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Lorena Paixão Oliveira¹

lore1977oliveira@gmail.com

Instituto Federal de Educação, Ciência e Tecnologia Baiano

Luana Laís Almeida dos Santos

Universidade Federal do Recôncavo da Bahia

Lucas Silva Costa³

Universidade Estadual de Santa Cruz

Maurício Antonio Coelho

Embrapa Cassava & Fruits

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**Rootstock-dependent growth, physiological responses and water-use efficiency of 'Tahiti' acid lime
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Lorena da Paixão Oliveira¹; Luana Laís de Almeida dos Santos²;

Lucas da Silva Costa³; Maurício Antonio Coelho Filho⁴

¹Instituto Federal de Educação, Ciência e Tecnologia Baiano, Campus Guanambi, Guanambi, BA, Brasil.

lore1977oliveira@gmail.com ; ²Universidade Federal do Recôncavo da Bahia, Cruz das Almas, BA;

luanalaais@gmail.com²; ³ Universidade Estadual de Santa Cruz, Ilhéus, BA, lwkasc78@gmail.com

⁴ Embrapa Mandioca e Fruticultura, Cruz das Almas, BA, Brasil. mauricio-antonio.coelho@embrapa.br

Corresponding author: Lorena da Paixão Oliveira (lore1977oliveira@gmail.com)

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Abstract

Climate change and increasing water-related risks reinforce the need to select adapted rootstocks and efficient irrigation strategies for ‘Tahiti’ acid lime. This study evaluated the biometric and physiological responses of plants grafted onto five rootstocks and subjected to four water-management strategies in a four-year-old drip-irrigated orchard located in a dry subhumid climate region. The experiment was conducted in a randomized block design with three replicates in a 5×4 factorial scheme. The evaluated rootstocks were Swingle citrumelo, Flying Dragon, BRS Matta, LVK $\times$ LCR-38, and HTR-069, under rainfed conditions, full irrigation, moderate deficit irrigation, and severe deficit irrigation. Irrigation timing was determined by monitoring soil water content throughout the soil profile using TDR probes. Plant growth, yield, production efficiency, water-use efficiency, gas exchange, and leaf water potential were evaluated. Rootstock genotype significantly affected vegetative vigor, plant height, rootstock stem diameter, cumulative yield, canopy volume, production efficiency, and water-use efficiency. Irrigation management affected biometric variables depending on the evaluation year and altered gas exchange and leaf water potential. No significant interactions between irrigation management and rootstock were observed for the biometric and physiological variables. Flying Dragon and BRS Matta showed higher yields and production efficiencies. Water-use efficiency was inversely proportional to the applied irrigation depth. Therefore, these rootstocks are promising alternatives for irrigated and rainfed orchards under subhumid climate conditions. However, Flying Dragon requires further monitoring because of its reported sensitivity to water stress under conditions of regional climate variability.

Keywords: Citrus rootstocks; Deficit irrigation; Gas exchange; Leaf water potential; Water productivity; Drought tolerance.

1. Introduction

‘Tahiti’ acid lime [*Citrus latifolia* (Yu. Tanaka) Tanaka] is a citrus species of Asian origin that was first identified in India (Santos Filho et al., 2005). It is the fifth most exported fruit in Brazil (De Almeida et al., 2018) and plays an important role in Brazilian fruit production, as it is one of the country’s most commercially important citrus fruits. Approximately 82% of its production is exported, mainly as juice (Telhado et al., 2021). Moreover, its cultivation has become an increasingly profitable agricultural activity. In 2018, approximately 114,439.62 tonnes were marketed (FAO, 2018), of which 96% corresponded to ‘Tahiti’ acid lime. This production generated approximately BRL 1.54 billion, with the state of Bahia accounting for BRL 90.25 million (IBGE, 2019). As cultivated areas expand across different edaphoclimatic regions in Brazil, further studies are needed to identify suitable rootstocks for ‘Tahiti’ acid lime production.

Understanding the responses of citrus scions and their interactions with rootstocks adapted to specific environmental conditions and crop-management practices is essential because rootstocks influence several plant characteristics, particularly resistance or tolerance to environmental and biotic stresses (Carboneau, 1985; Souza et al., 2001; Cerqueira et al., 2004). Scion–rootstock combinations affect yield, precocity, the organic and mineral composition of leaves and fruits, nutrient uptake and use, tolerance to salinity, drought and frost,

resistance to diseases and pests, and fruit quality and postharvest performance (Pompeu Júnior, 1991; Nogueira et al., 2001). Variability in plant responses and the availability of different genetic combinations are highly important for the citrus industry, which should not rely on a limited number of rootstocks (Carneiro, 2014). However, this variability also represents a challenge for breeding programmes seeking superior genotypes adapted to different soil, water and environmental management strategies. Consequently, several breeding programmes have evaluated hundreds of new hybrid rootstocks to promote varietal diversification (Rocha et al., 2009).

‘Tahiti’ acid lime is predominantly grown under rainfed conditions in Brazil. Therefore, scion–rootstock combinations adapted to different production regions and capable of achieving high yields and water-use efficiency are desirable (Lauriane et al., 2015). In irrigated systems, rootstock selection must consider local edaphoclimatic conditions, irrigation regimes, water availability, production costs and crop productivity per unit of water applied (Bastos et al., 2014).

‘Tahiti’ acid lime has received considerable research attention because of the growing interest in indices that can support breeding programmes in evaluating germplasm and identifying genotypes with contrasting responses to water deficit and stomatal conductance. Understanding the physiological and biochemical mechanisms underlying these differential responses is essential for selecting drought-adapted genotypes (Duarte et al., 2017).

This study aimed to determine the physiological and biometric responses of ‘Tahiti’ acid lime grafted onto five rootstocks and subjected to four irrigation-management strategies, with particular emphasis on improving water-use irrigation efficiency.

2. Materials and methods

2.1. Experimental site

This study was conducted at the experimental site of the Brazilian Agricultural Research Corporation (EMBRAPA) in the city of Cruz das Almas, in the Recôncavo region of Bahia state, Brazil. The geographic coordinates are 12°40'39" S latitude, 39°06'23" W longitude, and an altitude of 225 m. According to the Thornthwaite (1984) classification, the regional climate is C1dA'a' (dry sub-humid), with mean monthly temperature and relative humidity of 23.9 °C and 81%, respectively. The municipality has an average annual rainfall of 1,131.2 mm, with the highest concentration of rainy days occurring from March to August, while the driest periods occur between September and February (Silva et al., 2016).

The study was carried out in a ‘Tahiti’ acid lime orchard established on a 2,964 m² experimental plot (52 m wide by 57 m long) (Fig. 1). The orchard has been established for four years (2018–2021) and contains a total of 360 trees spaced at 4.0 m x 2.0 m, subjected to different irrigation strategies. The soil in the experimental area is typical of the coastal tablelands—a dystrophic Yellow Latosol with a sandy clay loam texture (Table 1) located on flat terrain.



Fig. 1 Aerial view of the experimental unit (irrigation sector) at Embrapa Cassava & Tropical Fruits in Cruz das Almas, Bahia, captured by drone. Photo: T.M. Silva and M.A. Coelho Filho, 2020

The results of the physical-hydraulic and chemical analyses (Tables 1 and 2) formed the basis for soil management in the experimental area ranging from initial operations such as plowing, harrowing, and furrowing for the planting of grafted seedlings, to annual soil amendment and fertilization. All management practices were carried out in accordance with Embrapa's technical recommendations for the soil type and region under study.

Table 1. Distribution of sand, silt, and clay; textural class; soil bulk density (Ds); and field capacity (CC) along the profile of a dystrophic Yellow Latosol (Oxisol) at Embrapa Cassava & Tropical Fruits, Bahia.

Horizon	Depth	Sand	Silt	Textural	Class	Ds	CC
	(m)	(g Kg ⁻³)				Kg dm ⁻³	(m ³ m ⁻³)
AP	0 - 0,20	732	87	181	Sandy loam	1,67	0,1785
AB	0,20 - 0,40	629	68	303	Sandy clay loam	1,66	0,1964
BA	0,40 - 0,70	600	77	323	Sandy clay loam	1,43	0,1896
BW1	0,70 - 1,00	535	81	384	Sandy clay	1,39	0,2105
BW2	1,00 - 1,40	467	127	406	Sandy clay	1,35	0,2285
BW3	1,40 - 1,60+	459	96	445	Clay	1,43	0,2189

Source: Souza and Souza (2001) and Santos (2016).

Table 2. Results of soil chemical analysis performed by the Soil Chemistry Laboratory for the 'Tahiti' acid lime orchard area at Embrapa/CNPMPF, in the municipality of Cruz das Almas, Bahia.

Z(m)	Ph	P	K	Ca	Mg	Mg+Ca	Al	Na	H+Al	SB	CTC	V	MO
mg dm ⁻³		cmolc dm ⁻³				% g kg ⁻¹							
0-20	6	47	0,31	1,7	0,82	2,52	0	0,03	1,87	2,86	4,73	60	11
20-40	6,3	17	0,24	1,27	0,67	1,94	0	0,04	1,98	2,22	4,2	53	7

Note: Depth (z), pH, potassium (K), calcium (Ca), magnesium (Mg), magnesium plus calcium (Mg+Ca), aluminum (Al), sodium (Na), hydrogen plus aluminum (H+Al), base saturation (SB), cation exchange capacity (CEC), organic matter (OM).

2.2. Experimental design

The experiment was conducted in two stages. In the first stage, biometric analyses were performed using a randomized block design with three replications in a 5×4 factorial arrangement, comprising five genotypes and four irrigation treatments. Each experimental plot consisted of six plants, with four plants serving as the net plot, in accordance with the applied treatments. The acid lime plants were grafted onto the following rootstocks: Swingle citrumelo (G1), Flying Dragon (G2), BRS Matta (G3), LVK $\times$ LCR-38 (G4), and HTR-069 (G5). The second stage involved physiological analyses using a completely randomized design with four replications in a 3×4 factorial arrangement, comprising three genotypes, four irrigation treatments, and two blocks. Each experimental plot consisted of six plants, with two plants serving as the net plot, in accordance with the applied treatments. The acid lime plants were grafted onto the following rootstocks: Swingle citrumelo (G1), Flying Dragon (G2), and BRS Matta (G3). The same treatments were used at both stages, designated as follows: Treatment 1 – rainfed cultivation (S); Treatment 2 – irrigation allowing 60% depletion of available soil water (Full irrigation – I); Treatment 3 – irrigation allowing 50% depletion (Moderate deficit irrigation – IDM); and Treatment 4 – irrigation allowing 30% depletion (Severe deficit irrigation – IDS).

2.3. Climate monitoring

Data regarding minimum temperature (T_{min}), mean temperature (T_{mean}), maximum temperature (T_{max}), mean relative humidity (RH), and rainfall were obtained from the agrometeorological station at Embrapa Cassava & Fruits in the city of Cruz das Almas, Bahia. The climatic data presented cover the experimental evaluation period from January 2018 to June 2021; the lowest temperature recorded was 18.6°C in August 2020 (Fig. 2), while the highest was 34.7°C in February 2019, and the mean temperature generally ranged from 21.7°C to 25.6°C throughout the experiment. The mean relative humidity was 88.6% in September 2020. Low rainfall occurred in the experimental area during the period from October 2019 to February 2020—the months when the water deficit treatment was applied—leading to a better response to the adopted irrigation management strategies, as reflected in the plants' physiological indicators. April 2020 was the wettest month (326.1 mm), replenishing soil water storage throughout the root system and mitigating the effects of the deficit irrigation treatments, whereas the lowest accumulated rainfall was 6.1 mm, recorded in December 2020. Fig. 3 shows the months during which field harvests took place.

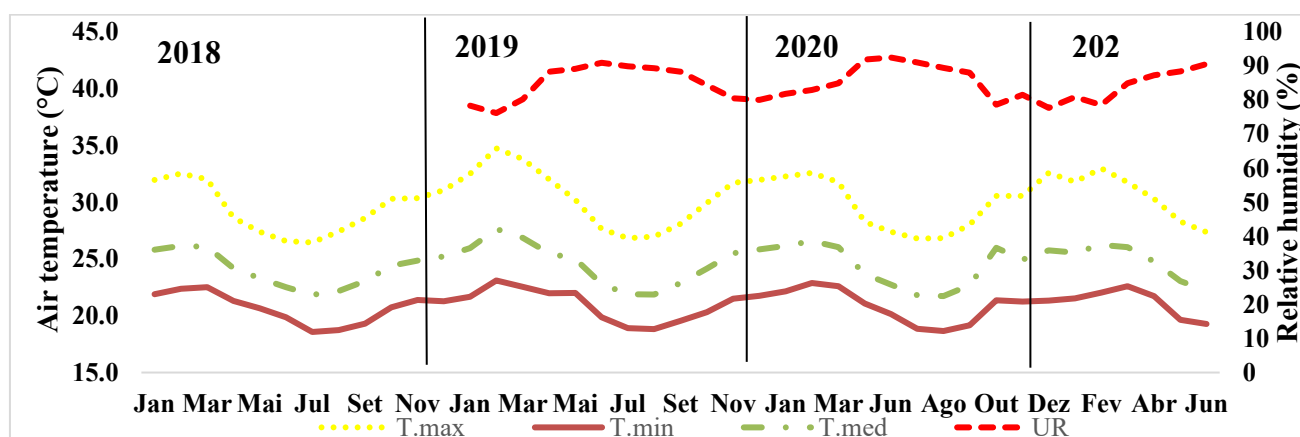


Fig. 2 Minimum (Tmin), mean (Tmed), and maximum (Tmax) temperatures and relative humidity (RH) during the evaluation of ‘Tahiti’ acid lime trees from January 2018 to June 2021. Source: Automatic weather station at Embrapa Cassava & Fruits in the city of Cruz das Almas, BA

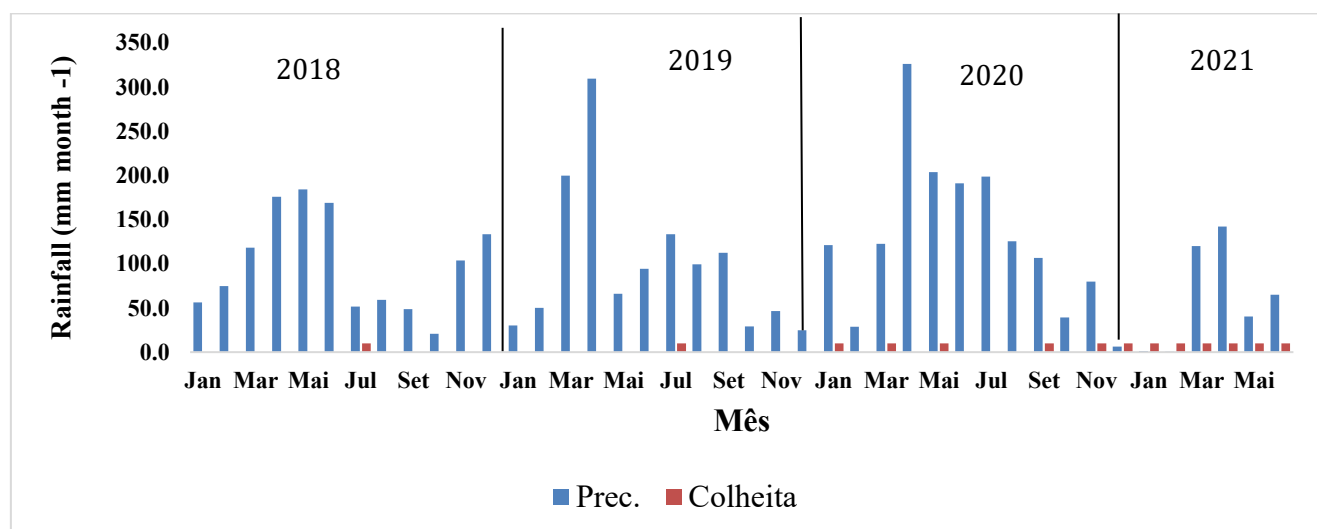


Fig. 3 Rainfall and harvest timing during the evaluation of ‘Tahiti’ acid lime trees from January 2018 to June 2021. Source: Embrapa Cassava & Tropical Fruits automatic weather station in Cruz das Almas, BA

2.4. Irrigation management

The plants were irrigated via a drip system featuring ten emitters per plant, each with a flow rate of 4 L h^{-1} and spaced 0.5 m apart. The drip line was positioned 30 cm from the plant trunk, with a layout comprising four manifold lines, each serving three lateral except for the first and fourth lines, which included the border rows. To minimize interference in water regimes between treatments, the experiment was arranged in order from the least irrigated to the most irrigated. Soil water content used to determine when to irrigate was monitored daily throughout the experimental evaluation period using time-domain reflectometry (TDR).

Soil moisture was monitored daily using TDR probes constructed according to Coelho et al. (2005). Each probe consisted of three parallel stainless-steel rods, 0.09 m in length and 0.4 cm in diameter. The probes were

installed within the soil horizons (0–0.20 m, 0.20–0.40 m, 0.40–0.70 m, and 0.70–1.00 m) at a distance (D) of 30 cm from the stem of each plant and at depths (Z) of 10, 30, 55, and 90 cm (Table 2).

The percentages used in the water management strategies were based on soil water storage within each horizon (Table 1). Given the sub-humid nature of the region, it is assumed that a lower localized irrigation frequency is permissible; this study bases that frequency on the variation of available water within the wetted bulb formed by the drippers and the crop's root zone. This zone encompasses the effective root depth of the citrus plant, with 80% of the root system located between 50 and 60 cm below the soil surface. This characteristic results in low resistance to prolonged periods of water deficit (Sentelhas, 2005).

2.5. Biometric variables

Biometric measurements of the orchard plants in each experimental plot were collected throughout the experimental period, spanning from January 2018 to March 2021. A total of 120 plants were evaluated two per plot representing 10 replicates distributed across the onset of dry and rainy seasons. The following variables were studied: plant height (PH - m), stem diameter below the graft union (DAB - m), and stem diameter above the graft union (DAC - m). These variables were used to calculate the vegetative vigor index (VVI), measured 5 cm from the graft union, and canopy volume (CV - m). Two plants per plot were evaluated, totaling 120 plants assessed during each campaign.

Plant height was measured from the soil surface to the top of the plant. Diameters were measured based on the predominance of lateral branches at the graft union. Measurements were taken using a graduated ruler and an analog caliper.

Canopy volume (CV) was calculated according to Pompeu Junior (1991), using the equation 1.

$$V_c = \frac{2}{3} \times \pi \times (r^2) \times h$$

Where:

V_c - crown volume (m³)

r - crown radius (m)

h - plant height (m)

2.5.1. Vegetative vigor index

Based on the data obtained, the vegetative vigor index (VVI) was calculated using individual measurements of all plants specifically plant height (H), mean canopy diameter (CD), and rootstock trunk diameter (RTD) applying the formula proposed by Bordignon et al. (2003):

$$VVI = [H + CD + (RTD \times 10)]/100$$

H – Plant height;

CD – Mean canopy diameter;

RTD – Diameter below the graft union;

2.5.2. Yield

Yield assessments were conducted over several years, covering 15 harvests of ‘Tahiti’ acid lime between 2018 and the first six months of 2021. Within each six-plant plot, the two end plants were excluded from the analysis, meaning only the four intermediate plants were recorded, resulting in a total of 60 evaluated plants.

2.5.3. Production efficiency

To analyze production efficiency, the canopy volume (V_c) in m^3 obtained between January 2018 and March 2021 was considered and related to productivity per plant and canopy volume according to Equation 1:

$$EP = P/V_c$$

Where:

EP – Production efficiency ($kg \cdot m^{-3}$);

P – Productivity ($kg \cdot plant^{-1}$);

V_c – Canopy volume (m^3).

2.5.4. Total and irrigation water-use efficiency

Water use efficiency is determined by the ratio between the amount of water effectively used by the crop and the amount withdrawn from the source. To determine total water use efficiency (EUA_{it}) and irrigation water use efficiency (EUA_i), data on total production (P) for the years 2018, 2019, 2020, and 2021 were required, along with the volume of water applied (L_{am}) in each treatment for the same period.

$$EUA = P/L_{am}$$

Where:

EUA – Water use efficiency ($kg \cdot m^{-3}$);

P – Productivity ($kg \cdot plant^{-1}$);

L_{am} – Water depth applied to the orchard ($m^3 \cdot plant^{-1}$).

$$EUA = Prec/L_{am}$$

EUA – Total water use efficiency ($kg \cdot mm^{-3}$);

Prec – Precipitation (mm);

L_{am} – Water depth applied to the orchard ($m^3 \cdot plant^{-1}$).

2.6. Physiological assessment of water stress

The physiological aspects monitored over time in response to the treatments were: gas exchange (stomatal conductance (g_s), internal CO₂ concentration (C_i), photosynthesis (A), and transpiration (E)) and leaf water potential (Ψ_w). These analyses were conducted concurrently, characterizing the plant's water status on February 8 (start of the dry season) and April 3 (end of the period). Three genotypes were selected for the evaluations Citrumelo Swingle (G1), Flying Dragon (G2), and BRS Matta (G3) based on their specific characteristics. Citrumelo Swingle (G1) is tolerant to gummosis; although its use is relatively recent, it is promising due to the qualities it imparts to the fruit, resulting in superior fruit quality compared to plants grafted onto other rootstocks. Citrumelo Swingle served as the reference for soil moisture measurements due to its large size and, consequently, the greater extent of its root system. Flying Dragon (G2) is characterized primarily by the dwarfing effect it confers on grafted plants, which can facilitate cultural practices and optimize planting areas by allowing for intercropping; it is also drought-tolerant. BRS Matta (G3) exhibits good fruit productivity and is tolerant to citrus tristeza virus and citrus decline; its low stature with a height of less than 2.5 m facilitates field management.

2.6.1 Gas exchange

Stomatal conductance (g_s), internal CO₂ concentration (C_i), photosynthesis (A), and transpiration (E) were estimated at the end of each treatment using a portable infrared gas analyzer (IRGA), model LI-1600 (Li-Cor, Nebraska, USA), between 8:00 a.m. and 10:00 a.m. Measurements were taken on a fully expanded leaf located between the first and fifth leaf positions from the shoot apex.

2.6.2. Leaf water potential (Ψ_w)

Leaf water potential (Ψ_w) was determined using a Scholander pressure chamber (M670, PMS Instrument Co., Albany, OR, USA), always assessing the second or third fully expanded, mature leaf from the middle section of the canopy during the morning (Ψ_{am}), between 8:00 and 10:00 AM. Three plants per plot were analyzed, totaling three leaf readings per plot across eight plots (Fig. 8-B). Leaves were detached using a blade. Measurements were performed during the dry-season evaluation period described above.

2.7. Statistical analysis

Statistical analysis was performed using the SISVAR software, version 5.3 (FERREIRA, 2011), with data subjected to analysis of variance (ANOVA). Biometric data followed a randomized block design and were analyzed via ANOVA in a $4 \times 5 \times 3$ factorial scheme, comprising four irrigation management types, five genotypes, and three replicates. Physiological data followed a completely randomized design and were analyzed via ANOVA in a $4 \times 3 \times 4$ factorial scheme, comprising four irrigation management types, three

genotypes, and two blocks. Means were compared using Tukey's test at the 5% significance level, and significant interactions were further analyzed (decomposed).

3. Results and discussion

There was a significant effect ($p < 0.05$) of genotypes and irrigation management—varying according to the evaluation year—on all analyzed variables: vegetative vigor index (VVI), plant height (PH), rootstock stem diameter (RSD), cumulative yield (CY, kg plant^{-1}), productive efficiency (PE, kg plant^{-1}), and canopy volume (CV, m^3) (Table 3). Irrigation management physiologically affected the plants, indicating water stress based on stomatal conductance (gs), photosynthesis (A), transpiration (E), leaf water potential (Ψ_w), and internal CO_2 concentration (Ci) (Table 4). There was an effect of management and genotype on water use efficiency (WUE – $\text{kg plant}^{-1} \text{mm}^{-1}$) and total water use efficiency (WUEt – $\text{kg plant}^{-1} \text{mm}^{-1}$) in 2021 (Table 5).

Table 3. Plant height (PH m), rootstock stem diameter (RSD cm), Vegetative Vigor Index (VVI), yield (kg plant^{-1}), canopy volume (CV m^{-3}), and productive efficiency (kg plant^{-1}) from 2018 to 2021 for 'Tahiti' acid lime [*Citrus latifolia*]

246 (Yu.Tanaka) Tanaka] trees in an orchard with different rootstock combinations. Brazilian Agricultural Research
 247 Corporation (Embrapa) – Cassava & Tropical Fruits, Cruz das Almas, Bahia.

FV	GL	AP (m)	DPE (cm)	IVV		Production (kg plant ⁻¹)			VC (m ³)	EP (kg / m ³)
		2021	2021	2021	2018	2019	2020	2021	2021	2021
MI	3	0,34 ^{ns}	0,03*	0,17 ^{ns}	0,01**	0,14 ^{ns}	0,79 ^{ns}	0,44 ^{ns}	0,30 ^{ns}	0,66 ^{ns}
GE	4	0,00**	0,00**	0,00**	0,07 ^{ns}	0,03*	0,00**	0,00**	0,00**	0,00**
MIxGE	12	0,59 ^{ns}	0,16 ^{ns}	0,48 ^{ns}	0,11 ^{ns}	0,15 ^{ns}	0,24 ^{ns}	0,38 ^{ns}	0,81 ^{ns}	0,47 ^{ns}
CV(%)		10,94	7,44	6,93	39,04	96,79	42,26	39,04	25,44	41,15
Genotype mean										
Citrumelo Swingle		3,35 a	119, 54 a	7,54 a	0,10 a	0,22 b	2,93 c	2,89 c	15,67 a	0,04 c
Flying Dragon		2,27 c	88 67 bc	5,61 c	0,17 a	1,50 ab	11,61 b	7,54 b	7,03 c	0,28 b
BRS Matta		2,21 c	81,41 c	5,44 c	0,07 a	1,92 a	18,90 a	14,32 a	6,64 c	0,54 a
HTR-069		2,83 b	94,46 b	6,52 b	0,10 a	1,34 ab	9,46 b	4,49 bc	11,09 b	0, 11 c
LVK x LCR–38		2,72 b	89,52 bc	6,37 b	0,33a	1,58 ab	8,81 b	6,13 b	10,72 b	0,14 c
Average irrigation management										
T1		2,57 a	89,87 b	6,12 a	0,16 ab	1, 41 a	10,47 a	6,10 a	9,81 a	0,20 a
T2		2,66 a	96,50 ab	6,22 a	0,01 b	0,67 a	10,84 a	7,31 a	9,38 a	0,24 a
T3		2,72 a	95,66 ab	6,40 a	0,14 ab	1,74 a	10,07 a	7,68 a	10,99 a	0,24 a
T4		2,76 a	96,86 a	6,44 a	0,30 a	1,43 a	9,99 a	7,29 a	10,72 a	0,21 a

248 Note: SV = Source of variation; DF = Degrees of freedom; IM = Irrigation management; G = Genotype; ns =
 249 not significant; * = significant at 0.05; ** = significant at 0.01. Means followed by the same letter in the column
 250 do not differ significantly at the 5% level according to Tukey's test.

251 Table 4. Analysis of variance for water potential (Ψ_w , MPa), internal CO₂ concentration (C_i), transpiration (E), stomatal
 252 conductance (g_s), and photosynthesis (A) from 2018 to 2021 in a 'Tahiti' acid lime orchard with different rootstock
 253 combinations—Citrumelo Swingle (G1), Flying Dragon (G2), and BRS Matta (G3)—subjected to different treatments:
 254 Treatment 1 (S), Treatment 2 (Full irrigation - I), Treatment 3 (Moderate deficit irrigation - IDM), and Treatment 4

255 (Severe deficit irrigation - IDS). Brazilian Agricultural Research Corporation (Embrapa) – Cassava & Tropical Fruits,
 256 Cruz das Almas, Bahia.

FV	GL	Ψ_w (Mpa)	CI ($\mu\text{mol CO}_2 \text{ m}^2 \text{ s}^{-1}$)		E ($\text{mmol H}_2\text{O m}^2 \text{ s}^{-1}$)		GS		A	
Analise de variância			AV 1	AV 2	AV 1	AV 2	AV 1	AV 2	AV 1	AV 2
MI	2	0,00*	0,00*	0,35ns	0,02*	0,02*	0,00*	0,00*	0,00*	0,03*
GE	3	0,46ns	0,14ns	0,52ns	0,18ns	0,51ns	0,01*	0,25ns	0,00*	0,36ns
MIxGE	6	0,91ns	0,43ns	0,91ns	0,78ns	0,51ns	0,67ns	0,82 ns	0,21ns	0,98ns
CV(%)		13,3	15,5	23,07	82,67	37,05	36,23	51,67	36,02	46,95
Genotype mean										
Citrumelo Swingle		-1,10 a	307 b	238 a	1,76 a	1,26 a	0,07 ab	0,04 a	5,37 ab	4,03 a
Flay Dragon		-1,13 a	383 a	261 a	1,00 a	1,27 a	0,05 b	0,04 a	3,90 b	3,62 a
BRS Matta		-1,25 a	258 b	251 a	1,35 a	1,44 a	0,08 a	0,06 a	5,96 a	4,74 a
Average irrigation management										
T1	-1,55 a		316 a	225 a	0,79 b	0,96 b	0,04 b	0,03 b	2,34 c	3,00 b
T2	-1,35 ab		236 b	254 a	1,03 ab	1,29 ab	0,05 b	0,04 ab	4,91 b	3,93 ab
T3	-1,07 b		261 b	255 a	2,2 a	1,43 ab	0,08 a	0,05 ab	6,03 bc	4,13 ab
T4	-0,066 c		256 b	266 a	1,45 ab	1,61 a	0,09 a	0,07 a	7,04 a	5,48 a

257 SV Source of variation; DF Degrees of freedom; ns not significant; * significant at 0.05; ** significant at 0.01;
 258 Evaluation (A1 and A2); Treatment (T1, T2, T3, and T4). Means followed by the same letter in the column do
 259 not differ significantly at the 5% level according to Tukey's test.

260 Table 5. Water use efficiency and total irrigation water use efficiency (EUAt) from 2018 to 2021 for 'Tahiti' acid lime
 261 [Citrus latifolia (Yu. Tanaka) Tanaka] trees in an orchard with different rootstock combinations. Brazilian Agricultural
 262 Research Corporation (Embrapa) – Cassava & Tropical Fruits, Cruz das Almas, Bahia.

FV	GL	EUA (Kg planta^{-1})				EUA TOTAL (Kg planta^{-1})			
		2018	2019	2020	2021	2018	2019	2020	2021
MI	2	0,00**	0,08 ^{ns}	0,47 ^{ns}	0,00**	0,01**	0,15 ^{ns}	0,77 ^{ns}	0,00**
GE	4	0,02*	0,01**	0,00**	0,00**	0,07 ^{ns}	0,03*	0,00**	0,00**
MI x GE	8	0,60 ^{ns}	0,63 ^{ns}	0,39 ^{ns}	0,00**	0,74 ^{ns}	0,90 ^{ns}	0,08 ^s	0,00**
CV(%)		126,35	72,81	49,25	38,15	145,63	96,93	42,19	37,86

FV	GL	EUA (Kg planta ⁻¹)				EUA TOTAL (Kg planta ⁻¹)		
Genotype mean								
Citrumelo Swingle	0,004 ab	0,00 b	0,08 c	0,02 d	0,00 a	0,00 b	0,00 d	0,00 c
Flay Dragon	0,013 ab	0,039 ab	0,30 b	0,09 b	0,00 a	0,00 ab	0,00 ab	0,02 b
BRS Matta	0,003 b	0,048 a	0,62 a	0,13 a	0,00 a	0,00 a	0,00 a	0,07 a
HTR-069	0,004 b	0,043 ab	0,28 b	0,05 cd	0,00 a	0,00 ab	0,00 bc	0,01 bc
LVK x LCR-38	0,019 a	0,048 a	0,29 b	0,06 bc	0,00 a	0,00 ab	0,00 c	0,01 b
Average irrigation management								
T1					0,015 ab	0,00 a	0,00 a	0,03 a
T2	0,00 b	0,03 a	0,39 a	0,15 a	0,013 b	0,00 a	0,00 a	0,02 ab
T3	0,01 ab	0,04 a	0,50 a	0,08 b	0,014 ab	0,00 a	0,00 a	0,01bc
T4	0,02 a	0,06 a	0,37 a	0,05 a	0,003b	0,00 a	0,00 a	0,01 c

Note: SV = Source of variation; DF = Degrees of freedom; IM = Irrigation management; G = Genotype; ns = not significant; * = significant at 0.05; ** = significant at 0.01. Means followed by the same letter in the column do not differ significantly at the 5% level according to Tukey's test.

3.1. Biometric variables

3.1.1. Plant height

Analysis of the PH (m) data reveals a significant effect ($p < 0.05$) only for the genotypes (Table 4); 'Swingle' citrumelo (G1) stood out with a mean value of 3.35 m, the highest among the analyzed genotypes (Figure 4A). Plant height reflects growth; it is important to note that variations in this trait can arise from several factors, such as propagation method, cultivar, water availability, and fertilization management, among others (DUARTE et al., 2012).

Setin et al. (2009) observed plant growth on 'Swingle'a variety more sensitive to drought. Although the trunk diameter, canopy size, and consequent early development of sweet orange orchards on 'Swingle' are characteristics typically induced by **Poncirus trifoliata** and some of its hybrids, the intensity of this growth still depends on the water stress experienced in the orchard.

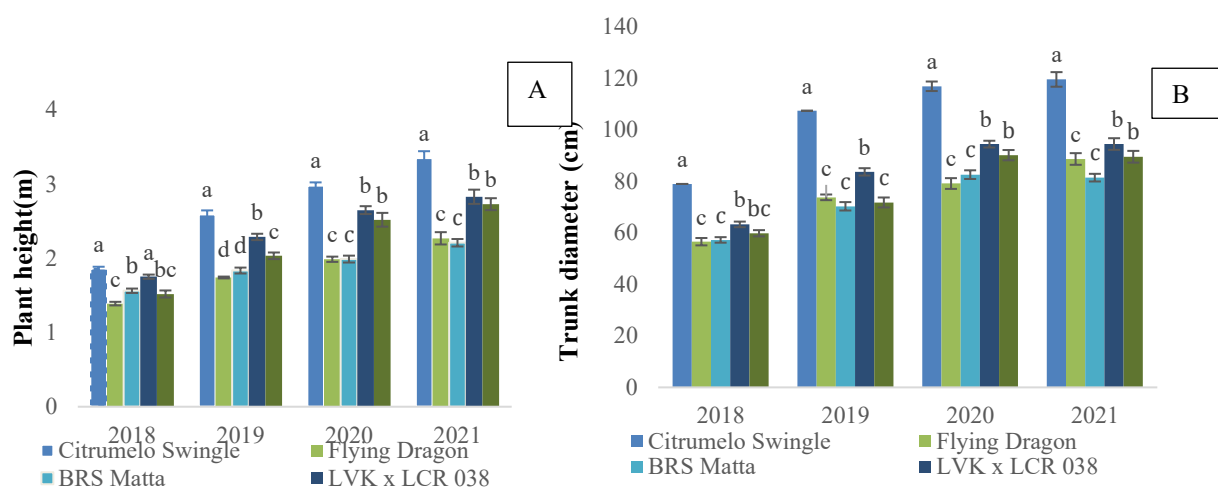


Fig. 4 Plant height (A) and trunk diameter (B) of a 'Tahiti' acid lime [*Citrus latifolia* (Yu. Tanaka) Tanaka] orchard using different rootstock combinations: Swingle citrumelo (G1), Flying Dragon (G2), BRS Matta (G3), HTR-069 (G4), and LVK × LCR–38 (G5). Period: January 2018 to March 2021; Embrapa Cassava & Fruits, Cruz das Almas, Bahia. Means followed by the same letter in the column do not differ significantly at the 5% level according to Tukey's test

3.1.2. Trunk diameter

Analysis of the trunk diameter (TD) data revealed a significant effect for the factors of genotype and irrigation management when analyzed individually (Table 3). Trunk diameter at the graft union serves as an indicator of compatibility between the rootstock and the scion; thus, it was observed that Swingle citrumelo (G1) exhibited a mean value of 119.54 cm, standing out compared to the other genotypes analyzed and demonstrating compatibility with the rootstock under study (Figure 4B). An analysis of irrigation management data revealed that the 'Swingle' citrumelo genotype (G1) performed best under treatment 4 (irrigation allowing for 30% depletion severe deficit irrigation, or IDS), showing a mean value of 96.8 cm. Thus, it is evident that greater water availability is associated with greater trunk diameter (cm).

According to Rodrigues (2018), the compatibility of the rootstocks with 'Tahiti' acid lime was high; the rootstock-to-scion stem diameter ratio (RD) exceeded 0.80, approaching full compatibility. This suggests good affinity between the scion and the studied rootstocks a factor just as important as agronomic attributes and resistance to biotic and abiotic stresses when selecting rootstocks.

Figueiredo et al. (2002) found that mean plant diameter was influenced by the rootstocks; 'Catania 2' stood out by inducing the highest values, differing significantly from most rootstocks, except for 'Morton', 'Orlando', and 'EEL' trifoliate orange. Mean scion height was also influenced by the rootstocks, with 'Orlando' yielding the highest value and differing from 'Cravo' lemon when used as a rootstock for 'Tahiti' lime under the prevailing edaphoclimatic conditions.

3.1.3. Vegetative vigor index

Vegetative vigor indices were analyzed over time specifically in 2018, 2019, 2020, and 2021. A significant individual effect ($p < 0.05$) was observed for both genotypes and irrigation management in 2019, whereas in 2018, 2020, and 2021, a significant effect was found only for the genotypes (Table 3).

According to Bordignon et al. (2003), the vigor index considering plant height, canopy diameter, and rootstock trunk diameter is arguably the parameter that best reflects the plants' vegetative vigor, despite the evident correlation among its components.

It was observed that the 'Swingle' citrumelo genotype exhibited a higher vegetative vigor index compared to the other genotypes evaluated. Pompeu Jr. and Blumer (2011) studied 'Swingle' citrumelo as a potential rootstock for 'Valencia' orange in a six-year-old orchard. It was noted that 'Swingle' citrumelo induces taller plants and larger canopy diameters (Figure 5).

In 2021, the vegetative vigor index of 'Swingle' citrumelo was approximately 13.62% and 15.55% higher than that of the LVK $\times$ LCR 038 and HTR 069 rootstocks, which followed closely with intermediate growth habits. 'Flying Dragon' and 'BRS Matta' induced a dwarfing growth habit in the 'Tahiti' acid lime canopy. This offers advantages such as facilitating cultural practices, fruit harvesting, and sanitation pruning, as well as allowing for increased planting density; consequently, their indices during this period were 25.64% and 27.83% lower than that of the most vigorous genotype.

Plants grafted onto 'Flying Dragon' typically reach heights of less than 2.5 m, according to Pompeu Jr. (2005)—a finding corroborated by field observations in the most recent evaluation, where the average height was 2.28 m.

'BRS Matta' was classified by Costa et al. (2021) as having a truly dwarfing growth habit in their study on hybrids for 'Valencia' orange. This genotype... It is possible to induce a plant height within the 2.05 to 2.74 m range. In the experiment, conducted over four years, the observed height was 2.22 m

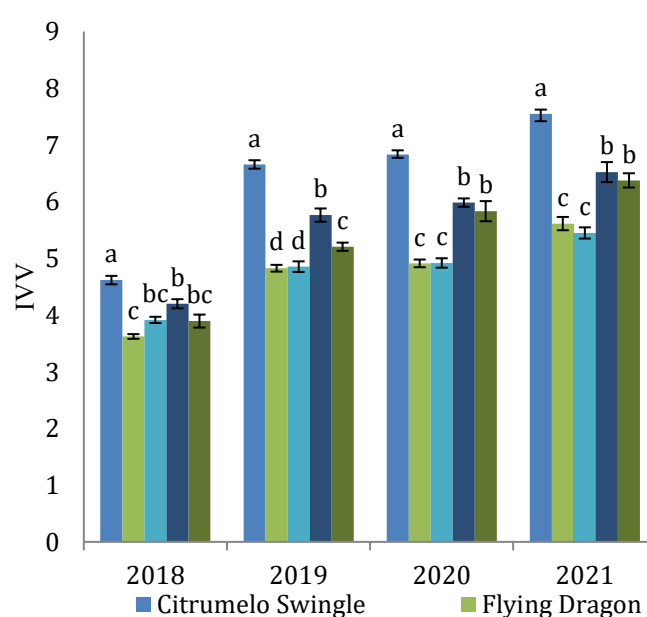


Fig. 5 Vegetative vigor index of the 'Tahiti' acid lime [*Citrus latifolia* (Yu. Tanaka) Tanaka] orchard using different rootstock combinations: Citrumelo Swingle (G1), Flying Dragon (G2), BRS Matta (G3), HTR-069 (G4), and LVK × LCR-38 (G5). Period: January 2018 to March 2021; Embrapa Cassava & Fruits, Cruz das Almas, Bahia

3.1.4. Canopy volume

Canopy volume was directly related to the average fruit yield per tree during the 2018–2021 period (Table 3); that is, larger trees induced by vigorous rootstocks produced more fruit. There was no significant interaction between water management and genotypes. A significant effect of water management was observed only when analyzed individually for the year 2019. There was a significant effect of genotypes ($p < 0.05$) on the canopy volume (V_c) of 'Tahiti' acid lime when analyzed individually across all years in question (Table 3).

An analysis of the data reveals that the Citrumelo Swingle (G1) genotype exhibited the highest mean canopy volume (15.66 m^3), followed by LVK × LCR-38 (G5) and HTR-069 (G4) with means of 11.09 m^3 and 10.72 m^3 , respectively—values superior to those of the other genotypes. Conversely, the Flying Dragon (G2) and BRS Matta (G3) genotypes showed the smallest canopy volumes (7.03 m^3 and 6.64 m^3), suggesting a dwarfing characteristic for these rootstocks; the data analyzed refer to the year 2021 (Figure 6).

Fig. 6 Canopy volume of 'Tahiti' acid lime [*Citrus latifolia* (Yu. Tanaka) Tanaka] trees on different rootstock combinations: Swingle citrumelo (G1), Flying Dragon (G2), BRS Matta (G3), HTR-069 (G4), and LVK × LCR-38 (G5), during the 2018–2021 period. Brazilian Agricultural Research Corporation (Embrapa) – Cassava & Fruits, Cruz das Almas, Bahia. Means followed by the same letter in the column do not differ significantly at the 5% level according to Tukey's test

Similar results were found by Silva (2017) in Viçosa, Minas Gerais, when evaluating the interaction characteristics of the same scion with Flying Dragon. Costa et al. (2019) found that the canopy volume of 'Tahiti' acid lime grafted onto BRS Matta, Swingle citrumelo, and HTR-069 showed statistically similar, intermediate values compared to the results obtained with 'Cravo' lemon and Flying Dragon. Regarding the effect of irrigation depth, a significant difference was detected only in the third year of cultivation, with the 50% ETc treatment standing out; this demonstrates the adaptability of 'Tahiti' acid lime to the different rootstocks used.

According to Espinoza-Núñez et al. (2011), the 'Tahiti' cultivar grafted onto 'Flying Dragon' exhibited dwarfing, with canopy volume reduced by one-third to one-half compared to 'Cravo' lemon trees, in six-year-old plants under both irrigated and rainfed conditions.

3.1.5. Yield

In 2018, irrigation management affected plant productivity. In 2019, 2020, and 2021, productivity was not affected by management (Table 3). The evaluated genotypes affected productivity ($P < 0.05$) in 2019, 2020, and 2021. There was no significant interaction between irrigation management and genotypes regarding the yield variable (kg plant^{-1}) (Table 3).

An examination of the yield data from 2019, 2020, and 2021 reveals that production increased over the years evaluated; the BRS Matta genotype stood out (18.9079 kg ha⁻¹), followed by the Flying Dragon genotype (11.6158 kg ha⁻¹) and LVK × LCR-038 (9.4665 kg ha⁻¹). These data were observed in 2020, a year in which six fruit harvests were carried out (Fig. 3). Therefore, the combinations of Tahiti acid lime on BRS Matta and Flying Dragon were the most productive during the years evaluated, demonstrating adaptation to water deficit. This results in higher production efficiency, suggesting the feasibility of high-density planting for these materials to achieve greater productivity per area. Accumulated yield in the early years—or early bearing—is an increasingly important attribute in rootstock selection (RODRIGUES et al., 2018).

Da Silva et al. (2018) found that the LVK × LCR-038 cultivar showed the highest mean (7.67) for the variable "number of fruits," a characteristic indicating early bearing and higher field productivity. Despite exhibiting signs of water stress, such as leaf curling, the LVK × LCR-038 cultivar demonstrates early bearing.

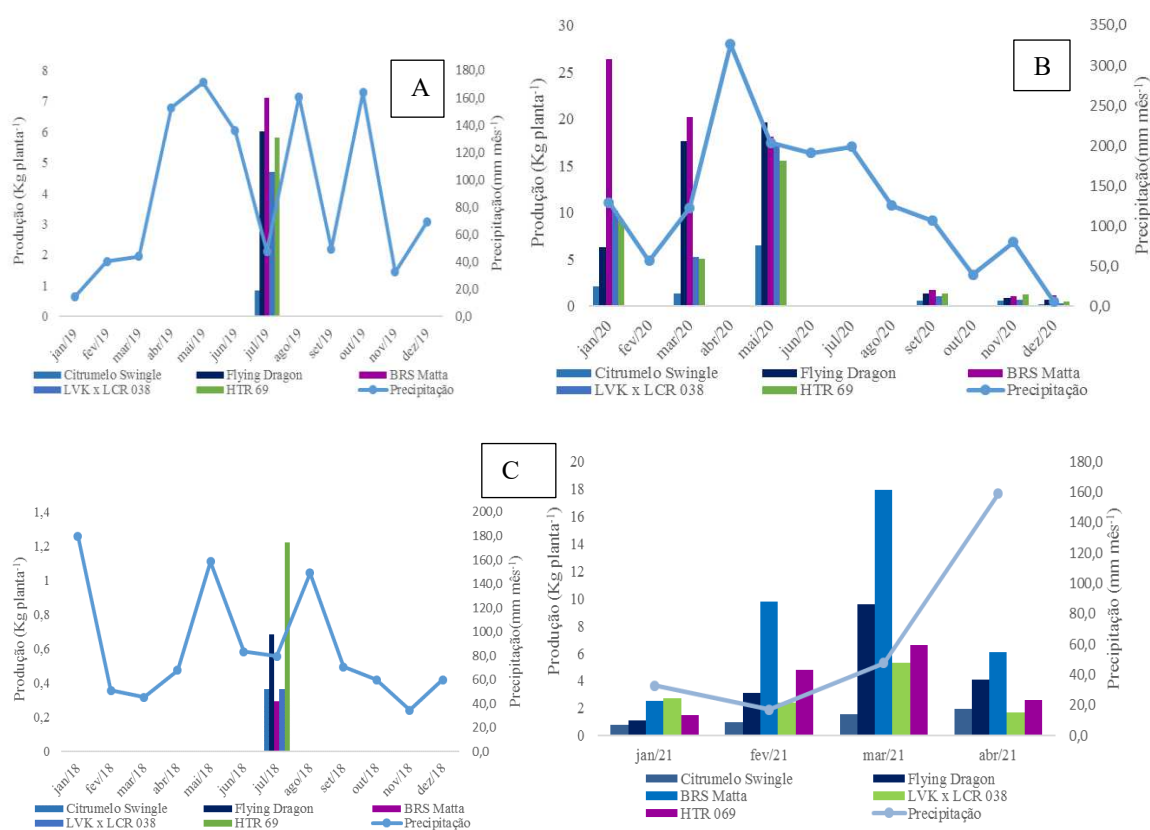


Fig. 7 Cumulative productivity of the 'Tahiti' acid lime orchard [*Citrus latifolia* (Yu.Tanaka) Tanaka], in different rootstock combinations. In the years 2018 (A), 2019 (B), 2020 (C), 2021 (D), Brazilian Agricultural Research

Corporation - Cassava and Fruticultura, Cruz das Almas, Bahia. Means followed by the same letter in the column do not differ significantly at the 5% level according to the Tukey test

Regarding irrigation management, a significant effect was observed in 2018; however, this did not affect the 'Tahiti' acid lime genotype. The duration of water stress influenced the timing and productivity of the acid lime but did not significantly affect cumulative production in the other years evaluated. The duration of water stress shifted the timing of peak production across treatments, facilitating orchard irrigation management (Figure 7). Alves Júnior (2006) found no significant difference among treatments in the second year of evaluation for 'Tahiti' acid lime plants on 'Swingle' rootstock subjected to irrigation depths ranging from 25% to 100% of ETc, with an average productivity of 12.9 t ha⁻¹.

3.1.6. Production efficiency

Production efficiency (Ep: kg of fruit per m³ of canopy) is a key variable in citrus rootstock selection, as it relates to more efficient resource use. An analysis of the data reveals that production efficiency was affected by genotypes in all years evaluated; there were isolated effects of irrigation management in 2018, but no genotype-by-management interactions were observed (Table 4). When evaluating the isolated effect of genotypes, production efficiency (Ep m³) was higher for plants grafted onto BRS Matta (G3), which showed the highest mean value (0.695 kg/m³) during the early months of 2021, making it the most efficient in terms of kilograms of fruit per cubic meter of canopy (Figure 8). The Flying Dragon (G2) rootstock exhibited a production efficiency (Ep) of 0.4169 kg/m³ during the 2019–2020 period. Due to their low production levels, the LVK × LCR-038 (G5) (0.0424 kg/m³), HTR-069 (G4) (0.1862 kg/m³), and Citrumelo Swingle (G1) (0.1985 kg/m³) rootstocks (Fig. 18) showed the lowest production efficiencies.

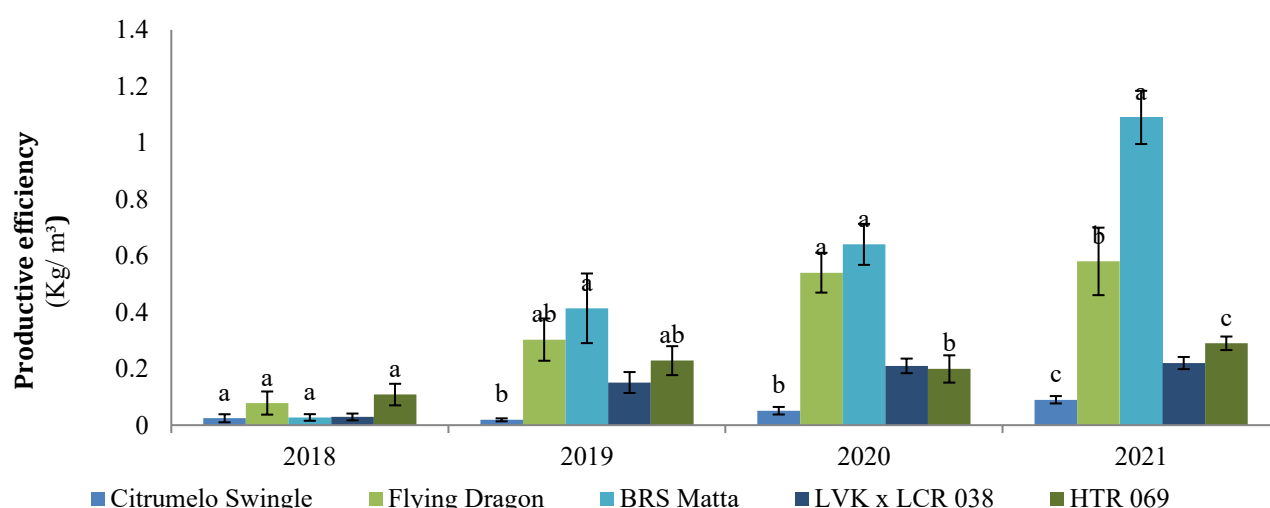


Fig. 8 Productive efficiency (Ep) of a 'Tahiti' acid lime [*Citrus latifolia* (Yu. Tanaka) Tanaka] orchard using different rootstock combinations: Swingle citrumelo (G1), Flying Dragon (G2), BRS Matta (G3), HTR-069 (G4), and LVK × LCR-38 (G5), during the 2018–2021 period. Brazilian Agricultural Research Corporation (Embrapa) – Cassava &

Tropical Fruits, Cruz das Almas, Bahia. Means followed by the same letter in the column do not differ significantly at the 5% level according to the Tukey test

Rodrigues et al. (2018) used the LVK × LCR 038 hybrid as one of the rootstocks in a 'Tahiti' acid lime orchard; after six years of cultivation, the orchard's productive efficiency was 0.84 kg m⁻³, and the canopy volume reached an average of 45.47 m³. The relationship where higher vigor corresponds to lower production was observed with LVK × LCR 038 in the experiment, which showed a canopy volume of 11.09 m³ and a productive efficiency of 0.22 kg m⁻³ (Table 4).

Yildirim et al. (2010) discuss the effect of shading on orchard yield, noting that a dense canopy prevents light from reaching all leaves, thereby resulting in lower energy production. Given the spacing adopted in the present study (4 × 2 m), Swingle citrumelo, LVK × LCR 038, and HTR 069—being more vigorous—increased leaf self-shading, reducing the canopy's light-use efficiency compared to smaller-sized plants. Plant density certainly contributed to this result. In orchards with wider spacing, such as 3 × 6 m, 'Swingle' citrumelo achieved yields of 21.89 kg per plant over three years under irrigated conditions (Amorim, 2015). Under the conditions of the orchard in question—with 2 × 4 m spacing—it produced only 0.59 kg per plant during the same period. Such massive vegetative growth within and between rows prevents light from reaching all the leaves, thereby causing a drop in yield.

On the other hand, 'Flying Dragon' shows excellent responses in high-density plantings. Studies by Stuchi and Silva (2005) on a 'Tahiti' acid lime orchard using this genotype observed that the narrower the in-row spacing, the higher the area productivity whether under rainfed or irrigated conditions though productivity efficiency is enhanced with irrigation.

Based on this premise, Bacar et al. (2017) noted that rootstocks promoting smaller tree sizes generally exhibit higher productive efficiency compared to those inducing voluminous canopies. In this context, high-density planting using dwarfing rootstocks favors increased productivity. Regarding the parameters of total water use efficiency and irrigation water use efficiency, an interaction between irrigation management and rootstocks was observed in 2021 (Table 4). This result can be explained by the production intensity and the continuous dry spells occurring between December and March.

3.1.7. Physiological variables

Soil moisture and water extraction values within the soil profile—recorded on March 8, 2021, prior to irrigation for the three treatments, and on March 9, 2021, after irrigation (Figure 9)—were correlated with leaf water potential (Ψ_w) and gas exchange.

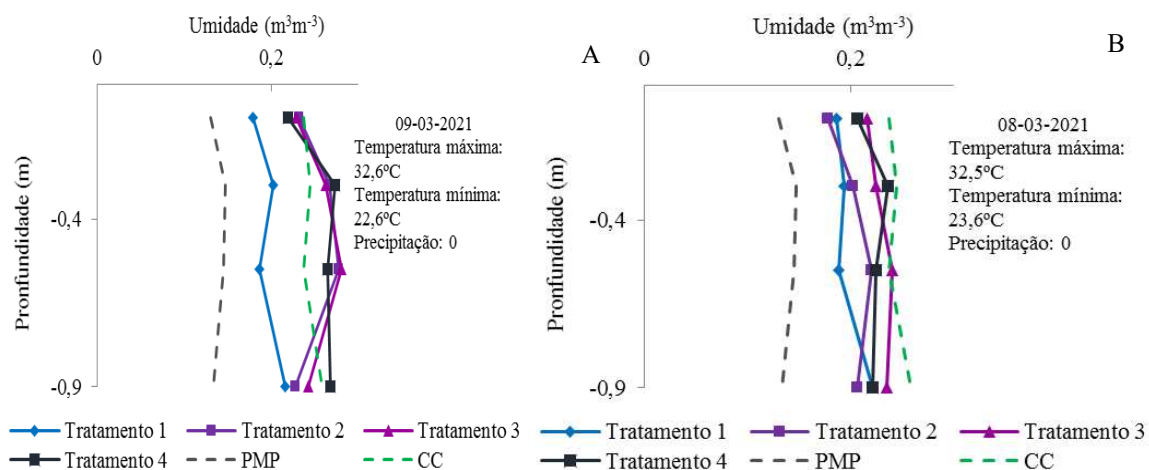


Fig. 9 Soil moisture content in soil profiles monitored by antennas installed at depths of 10 cm, 30 cm, 55 cm, and 90 cm on March 8, 2021 (A)—prior to irrigation across the three treatments—and on March 9, 2021 (B)—following irrigation applications of 7.93 mm (Treatment 2), 6.06 mm (Treatment 3), and 5.6 mm (Treatment 4)—in Cruz das Almas, Bahia

Irrigation timing was determined based on soil moisture and water extraction values within the soil profile, with the water replacement depth calculated to restore moisture to field capacity. Irrigation management was carried out whenever results exceeded the thresholds of 60% for Treatment 2, 50% for Treatment 3, and 30% for Treatment 4. Consequently, irrigation intervals were scheduled according to these data, occurring most frequently under full irrigation, followed by the treatment allowing 50% depletion and the treatment allowing a 60% deficit (Figure 10).

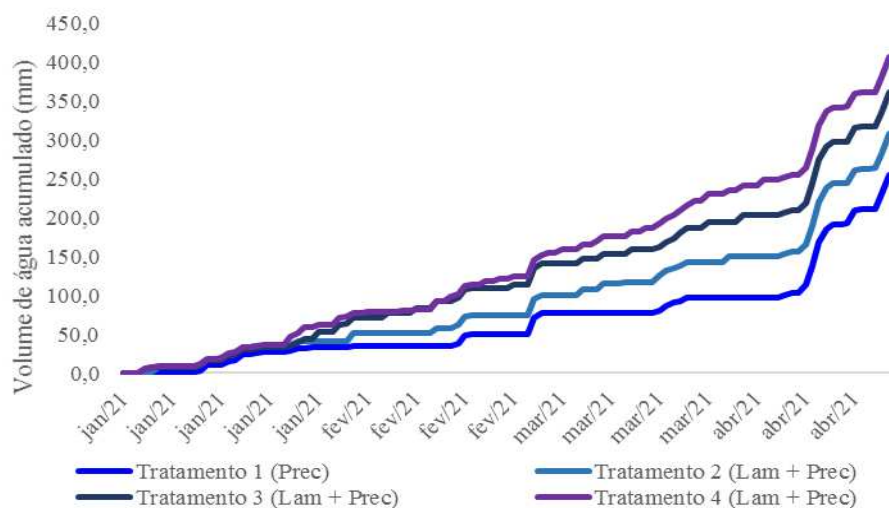


Fig. 10 Accumulated water volume received in 2021 at the experimental site according to water management strategies: precipitation values only for Treatment 1, and irrigation volumes plus precipitation for the subsequent treatments, in Cruz das Almas, Bahia

3.1.8. Leaf water potential (Ψ_w)

Water potential is the most reliable measure for determining plant water status, provided that experimental conditions are well controlled. Leaf water potential values indicated no significant differences among the rootstocks. A significant difference was observed regarding irrigation management (Table 4).

Analysis of the treatments revealed that rainfed conditions (T1) had the greatest negative impact on the leaf water potential (Ψ_w) of the combinations—particularly the BRS Matta combination, which showed a significant reduction (-1.68 MPa), followed by Flying Dragon (-1.48 MPa). This reduction was more pronounced compared to the other combinations, highlighting the drought susceptibility of this genotype (Fig. 9).

Fig. 11 Water potential (Ψ_w , MPa) of a 'Tahiti' acid lime orchard [*Citrus latifolia* (Yu. Tanaka) Tanaka] using different rootstock combinations—Citrumelo Swingle (G1), Flying Dragon (G2), and BRS Matta (G3)—and treatments: Treatment 1 (S), Treatment 2 (Full irrigation - I), Treatment 3 (Moderate deficit irrigation - IDM), and Treatment 4 (Severe deficit irrigation - IDS). Year: 2021. Brazilian Agricultural Research Corporation (Embrapa) – Cassava & Tropical Fruits, Cruz das Almas, Bahia. Means followed by the same letter in the column do not differ significantly at the 5% level according to Tukey's test

According to Medina et al. (2005), in citrus cultivation, leaf water potentials equal to or lower than -2.0 MPa are considered severe. In a study on the response to water deficit in 'Cravo' lemon and 'Swingle' citrumelo seedlings combined with five scion varieties, leaf water potential values of -2.08 MPa were observed after 16 days of induced water deficit, whereas irrigated plants averaged -0.48 MPa (Donato et al., 2007).

Brito (2018) found that Ψ_w remained consistently below -1 MPa in treatments with lower soil water availability during the driest evaluation period, making irrigation necessary in regions prone to drought to improve crop performance and productivity.

Cerqueira et al. (2004) observed that the water potential (Ψ_w) variable showed no significant differences among rootstocks under irrigated conditions or after 4 days of water deficit. After 8 days of irrigation suspension, significant differences were observed among the evaluated genotypes; 'Cravo' and 'Volkameriano' lemon trees did not differ from each other and exhibited the most negative (Ψ_w) values during the water deficit period, showing a 350% decrease compared to the irrigated period. After 12 days of water deficit, all genotypes showed a reduction in water potential, with the hybrids HTR-051 (87%) and TSK x CTTR-017 (175%) being the least sensitive. The 'Volkameriano' lemon tree (450%) exhibited the most negative potential, indicating

greater sensitivity. It is worth noting that, in addition to the decrease in Ψ_w under reduced water availability, a reduction in this variable can also occur with rising temperatures, a phenomenon linked to increased transpiration rates (Cruz et al., 2007). Regarding climatic data, the maximum temperature during December—the period when Ψ_w analyses were conducted—was 32°C; Ramos et al. (2001) highlight that average temperatures between 25°C and 31°C are recommended for the optimal development of ‘Tahiti’ limes. The hot weather may have also influenced Ψ_w values across all treatments.

3.1.9. Leaf gas exchange

Two evaluations of leaf gas exchange were performed; this is a crucial variable, as it allows for the assessment of water vapor loss and the influx and efflux of carbon dioxide and oxygen. The first evaluation took place on February 8, 2021 (considered the dry season), and the second on April 3, 2021 (the beginning of the wet season). An analysis of the data reveals a significant effect of irrigation management on internal CO₂ concentration (C_i) only during the first evaluation. Irrigation management had a significant effect on transpiration (E (mmol H₂O m⁻² s⁻¹)), stomatal conductance (g_s), and photosynthesis (A) in both evaluations, as did the genotypes, with variations observed across the evaluation periods (Table 3).

3.1.10. Internal CO₂ concentration (C_i)

An analysis of the internal CO₂ concentration (C_i) data showed a drop in C_i in plants subjected to the rain-fed treatment (T1)—where water deficit conditions were observed—due to stomatal closure. However, an increase in C_i can also occur due to reduced activity of enzymes involved in CO₂ fixation, decreased carboxylation, or increased photorespiration (MATTOS JUNIOR et al., 2005).

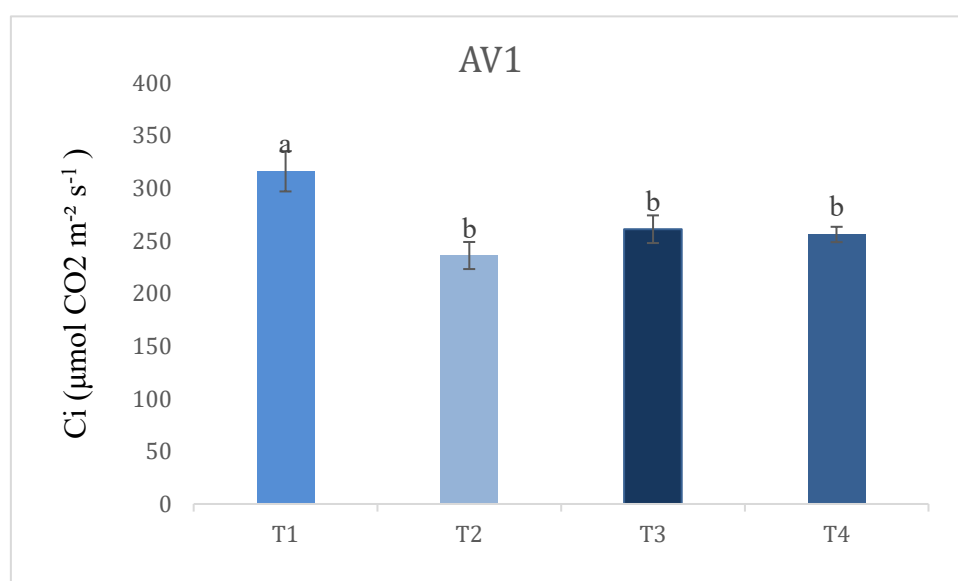


Fig. 12 Internal CO₂ concentration (C_i) of a 'Tahiti' acid lime orchard subjected to different treatments—Treatment 1 (S), Treatment 2 (Full irrigation - I), Treatment 3 (Moderate deficit irrigation - IDM), and Treatment 4 (Severe deficit irrigation - IDS)—in 2021. Brazilian Agricultural Research Corporation (Embrapa) – Cassava & Tropical Fruits, Cruz

das Almas, Bahia. Means followed by the same letter in the column do not differ significantly at the 5% level according to the Tukey test

Daley et al. (1989) found that a reduction in stomatal conductance can limit the rate of CO₂ uptake; consequently, C_i decreases in the intercellular spaces due to CO₂ consumption by photosynthetic activity.

Jadoski et al. (2005) found that internal CO₂ concentration (C_i) in the leaf mesophyll is reduced by stomatal closure, resulting in a decrease in the carbon dioxide assimilation rate. This relates to the increases recorded in internal carbon dioxide concentration and the gains in the CO₂ assimilation rate, as well as variations in climatic variables recorded on the day the evaluations were performed.

Transpiration (E) (1.61 mmol m⁻² s⁻¹), stomatal conductance (g_s) (0.072), and photosynthesis (A) (5.48) were higher in treatment T4 (irrigation allowing 30% depletion), differing statistically from the other treatments; this effect was most evident during the first evaluation. Soil water availability influences stomatal closure, limiting stomatal conductance and transpiration and consequently reducing the rate of photosynthesis (PEDROSO et al., 2014). It is worth noting that stomatal closure is the plant's first line of defense against soil water deficit, as this mechanism restricts water loss through transpiration; however, this process simultaneously leads to a reduction in CO₂ assimilation via photosynthesis. Stomatal closure occurs due to the dehydration of guard cells or in response to hormonal signals.

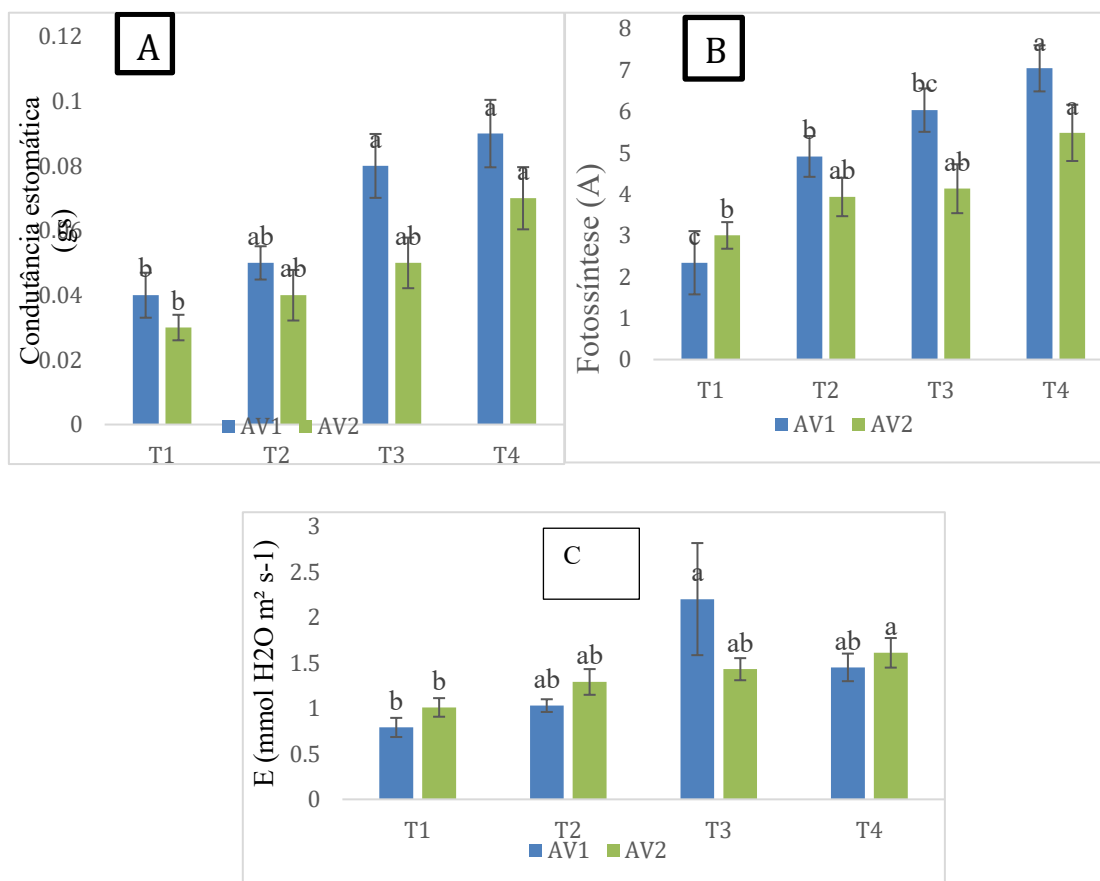


Fig. 13 Stomatal conductance g_s (A), photosynthesis A (B), and transpiration E (C) of the 'Tahiti' acid lime orchard subjected to different treatments: Treatment 1 (S), Treatment 2 (Full irrigation - I), Treatment 3 (Moderate deficit irrigation - IDM), and Treatment 4 (Severe deficit irrigation - IDS) in 2021. Brazilian Agricultural Research Corporation (Embrapa) – Cassava & Tropical Fruits, Cruz das Almas, Bahia. Means followed by the same letter in the column do not differ significantly at the 5% level according to Tukey's test

Despite the greater water availability in the control treatment (T4), many physiological characteristics respond more directly to changes in plant water status than to soil water content or tension (Table 3). Magalhães et al. (2008) found that the response of gas exchange and g_s following the start of irrigation suspension—in relation to the number of days without irrigation—was similar for both rootstocks; that is, values for A, E, and g_s decreased as the number of days without irrigation increased. The same occurred with instantaneous carboxylation efficiency; maximum values for both rootstocks were observed prior to the suspension of irrigation and decreased progressively as water deficit intensified.

Medina et al. (1998) observed similar results regarding the decline in photosynthetic metabolic activity in orange trees under water stress. Under water deficit conditions, variables related to gas exchange did not differ between rootstock types.

Brito et al. (2012) found that applying water depths of less than 75% of actual evapotranspiration (ETc) compromised gas exchange and photosynthesis in the citrus scion-rootstock combinations evaluated (scions: 'Tahiti' acid lime and 'Star Ruby' pomelo; rootstocks: 'Cravo Santa Cruz' lemon and Trifoliate Hybrid -069).

3.1.11. Total and irrigation water-use efficiency

Analysis of the data in the analysis of variance table for water-use efficiency and total water-use efficiency (Table 5) reveals a significant interaction ($p < 0.05$) between genotypes and irrigation management in 2021, highlighting the impact of the management practices employed during the evaluation period. This result can be attributed to production intensity and the continuous dry spells occurring between December and March.

Fig. 14 presents the total yield (kg plant^{-1}) of the 'Tahiti' acid lime orchard evaluated from January 2018 to July 2021. It was found that Treatment 1 (rain-fed) was the most efficient in terms of fruit production relying solely on rainfall (Fig. 18).

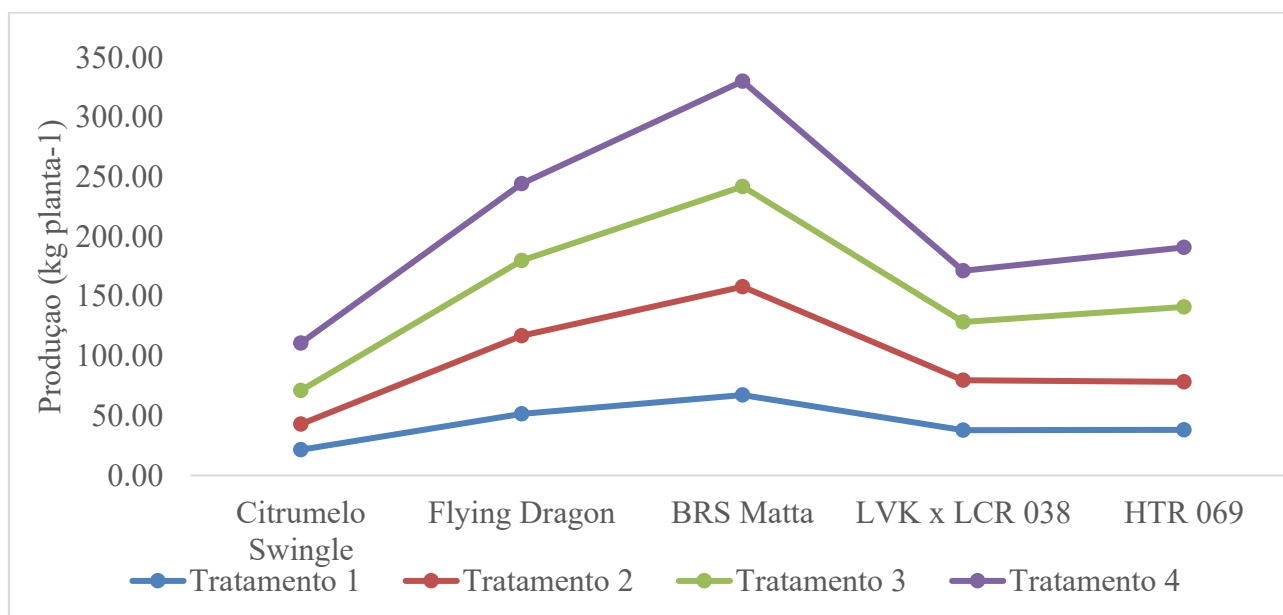


Fig. 14 Total yield of 'Tahiti' acid lime [*Citrus latifolia* (Yu.Tanaka) Tanaka] orchards on different rootstock combinations—Citrumelo Swingle (G1), Flying Dragon (G2), BRS Matta (G3), HTR-069 (G4), and LVK × LCR-38 (G5)—under four treatments: Treatment 1 (S), Treatment 2 (Full irrigation - I), Treatment 3 (Moderate deficit irrigation - IDM), and Treatment 4 (Severe deficit irrigation - IDS), in 2021. Brazilian Agricultural Research Corporation (Embrapa) – Cassava & Tropical Fruits, Cruz das Almas, Bahia. Means followed by the same letter in the column do not differ significantly at the 5% level according to Tukey's test

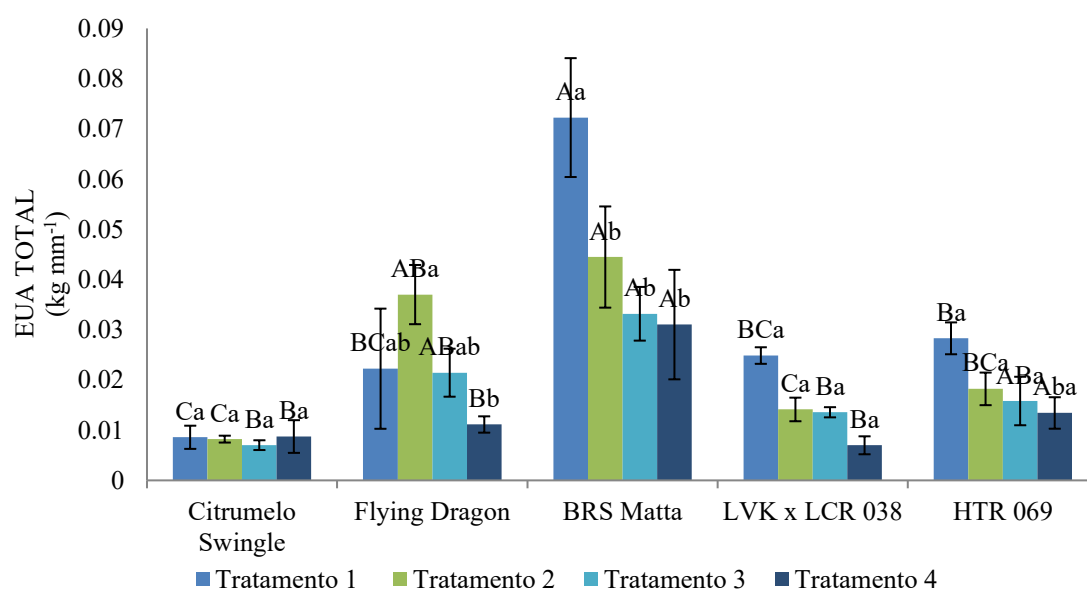


Fig. 15 Total water use efficiency (Total WUE) of a 'Tahiti' acid lime orchard [*Citrus latifolia* (Yu. Tanaka) Tanaka] on different rootstock combinations—Citrumelo Swingle (G1), Flying Dragon (G2), BRS Matta (G3), HTR-069 (G4), and LVK × LCR-38 (G5)—under four treatments: Treatment 1 (S), Treatment 2 (Full irrigation - I), Treatment 3 (Moderate deficit irrigation - MDI), and Treatment 4 (Severe deficit irrigation - SDI). Year: 2021. Embrapa Cassava & Fruits, Cruz

das Almas, Bahia. Means followed by the same letter in the column do not differ significantly at the 5% level according to Tukey's test

Fig. 16 Water use efficiency (WUE, kg plant⁻¹) of a 'Tahiti' acid lime [*Citrus latifolia* (Yu. Tanaka) Tanaka] orchard on different rootstock combinations: Swingle citrumelo (G1), Flying Dragon (G2), BRS Matta (G3), HTR-069 (G4), and LVK × LCR-38 (G5). The trees were subjected to four treatments in 2021: Treatment 1 (S – rainfed), Treatment 2 (I – full irrigation), Treatment 3 (IDM – moderate deficit irrigation), and Treatment 4 (IDS – severe deficit irrigation). Conducted by Embrapa Cassava & Fruits (Empresa Brasileira de Pesquisa Agropecuária), Cruz das Almas, Bahia. Means followed by the same letter in the column do not differ significantly at the 5% level according to Tukey's test

Irrigation resulted in higher WUE across all four treatments, with the BRS Matta (G3) genotype proving the most efficient. Under rainfed conditions (Treatment 1), BRS Matta was the most efficient in fruit production relying solely on rainfall (0.07 kg plant⁻¹; Fig. 18), owing to its superior drought tolerance. Thus, it is a suitable candidate for rainfed cultivation, whereas the other genotypes appear to require irrigation to achieve optimal performance—similar to the behavior observed with the 'Flying Dragon' trifoliate orange (Stuchi et al., 2003). It is worth noting, however, that the performance of the BRS Matta genotype varies depending on the orchard's location. Among the genotypes evaluated under the studied environmental conditions, BRS Matta demonstrated the highest tolerance to water stress, a finding that differs from the classification proposed by Costa et al. In a 2021 experiment conducted in Colômbia, SP, using 'Valencia' orange trees—characterized by high drought sensitivity—excellent fruit yields were induced; therefore, they can be considered for rainfed cultivation with wider tree spacing. Across all treatments, 'Swingle' citrumelo was the least efficient, a result attributed to its low yield, meaning the effect of irrigation levels on this genotype was not observed.

For 'Flying Dragon', the highest total water use efficiency (TWUE) values were observed under moderate and severe deficit irrigation (Treatments 2 and 3), with a decrease occurring under the water stress conditions of Treatments 1 and 4. Regarding the strategies applied to this rootstock, maintaining 60% of soil water storage proved to be the most efficient approach, as the rainfall received in 2021 was insufficient to meet the plant's water demands. 'Flying Dragon' showed statistically similar indices under both Treatment 3 and rainfed conditions; this pattern is also reflected in the rootstock's productive efficiency under deficit irrigation treatments.

Sutchi and Silva (2005) reported in their experiment that, due to 'Flying Dragon's' extreme drought sensitivity, data collection was only feasible during the wet season, as the plants would not retain fruit during dry months. Consequently, the introduction of irrigation led to increased yield and vigor.

Fig. 17 presents the yield (kg plant^{-1}) and total water use efficiency (kg m^{-3}) for the different genotypes evaluated over the experimental period (2018–2021). A trend of increasing yield over time was observed, as expected for an orchard that is still growing.

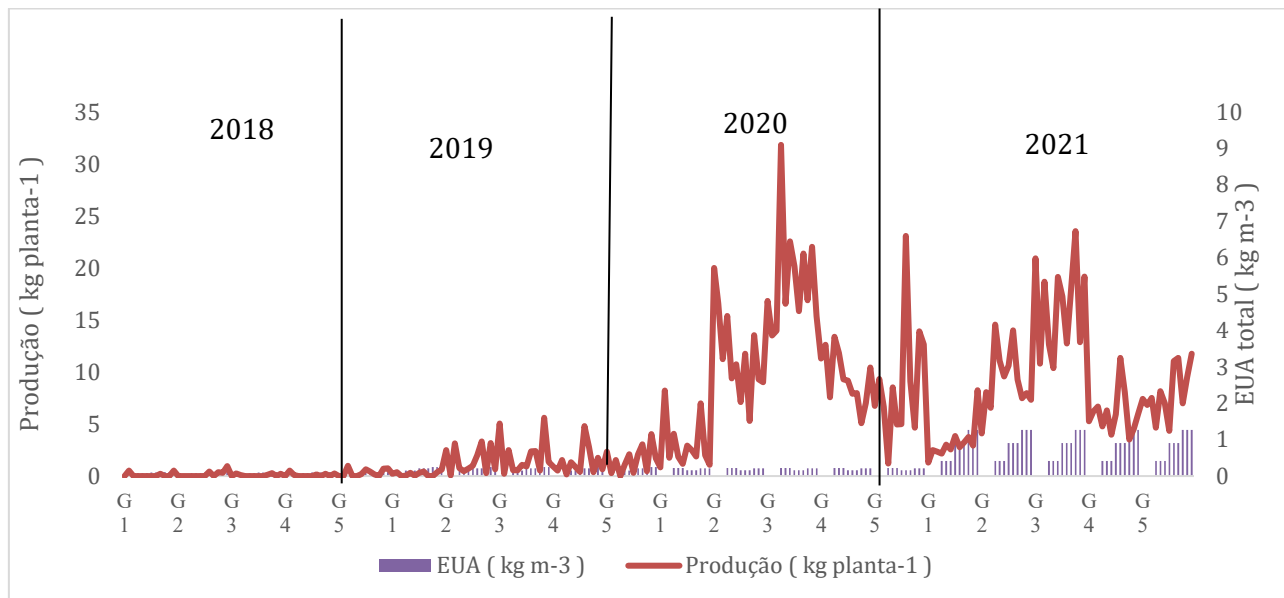
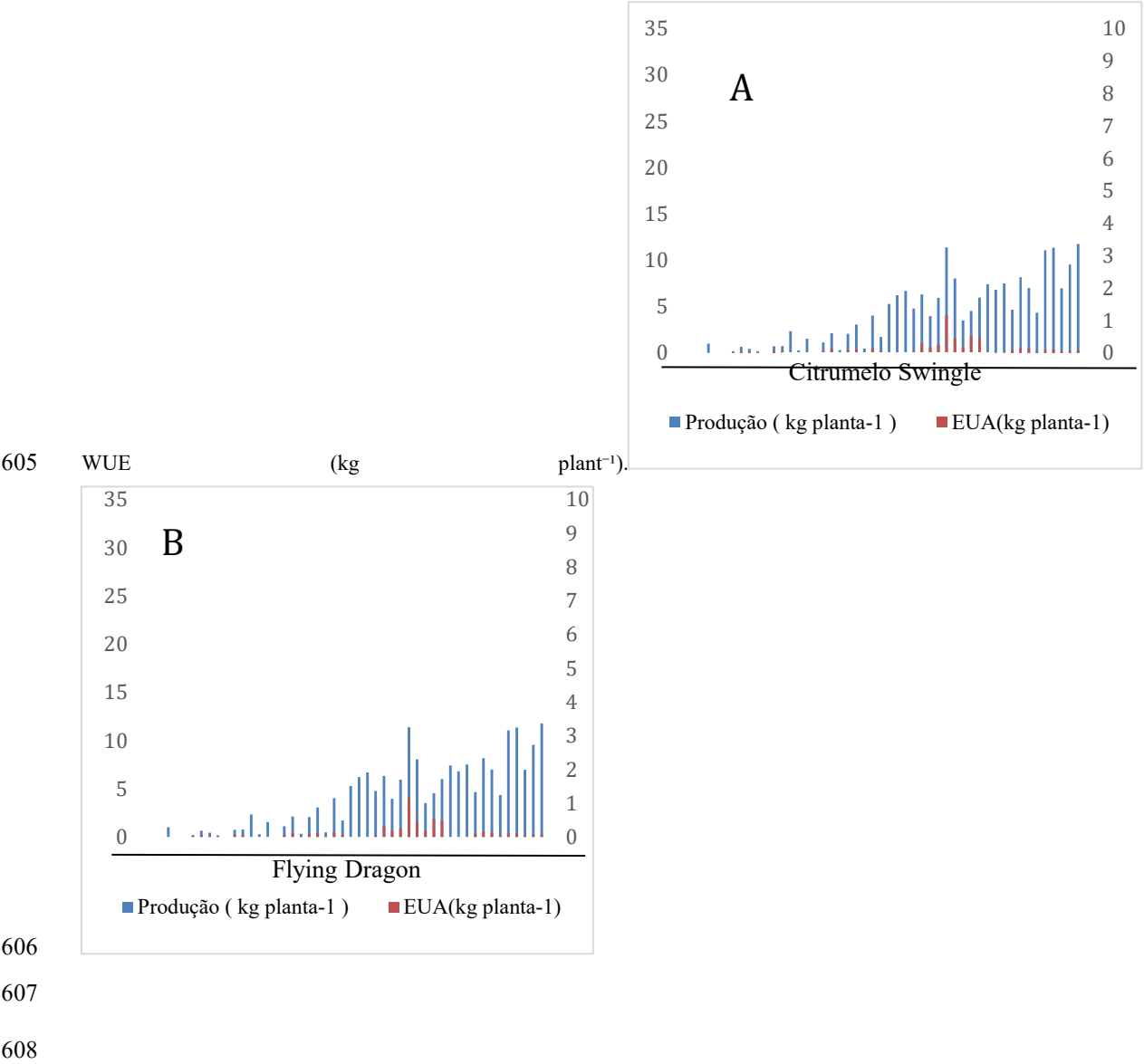


Fig. 17 Total water use efficiency (Total WUE) and yield (kg plant^{-1}) of the 'Tahiti' acid lime orchard [*Citrus latifolia* (Yu. Tanaka) Tanaka] on different rootstock combinations—Citrumelo Swingle (G1), Flying Dragon (G2), BRS Matta (G3), HTR-069 (G4), and LVK × LCR-38 (G5)—during the years 2018, 2019, 2020, and 2021. Embrapa Cassava &

602 Fruits, Cruz das Almas, Bahia. Means followed by the same letter in the column do not differ significantly at the 5% level
603 according to the Tukey test

604 Fig. 18 presents the yields (kg plant⁻¹) of each genotype analyzed individually during the experiment and their respective



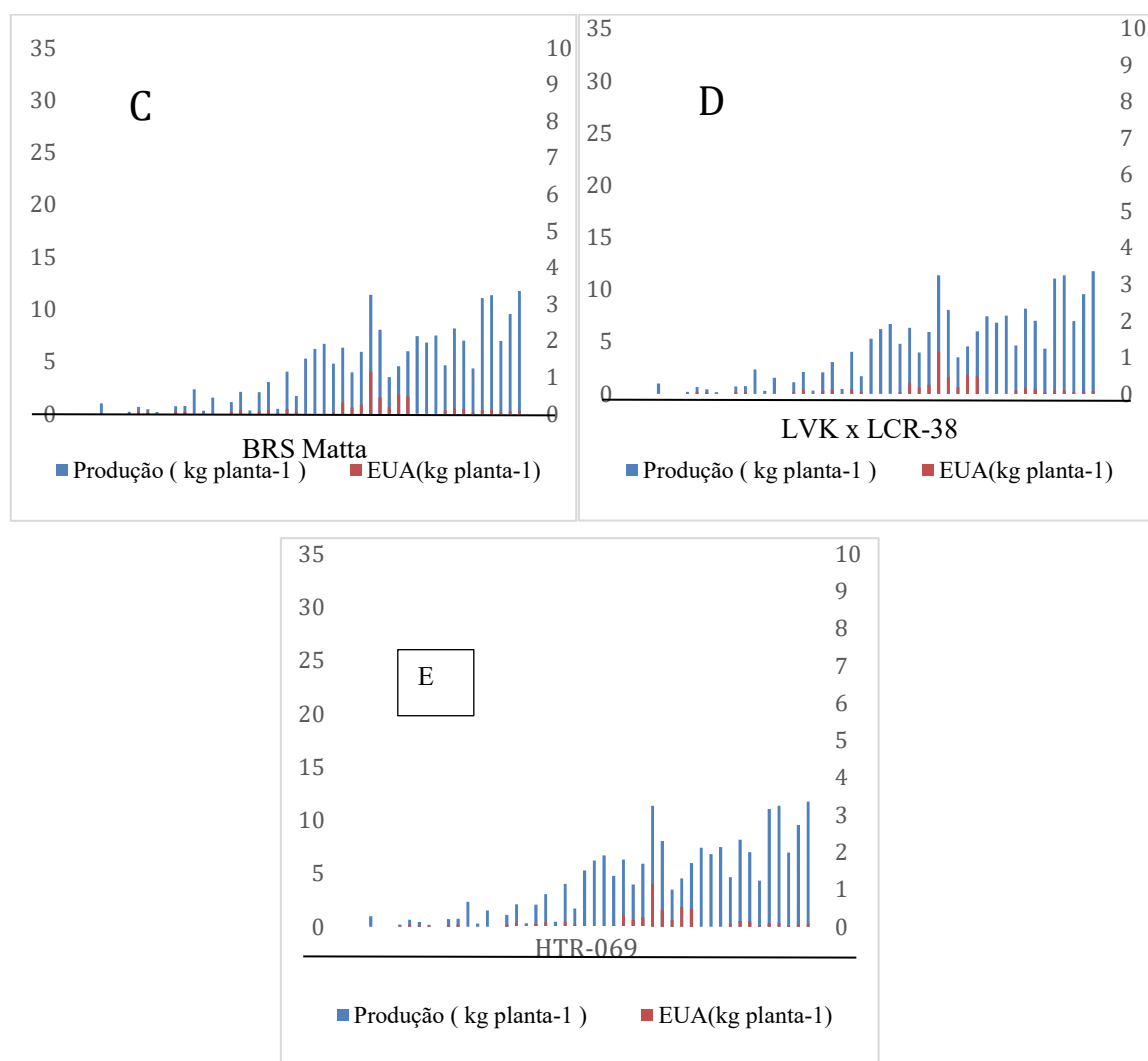


Fig. 18 (A, B, C, D, E). Total water use efficiency (Total WUE) and yield (kg plant⁻¹) of the 'Tahiti' acid lime orchard [*Citrus latifolia* (Yu. Tanaka) Tanaka] on different rootstock combinations—Citrumelo Swingle (G1), Flying Dragon (G2), BRS Matta (G3), HTR-069 (G4), and LVK × LCR-38 (G5)—during the years 2018, 2019, 2020, and 2021.

Brazilian Agricultural Research Corporation (Embrapa) – Cassava & Fruits, Cruz das Almas, Bahia. Means followed by the same letter in the column do not differ significantly at the 5% level according to Tukey's test

When considering only irrigation water, the effects of treatment 2 are even more pronounced in the BRS Matta and Flying Dragon genotypes; these were the only ones to respond to this combination of rootstock and water management. In her thesis, Costa (2019) characterized LVK × LCR 038 as having variable drought tolerance and low average yield, while HTR 069 showed high drought tolerance, variable yield, and high production efficiency. It was observed that, even with low yields, there was a downward trend as irrigation frequency increased.

Overall, in addition to allowing for lower water consumption, treatment 2 proved to be more efficient regardless of the genotype. Conversely, full irrigation showed a reverse effect: the more water added, the lower the efficiency. This is because citrus plants require stress to induce flowering; in subtropical regions, this is triggered by water stress involving a dry period followed by rehydration (Coelho et al., 1994). Excessive water application can hinder this process by preventing the suppression of vegetative buds required for the onset of flowering (Medina et al. 2005).

Sadras (2009) found that the yield per unit of applied irrigation water was slightly higher (5%) in crops subjected to deficit irrigation strategies compared to their conventionally irrigated counterparts, even though both groups received similar total irrigation volumes. Specifically, in 80% of cases, water use efficiency (WUE) was higher with deficit irrigation, Partial Root-zone Drying (PRD), or fixed partial root-zone irrigation, with increases averaging around 20%. However, in only 20% of cases was the WUE of PRD treatments superior to that of fixed partial root-zone irrigation.

Sampaio et al. (2010) analyzed the effect of water deficit combined with partial root-zone drying on yield and water use efficiency in a 'Tahiti' acid lime orchard in the semi-arid region of Bahia. They found no differences in water use efficiency among the water deficit treatments. Regarding raw WUE values, a non-significant increase was observed in the water deficit treatments compared to the control (T5).

Kirda et al. (2007) observed that the yield reduction under full irrigation was only marginal (10% to 14%)—despite a more than twofold increase in irrigation water use efficiency (IWUE) compared to TR—in a two-year study on tangerines; water use efficiency ranged from 4 to 5.6 kg m⁻³ for the 100% ETc treatment and from 9 to 15 kg m⁻³ for the 50% ETc deficit treatments, although the differences were marginal and not statistically significant.

4. Conclusions

- In high-density cultivation of 'Tahiti' acid lime [*Citrus latifolia* (Yu. Tanaka) Tanaka], it was observed that the greater the plant vigor, the lower the productive efficiency under the given conditions.
- 'Flying Dragon' showed high sensitivity to rainfed conditions but also high WUE, allowing for greater flexibility in irrigation frequency; statistically, this condition is also reflected in the productive efficiency of the rootstock under deficit irrigation treatments.
- Regarding the genotypes, 'BRS Matta' is a promising alternative for use in sub-humid climates, under both rainfed and irrigated conditions.
- The 'BRS Matta' genotype exhibits greater tolerance to water loss or a superior capacity to recover its original water potential when subjected to water deficit, as it maintained higher leaf Ψ_w than the other genotypes and responded more rapidly to environmental stimuli.

Statements and declarations

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Competing interests

The authors have no relevant financial or non-financial interests to disclose.

Data availability

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

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