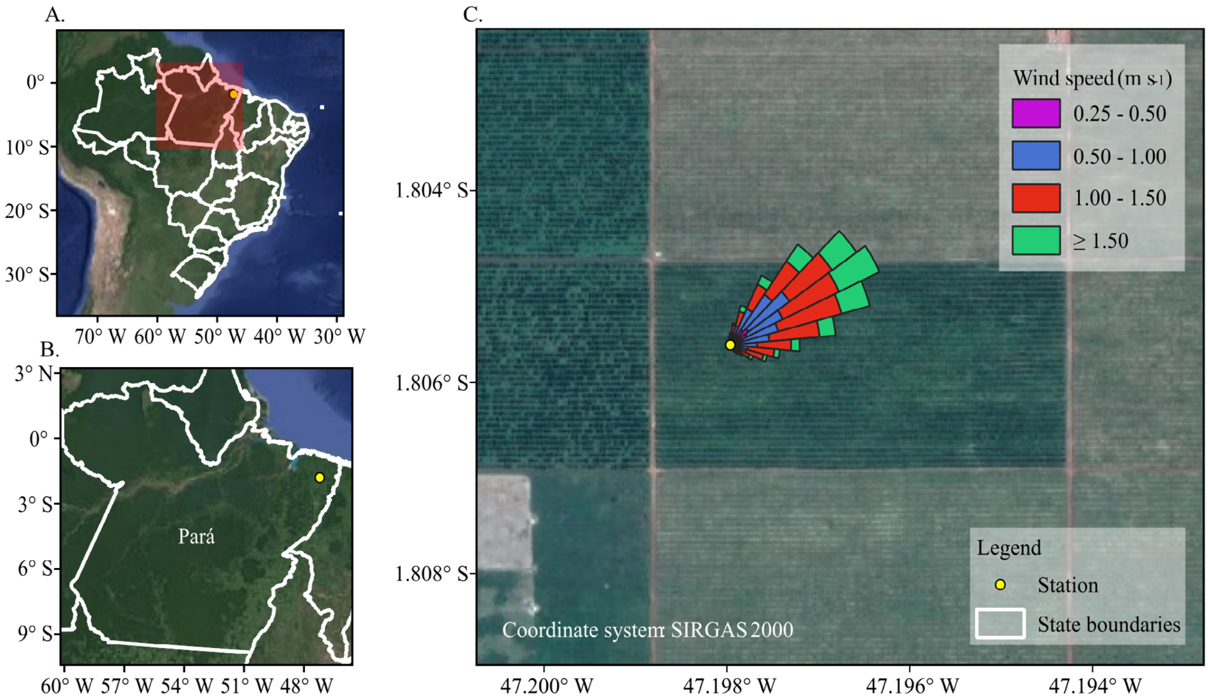


Figure 1. Location of the micrometeorological tower in the orchard (yellow point) and wind rose to show the distribution of wind speed and wind direction

Irrigation was performed to keep the soil water potential within the following ranges: below -50 kPa, from -30 to -50 kPa, from -10 to -30 kPa, and above -10 kPa. The treatments received the following amounts of irrigation: below -50 kPa, 115 mm; -50 to -30 kPa, 165 mm; -30 to -10 kPa, 260 mm; and above -10 kPa, 340 mm. Irrigation was performed following a randomized block design with four treatments and five blocks during the 2020 dry season. The characteristics of all the treatments are summarized in Table 1.

Each plot consisted of an area 6 m long (along the rows) and 6.8 m wide (perpendicular to the rows) containing three plants. Only fruits that grew inside this area were counted or harvested. Fruits and flowers were counted in each plot from June 2020 to May 2021, with periodicity varying from weekly to monthly. The harvested fruits were weighed using a digital scale with 1 mg precision, and the fruit diameter and length were measured with an analog caliper with a precision of 0.05 mm.

Air temperature and relative humidity sensors were installed 2.0 m above the tree canopy. A four-component net radiometer (model CNR4, Campbell Scientific Inc.) was installed 2 m above the canopy, and daily measurements of global radiation were obtained over two years from January 2020 to December 2021. The sensors were installed approximately 80 m from the western side and 100 m from the northern side of the lime orchard (Figure 1C). Precipitation was measured using an electronic rain gauge (model TB4, Campbell Scientific Inc.), and wind speed and direction were recorded using an electronic anemometer (model 03001 R. M. Young Wind Sentry Set, Campbell Scientific Inc.). Both units were installed 2 m above the canopy.

The soil moisture was estimated from the matric potential measured using four tensiometers installed in September 2020 at a depth of 30 cm. One tensiometer was installed below the canopy, aligned to the rows of trees, and 1 m away from the trunk for each treatment in block 1. Undeformed soil samples were obtained for each 10 cm depth to a depth of 1 m and replicated at four different positions inside the experimental area. The samples were exposed to tensions of 1, 2, 4, 6, 10, 50, 100, 500, 1,000, and 1,500 kPa, and the moisture remaining after the treatments was measured by weighing the samples on a high-precision scale. After these procedures, the van Genuchten (1980) equation (Eq. 1) was fitted to the obtained data. The coefficients of the fitted equations are presented in Table 2.

$$\theta = \theta_r + \frac{\theta_s - \theta_r}{\left[1+(\alpha h)^n\right]^m} \quad (1)$$

where:

h is the soil matric potential measured with the tensiometer;

α, n, and m are the coefficients of the equation;

θ is the volumetric soil moisture ($m^3\ m^{-3}$); and

θ_r and θ_s are the residual and saturated volumetric soil moistures, respectively.

The soil moisture at field capacity θ_{fc} was calculated using Eq. 1 with h = 10 kPa, and the wilting point θ_{wp} was considered to be the same as θ_r.

The relative soil moisture (θ_{rel}) adopted was calculated as

$$0 \le \theta_{rel} = \frac{\theta - \theta_{wp}}{\theta_{fc} - \theta_{wp}} \le 1 \quad (2)$$

where:

θ is the volumetric soil moisture obtained from Eq. 1.

On October 15th, during the dry season of 2020, when irrigation was still being performed, measurements of carbon assimilation rate (A), stomatal conductance (g_s), and transpiration rate (E), as well as the weather-related variables vapor pressure deficit of leaves (VPD_L) and air (VPD_A) were measured with an LI-COR 6400XT infrared gas analyzer. Measurements were made between 06:00 and 09:00 (local time)

Table 1. Characteristics of each treatment

Treatment	h[1] (kPa)	Number of irrigations (days)	Water supplied through irrigation (m³ per plant)	Rainfall[2] (mm)
Below -50 kPa	30.4 ± 22.2	23	1.56	138
From -50 kPa to -30 kPa	25.9 ± 16.6	33	2.24	138
From -30 kPa to -10 kPa	11.8 ± 6.8	52	3.54	138
Above -10 kPa	5.9 ± 3.0	68	4.62	138

[1]Average soil matric potential from September to November. [2]Total rainfall from the beginning of July to the end of October; h: soil matric potential

Table 2. Physical attributes of the soil between 0 and 1 m depth and coefficients for the fitted van Genuchten equation for each layer of soil

Depth (m)	$\theta_r = \theta_{wp}$ ($m^3\ m^{-3}$)	θ_s ($m^3\ m^{-3}$)	α	n	m	θ_{fc} ($m^3\ m^{-3}$)	Bulk density ($g\ cm^{-3}$)
0.0-0.1	0.103	0.380	0.116	5.673	0.824	0.247	1.634
0.1-0.2	0.130	0.367	0.125	6.784	0.853	0.245	1.663
0.2-0.3	0.148	0.373	0.128	6.142	0.837	0.272	1.696
0.3-0.4	0.165	0.399	0.128	6.351	0.843	0.283	1.631
0.4-0.5	0.160	0.411	0.131	7.050	0.858	0.304	1.584
0.5-0.6	0.170	0.405	0.128	7.269	0.862	0.314	1.593
0.6-0.7	0.136	0.373	0.134	6.578	0.848	0.301	1.415
0.7-0.8	0.152	0.369	0.106	21.045	0.952	0.271	1.600
0.8-0.9	0.201	0.421	0.108	21.045	0.952	0.348	1.561
0.9-1.0	0.198	0.413	0.108	21.045	0.952	0.363	1.576

θ_r - Residual volumetric soil moisture; θ_s - Saturated volumetric soil moistureα, n, and m - Coefficients of the van Genuchten equation (Eq. 1); θ_{fc} - Soil moisture at field capacity in healthy fully-expanded leaves from the middle third of the canopy. Three samples were taken at different positions in the row of trees for each combination of treatment and block, totaling 60 samples.

For practical purposes, a full production cycle (from flowering until the harvest of the last fruits) was considered as 12 months from June (when the main flowering occurs) to May of the following year (when the majority of fruits have been harvested), based on observed data. The trees were pruned in the first week of June. The accumulated yield per month per plant (Y, kg per plant) was obtained by totaling the weight of all fruits harvested in each parcel from the beginning of the period (June) until the referred month and dividing it by three (the number of plants per parcel).

The value of Y between treatments for each month was compared using an analysis of variance, and the mean Y per treatment for each month was compared using Tukey's test at $p \leq 0.05$.

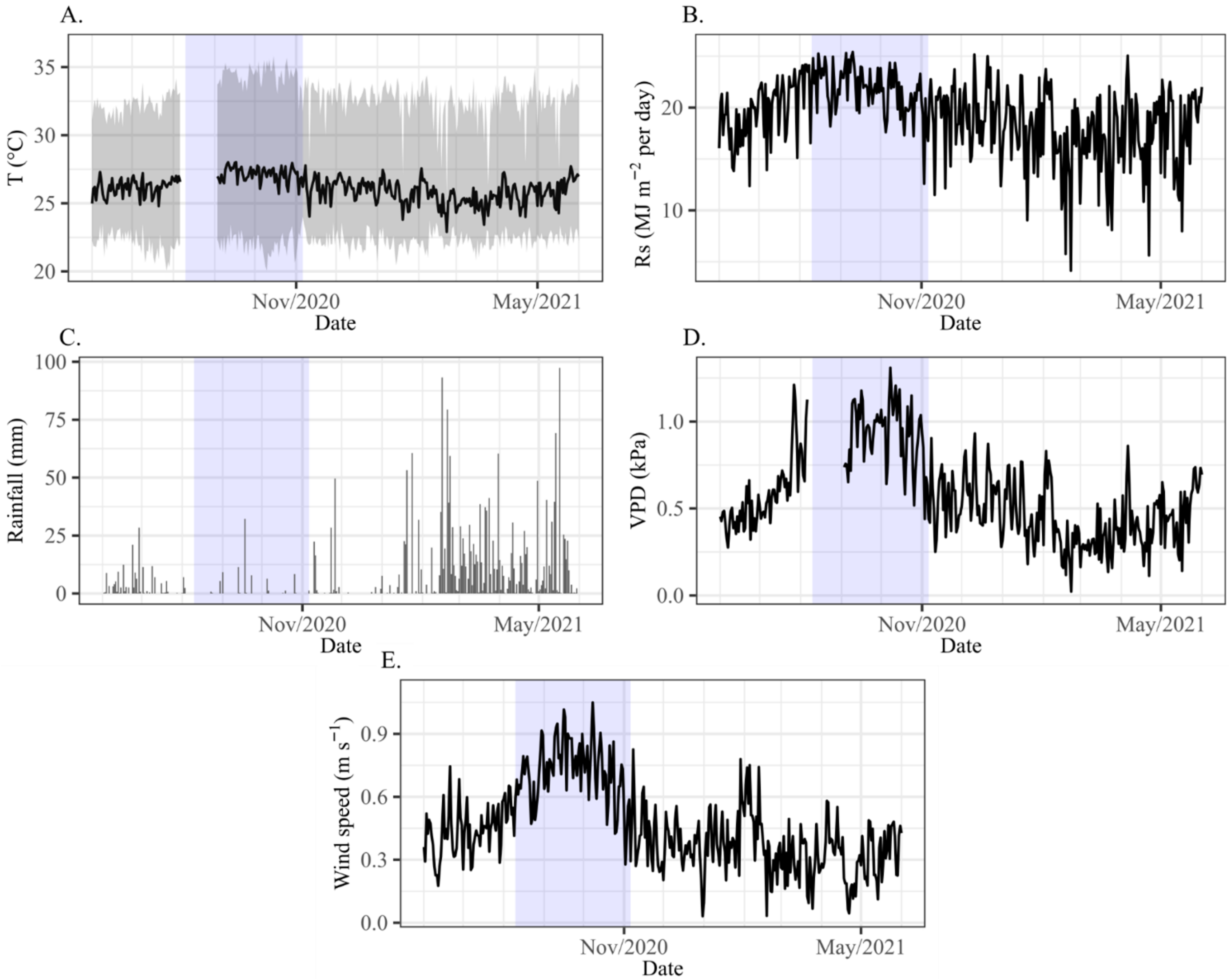
Since the data resulting from the number of flowers per plant did not follow a normal distribution, the data were transformed with $x_i' = \log(0.1 + x_i)$ before the analysis of variance and Tukey's test. The result of the transformation was tested for non-normality using the Shapiro-Wilk test at $p > 0.05$, and the result indicated a normal distribution of the transformed data.

Regression analysis and correlation tests were performed with the following pairs of variables: Y and h, Y and θ_{rel}, Y and g_s, Y and A, Y and E, A and gs, and A and E.

Results and Discussion

A decrease in the frequency and intensity of rainfall was observed in mid-June during the 2020–2021 harvest (Figure 2C), which may have caused some water stress to the plants. The dry season ended after mid-October 2020 with the occurrence of greater than 15 mm of rain (Figure 2C).

The high amount of rainfall in the rainy season of 2021 may be explained by the medium intensity La-Niña that began at the end of 2020 and persisted for most of 2021 and the first half of 2022 (NOAA, 2005). La Niña increases precipitation in most of the Amazon Basin and decreases the average air temperature (Moura et al., 2019). The average air temperature (Figure 2A) during the dry season of 2020 was 27.2 °C between September and October, while the average vapor pressure deficit was 0.97 kPa (Figure 2D), and the total global radiation (Figure 2B) of all days in the period was 2,659.8 MJ m^{-2}.



T - Air temperature; Rs - Global radiation; VPD - Vapor pressure deficit

Figure 2. Weather data measured in 2020 and 2021 in the orchard

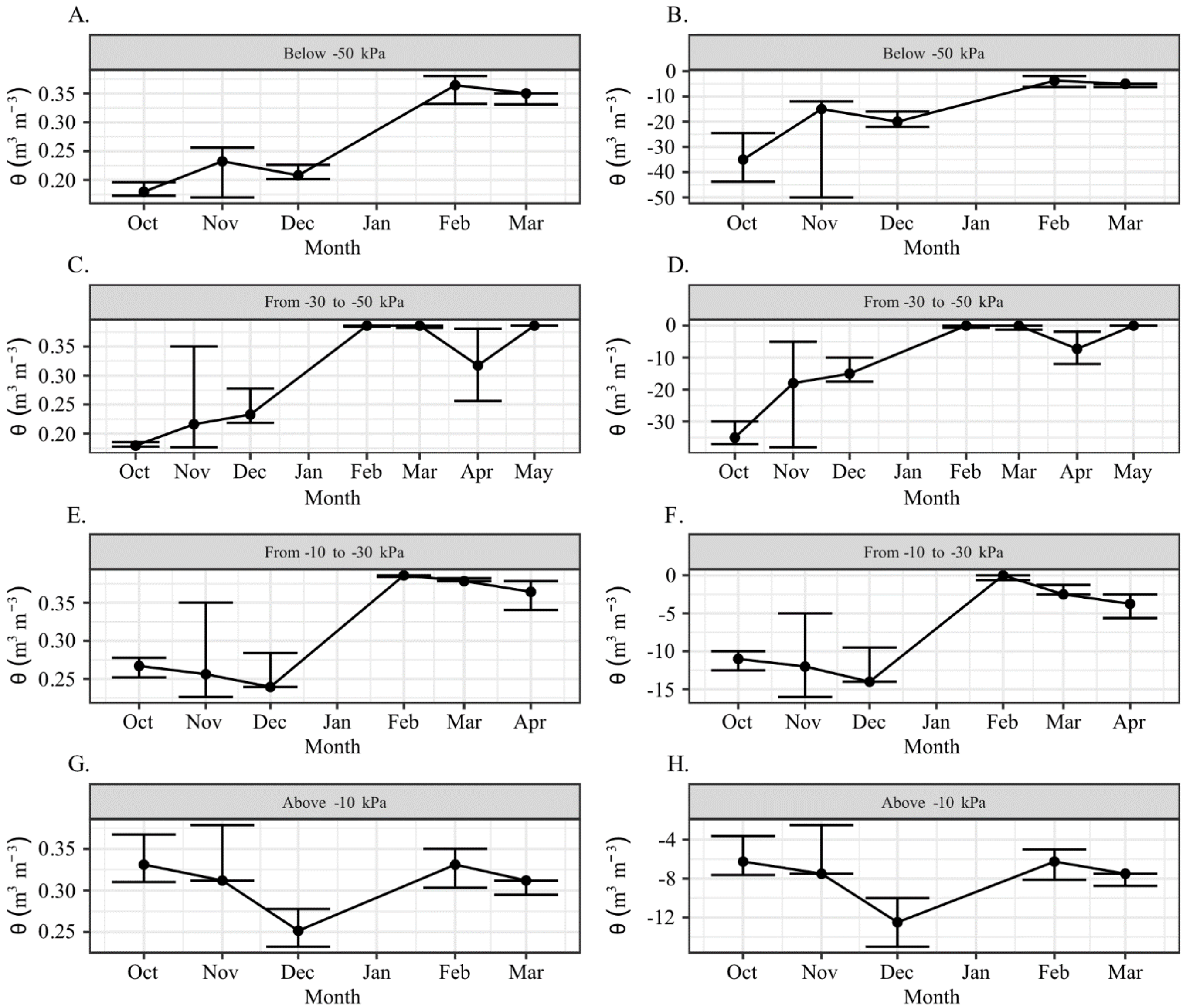
Although the soil moisture appeared similar when comparing the treatments with matric potentials below -30 kPa (Figures 3A and C) to the other treatments (Figures 3 E and G), the average matric potential reached by the former (Figures 3B and D) was considerably lower than that of the latter (Figures 3F and H), which were the treatments with the highest irrigation depths.

Two annual periods of intense flowering were observed: the first in mid-June and the second between the end of October and beginning of November. The flowering periods are shown in Figure 4A.

The first annual flowering coincided with the end of the rainy season, although it may have been stimulated by management practices such tree pruning at the beginning of June each year, since pruning is typically used to induce flowering in Tahiti lime (Lambert et al., 2015). The number of flowers observed in the treatment with a matric potential above -10 kPa during the first flowering of 2020–2021 (Figure 4A) indicated that the treatments between -10 and -30 kPa and above -10 kPa had a higher number of flowers than the treatments below -50 kPa and -30 and -50 kPa. However, the variability between plants was extremely high and therefore no significance was found for this difference during the period (first flowering of 2020–2021), which was expected since no differentiation occurred between the treatments until August 2020 when irrigation began. Furthermore, the number of fruits immediately after the first flowering remained similar among the different treatments, as shown in Figure 4B.

The second annual flowering occurred with the onset of the rainy season, and significant differences were observed between treatments, with an increase in the number of flowers per plant as irrigation was reduced (Table 3). This flowering occurred a few days after periods of intense rainfall in mid-October, and an increase in the number of fruits per plant was observed in treatments below -50 kPa in the weeks that followed the second flowering (Figure 4B).

No significant difference was observed between treatments after February 2021 in the total fruit yield accumulated from June 2020 to February 2021. However, fruit yield accumulated to February 2021 (Y_1 in Table 4) differed significantly between



θ - soil moisture, h - matric potential

Figure 3. Variation of the estimated volumetric soil moisture and measured matric potential obtained with tensiometers. Points indicate the median. The upper and lower limits of the error bar indicate the 1st and 3rd quartiles for each month, respectively

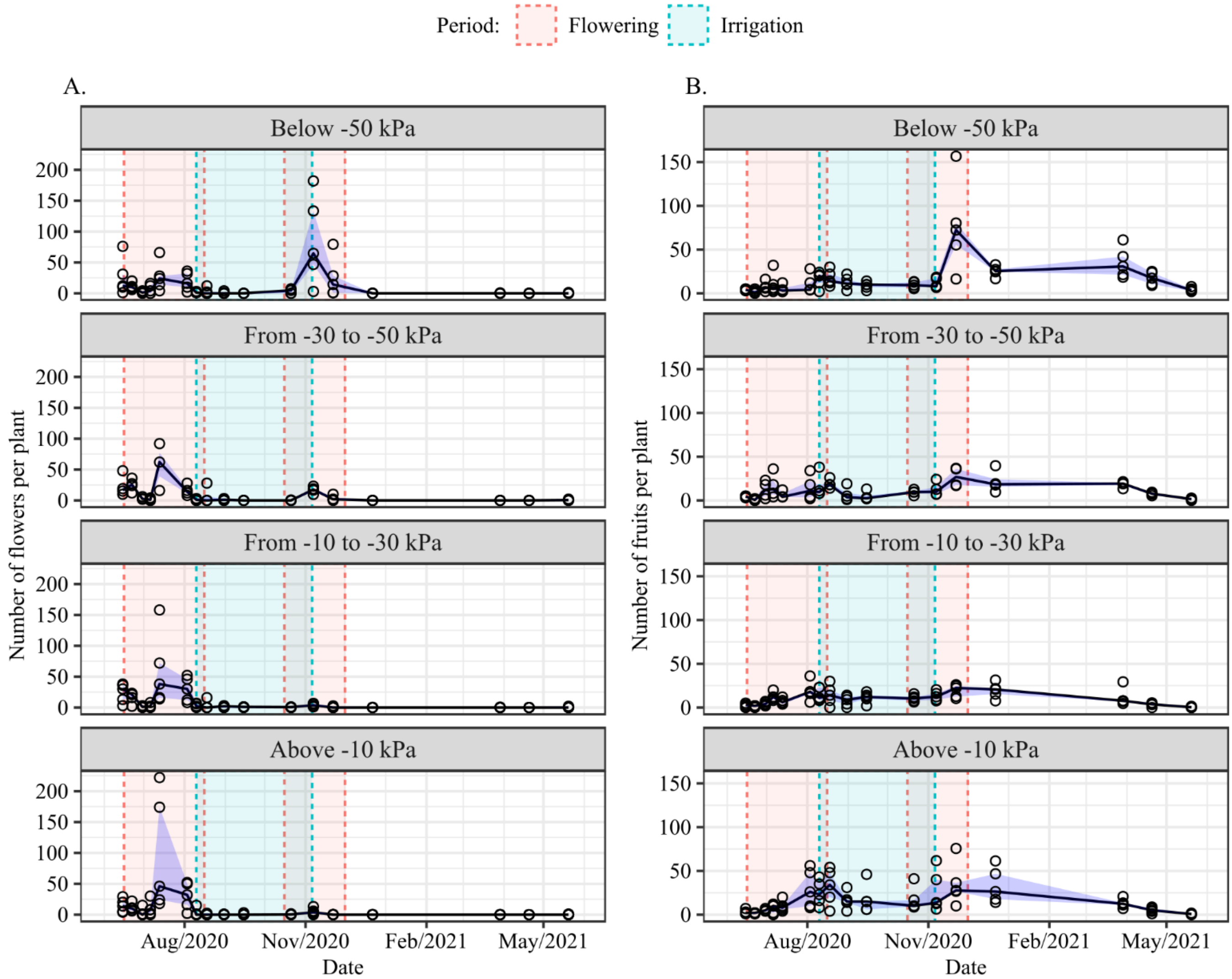


Figure 4. Number of flowers (A) and fruits (B) per plant for each treatment. The regions delimited in red and blue represent the periods of flowering and irrigation, respectively

Table 3. Average number of flowers and fruits per plant for each treatment on November 7th, 2020

Treatment	Number of flowers (flowers per plant)	Number of fruits (fruits per plant)
Below -50 kPa	85.9 (83.0%) a	11.5 (618.0%) a
From -30 to -50 kPa	17.0 (32.7%) ab	12.8 (43.6%) a
From -10 kPa to -30 kPa	4.0 (61.8%) b	13.1 (18.9%) a
Above -10 kPa	4.8 (105%) b	26.9 (18.8%) a

Different letters indicate significant differences ($p \leq 0.05$) by Tukey's test

treatments ($p < 0.05$), and was higher for the treatments with the greatest irrigation depth. In contrast, the total yield between March 2021 and the end of May 2021 was generally higher for treatments with lower irrigation, but without a statistically significant difference ($p < 0.05$) (Y_2 in Table 4).

The weight and size of fruits harvested to February were significantly affected (columns W, D, and L in Table 4) by water availability between June 2020 and February 2021. Fruits in the treatments with more irrigation were heavier and larger than fruits in the less irrigated treatments (W, D, and L for the treatment below -50 kPa compared to that above -10 kPa in Table 4).

Since the water deficit in the treatments with tensions below -30 kPa began in August 2020 immediately after the first annual flowering, fruits experienced severe water deficit during their early development (soil moisture and matric potential in Figure 3 and rainfall measurements in Figure 2C). These findings agree with reports that water deficit during the early development of fruits affects their physical characteristics (Chen et al., 2022).

Table 4. Average yield (Y), weight (W), diameter (D), and length (L) of fruits harvested in different treatments and years

Treatment	Y_1 (Jun-Feb)	Y_2 (Mar-May)	W	D	L
	(kg per plant)		(g)	(mm)	
Below -50 kPa	2.83 (37.1%) a	5.53 (16.6%) a	78.6 (22.3%) a	52.6 (8.2%) a	56.0 (8.2%) a
From -30 to -50 kPa	4.11 (27.0%) ab	3.25 (7.7%) a	86.3 (24.8%) b	53.8 (8.1%) bc	58.0 (9.9%) b
From -10 kPa to -30 kPa	4.15 (31.6%) ab	1.86 (91.9%) a	90.3 (30.3%) bc	54.7 (9.9%) cd	57.7 (11.2%) b
Above -10 kPa	6.89 (45.1%) b	2.06 (40.3%) a	92.1 (24.9%) c	55.1 (10.3%) d	58.2 (9.6%) b

Y_1 - Mean of the total weight of fruits harvested per tree from June to February of the following year; Y_2 - Mean of the total weight of fruits harvested from March to May of the same year; W, D, and L were calculated for fruits harvested from June to February of the following year. Different letters indicate significant differences ($p \leq 0.05$) according to Tukey's test. The numbers in parentheses indicate the coefficients of variation (CV)

Table 5. Average carbon assimilation rate (A), transpiration (E), and stomatal conductance (g_s) and their coefficients of variation (in parenthesis) for each treatment during the 2020–2021 harvest

Treatment	A (μmol CO_2 m^{-2} s^{-1})	E (mmol H_2O m^{-2} s^{-1})	g_s (mol H_2O m^{-2} s^{-1})
Below -50 kPa	6.89 (34.7%) a	1.46 (99.3%) a	0.0781 (107.0%) a
From -30 to -50 kPa	7.99 (27.7%) ab	1.54 (60.7%) a	0.0796 (63.8%) a
From -10 kPa to -30 kPa	10.0 (26.6%) b	1.68 (50.6%) a	0.0879 (55.0%) a
Above -10 kPa	9.51 (28.5%) b	1.71 (38.0%) a	0.0944 (47.1%) a

Different letters indicate significant differences ($p \leq 0.05$) by Tukey's test

Treatments with the lower irrigation depth in 2020 also had the lowest photosynthetic rate (Table 5) according to Tukey's test ($p < 0.05$). Significant correlations ($p < 0.05$) were found between all possible pairs of variables shown in Table 5 (A and E, A and g_s). However, the dispersion of points was high for E and g_s; therefore, no significant difference was observed for these variables among treatments.

Linear regression between A and E and between A and g_s resulted in the following equations (Table 6), all of which were statistically significant ($p \leq 0.05$).

The significant correlations between A and E ($r = 0.52$, $p \leq 0.05$) and A and g_s ($r = 0.49$, $p \leq 0.05$) suggest that both E and g_s may correlate well with water availability, despite no significant difference between water availability and these variables. Although the CO_2 assimilation rate (approximately 10.0 µmol CO_2 m^{-2} s^{-1}) found in this study was low for well-watered plants, it was coherent with that found in the scientific literature for citrus species. An assimilation rate below 15 µmol CO_2 m^{-2} s^{-1} has been reported for C. sinensis with adequate nutritional management, and it decreased below 5 µmol CO_2 m^{-2} s^{-1} with boron deficiency (Yang et al., 2022). In addition, a maximum assimilation rate of 11.0 µmol CO_2 m^{-2} s^{-1} was reported for 'Valencia' orange trees during the summer in Piracicaba, southeastern Brazil (Ribeiro & Machado, 2007).

High correlations were found between the fruit yield from June 2020 to February 2021 (Y, kg per tree) and the average soil matric potential (h, kPa) ($r = -0.57$, $p \leq 0.05$) in October and November, as well as between the average relative soil moisture (θ_{rel}) in October and November and Y ($r = 0.57$, $p \leq 0.05$).

The flow of water in the soil–plant–atmosphere continuum is driven by water potentials (Brodribb & Mencuccini, 2017), which appear to differ largely between treatments (Figures 3A, C, E, and G). The efficiency of irrigation strategies and recommendations based on soil water potential have been demonstrated in other experiments with different crops, such as rice (Kulmar et al., 2017) and strawberry (Létourneau et al., 2015). In addition, the fruit yield was consistent in the treatments with matric potentials below -30 kPa, which have a reduced supply of water during the period of fruit growth, reinforcing the hypothesis that fruit yield and fruit characteristics are impaired by water deficit.

Table 6. Regression coefficients, their respective confidence intervals, and the determination coefficient (R^2) calculated for each regression

Response variable	Explanatory variable	Intercept	Slope	R^2
A	g_s	6.5982 ± 1.107	23.6727 ± 10.800	0.24
A	E	6.2755 ± 1.156	1.46 ± 0.616	0.27

Although both the fruit yield that accumulated to February and physiological variables, such as carbon assimilation rate, transpiration, and stomatal conductivity, increased as irrigation increased, no correlation was found between gas exchange variables and fruit yield or size when comparing the fruit yield of each plot with the average A, E, or g_s of the plot. This may be due to the high dispersion found for gas exchange variables in general. For example, the determination coefficient for A and g_s was 0.24, and for A and E was 0.27 (Table 5). In addition, high variability was observed in fruit yield, even for parcels in the same treatment. The coefficient of variation for Y_1 in the treatment with matric potentials above -10 kPa (Table 4) was 45%, and for the treatments below -50 kPa, it was 37%. This suggests that more replications may be necessary to determine whether A, E, or g_s are correlated with fruit yield and the measured physical characteristics of the fruits.

In various citrus species, including Tahiti lime, flowering is induced by a variety of stressful conditions, and its intensity is proportional to the intensity of the stressing factor (Garmendia et al., 2019). Flowering can be increased by water deficits (Koshita & Takahara, 2004) and low temperatures (Southwick & Davenport, 1986). In contrast, the application of gibberellins inhibits flowering and increases the conversion of flowers into fruits (Garmendia et al., 2019). Such techniques have been used in the management of flowering and to induce fruit production during the period of highest prices, although they were not used in the current research.

While the first annual flowering observed in the experiment may be related to management practices such as the pruning of trees, as discussed previously, the second flowering appears to be related to changes in weather and water availability in the transition from the dry to rainy season at the end of October. This could explain why flowering increased with the reduction of irrigation in the dry season of 2020.

The weight of fruits varied significantly between treatments and increased with irrigation depth. This is an expected response to water availability and a similar behavior has been found in other experiments with citrus species (Al-Rousan et al., 2012).

Many fruits were harvested between October and December, which corresponds to the beginning of the wet season and immediately after the irrigation period. These fruits likely formed during the dry season; therefore, irrigation played a fundamental role in their development and final characteristics, such as weight and size.

The reduction in photosynthetic rate as irrigation decreased in the 2020–2021 period was expected. Values of A ranging between 6.89 and 10.0 µmol m^{-2} s^{-1} were within the normal range found in other studies (Ribeiro & Machado, 2007) and were predictably low for an evergreen plant with a C_3 photosynthetic metabolism (Wang et al., 2012), such as the Tahiti lime. Some values reported in the literature are between 5.5 and 7.0 μmol CO_2 m^{-2} s^{-1} for lemon (*C. limon*) (Wagner et al., 2021), and between 11.0 and 15.0 μmol CO_2 m^{-2} s^{-1} for sweet orange (*C. sinensis*) (Ribeiro & Machado, 2007; Yang et al., 2022).

Stomatal conductance was found to be inversely proportional to VPD_L, with correlation coefficient r = -0.91 ± 0.19 (correlation coefficient ± confidence interval, $p \le 0.05$). In *Citrus*, stomata close in response to dry air (Silva et al., 2018) particularly when the VPD_L is above 1.5 kPa (Ribeiro & Machado, 2007), even in well-irrigated plants. This VPD_L range was observed for 58 of 59 (more than 98%) samples in this study in the dry season of 2020. Therefore, stomatal conductance was expected to be low, even for treatments with the highest irrigation depths. The high VPD_L associated with low g_s may have impaired A for all treatments, since A was positively correlated with g_s (Table 6), with a correlation coefficient of r = 0.50 ± 0.17 ($p \le 0.05$). The high VPD_L was likely related to the scarcity of rainwater in the dry season of 2020, as well as the higher air temperatures in the same period, since VPD_L also correlates well with VPD_A (r = 0.95 ± 0.02, $p \le 0.05$).

The fruit yield was low. According to the SIDRA (2022), the average fruit yield per area reached by producers of Tahiti limes in the studied region was 19.65 t ha^{-1} in 2019, and 28.15 t ha^{-1} in 2020, which are higher than the yield obtained in the current study that varied between 4.42 and 6.15 t ha^{-1} among treatments in the 2020–2021 season. These values are also lower than the fruit yield reported in the scientific literature for Tahiti lime grafted onto Swingle citrumelo, which was 8.8 t ha^{-1} according to Cantuarias-Avilés et al. (2012), although the fruit weight in the treatments with matric potentials greater than -30 kPa in the current study was higher than the values reported by those authors (86.3 g). Two factors may have contributed to the low yield: (I) the use of Swingle citrumelo as rootstock, as most farmers in the region use Rangpur; Tahiti lime has been reported to be less productive when grafted onto Swingle citrumelo than when grafted onto Rangpur (Cantuarias-Avilés et al., 2012), and (II) the high vapor pressure deficit in 2020 may have some influence over the stomatal aperture, impairing photosynthesis and reducing fruit yield, as discussed above, even in well-irrigated treatments. Therefore, more research is needed to evaluate whether the Tahiti lime yield responds differently to the water supply when its development is favored by adequate nutrient management.

Conclusions

1. Irrigation depth was positively correlated with fruit yield at the beginning of the harvest season (to February).
2. Irrigation depth did not influence the total fruit yield.
3. Irrigation depth was negatively correlated with the second annual flowering of Tahiti lime in the Amazon.
4. Irrigation depth was positively correlated with the weight, diameter, and axial length of fruits harvested until February.
5. Carbon assimilation rate was reduced with the decrease in irrigation depth.

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