Ciência Rural, Santa Maria, v.54:04, e20220592, 2024 http://doi.org/10.1590/0103-8478cr20220592

ISSNe 1678-4596
CROP PRODUCTION

Ecophysiological responses of ´Turiaçu´ pineapple plants at vegetative and reproductive stages to soil fertilization and crop location

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ABSTRACT: Pineapple is a tropical fruit with high demand by the fruit market in Brazil. Fruits of the cultivar ´Turiaçu` stans out in local consumer markets due to its excellent quality. The objective of this work was to evaluate ecophysiological responses of ´Turiaçu` pineapple plants at the vegetative and reproductive stages to soil fertilization and crop location, and their effects in fruit yield. The study was conducted in the cities of São Luís and Turiaçu, MA, Brazil. Plants under mineral and organic fertilization in two locations, São Luís and Turiaçu, and in two seasons, dry and rainy season, were evaluated during dry and rainy seasons. Chlorophyll index, photochemical efficiency, gas exchange, and fruit yield were evaluated. The pineapple plants presented decrease in the photosynthetic activity, at both developmental stages and in both seasons, when grown in São Luís. The CO_2 photosynthetic assimilation decreased. The PSI and PSII activity, according with photosynthetic index, was more sensitive at the reproductive than at the vegetative stage. The organic fertilization was not appropriate for the ´Turiaçu` pineapple crops, regardless of the crop location. The fruit yields were 54.4% and 57.9% lower in São Luís, under mineral and organic fertilization, respectively. Thus, the ecophysiology of ´Turiaçu` pineapple was more affected by water availability than by soil fertility in the municipality of Turiaçu.
Key words: *Ananas comosus* L. Merril, chlorophyll index, fruit yield, gas exchange, photochemical efficiency.

Respostas ecofisiológicas de plantas de abacaxi ´Turiaçu´ em estágios vegetativos e reprodutivos à adubação do solo e localização da cultura

RESUMO: O abacaxi é uma fruta tropical com alta demanda pelo mercado de frutas no Brasil. Os frutos da cultivar ´Turiaçu`se destacam nos mercados consumidores locais pela excelente qualidade. O objetivo deste trabalho foi avaliar as respostas ecofisiológicas de plantas de abacaxizeiro ´Turiaçu`nos estádios vegetativo e reprodutivo à adubação do solo e ao local de cultivo, e seus efeitos na produção de frutos. O estudo foi realizado nas cidades de São Luís e Turiaçu, MA, Brasil. Plantas sob adubação mineral e orgânica foram avaliadas durante as estações seca e chuvosa. Foram avaliados teores de clorofila, eficiência fotoquímica, trocas gasosas e produção de frutos. As plantas de abacaxi apresentaram diminuição da atividade fotossintética, em ambas as fases de desenvolvimento e em ambas as estações, quando cultivadas em São Luís. A assimilação fotossintética de CO_2 diminuiu. A atividade de PSI e PSII foi mais sensível na fase reprodutiva do que na fase vegetativa. A adubação orgânica não foi adequada para as lavouras de abacaxi ´Turiaçu`, independente do local de cultivo. As produtividades de frutos foram 54,4% e 57,9% menores em São Luís, sob adubação mineral e orgânica, respectivamente. Assim, a ecofisiologia do abacaxi de ´Turiaçu`foi mais afetada pela disponibilidade hídrica do que pela fertilidade do solo no município de Turiaçu.
Palavras-chave: *Ananas comosus* L. Merril, teores de clorofila, rendimento de frutos, trocas gasosas, eficiência fotoquímica.

INTRODUCTION

Ananas comosus (L.) Merril is the third most important tropical fruit in the international market. Pineapple is grown practically in all Brazilian states, and is important for generation of employment and income. More than 1.5 million pineapple fruits were produced in 2017 in Brazil; Maranhão (MA) is the fourth largest producing state in Brazil (CARDOSO, 2013; DING & SYAZWANI, 2016; SIDRA, 2019).

´Turiaçu` pineapple is native to the municipality of Turiaçu, MA, Brazil, it stands out

Received 10.31.22 Approved 07.09.23 Returned by the author 08.24.23
CR-2022-0592.R1
Editors: Leandro Souza da Silva Maria do Céu Monteiro Cruz

because of its large acceptance by local consumers due to its sweetness, pleasant aroma, and color, which is, in general, more yellowish than that of other cultivars in the market (ARAÚJO et al., 2012; BARBOZA et al., 2018; REINHARDT et al., 2018).

Soil fertility and climate variations have significant impact on pineapple production. Temperature and rainfall affect directly photosynthetic metabolism and crop yield (FRANCO et al., 2014; WILLIAMS et al., 2017). Rainfall variations affect plants at the vegetative and reproductive stages, which extends or delay the growth time, affects fruit quantity and quality, and can increase production costs (DOREY et al., 2015; DOREY et al., 2016; DOREY et al., 2018).

Pineapple plants of the cultivar ´Turiaçu` present peculiar production and organoleptic characteristics; it is believed that they present higher fruit yield and quality only when grown in their origin location because of the local edaphoclimatic conditions. Thus, the hypothesis is that these plants present lower fruit yield when grown in other locations was tested in the present study. Therefore, the objective was to evaluate the ecophysiological response of these plants in Turiaçu, MA (origin location) and in São Luís, MA, Brazil, under two types of soil fertilization.

MATERIAL AND METHODS

Crop conditions and experimental design

The study was conducted in the municipalities of Turiaçu, MA, and São Luís, MA, Brazil, between 2017 and 2018. The orchards had not been irrigated. Turiaçu is located at the geographical coordinates 01°38'58.6''S and 45°29'25.9''W; and São Luís at the geographical coordinates 02°31'51''S and 44°18'24''W. The climate of both municipalities was classified as Aw', semi-humid, according to the classification of KOEPPEN (1948). The climate data during the experiment in both municipalities are presented in figure 1 (INMET, 2019).

Soil preparation of the areas consisted of a harrowing with 30 cm depth. Soil samples of the 0-20 cm layer (20 samples per location) were randomly collected throughout the experimental area of both locations after harrowing for chemical and physical analysis (Table 1).

The ´Turiaçu` pineapple was planted in March 2017, using healthy seedlings (suckers of 25 cm), with spacing of 1.0×0.3 m in simple rows (33,333 plants per hectare). The study was conducted in two locations, using a randomized block design with 10 repetitions per crop, and being evaluated two treatments (mineral fertilization and organic fertilization). The experimental plot consisted of three rows with 11 plants (33 plants per plot), and the evaluation area consisted of nine plants of the central rows.

In the plots with mineral fertilization, seedlings were planted in pits with planting fertilization consisted of P (10 g of triple superphosphate per pit) and boron (0.5 g of boric acid per pit); topdressing fertilization consisted of applications of N (9 g per plant) and P (5 g per plant) at 60, 120, and 180 days after planting (DAP), based on the soil analysis and recommendations of SPIRONELLO & FURLANI (1997).

In the plots with organic fertilization, seedlings were planted in furrows with planting fertilization consisted of 109 g chicken manure, 73 g of wood ashes, and 58 g of ground phosphate rock per plant. According to SEVERINO et al. (2006), wood ashes contain 0.5% N, 3.4% P_2O_5, 4.8% K_2O, 26.4% Ca, and 2.7% Mg; and chicken manures contain 3.0% N, 3.9% P_2O_5, 1.1% K, 4.7% Ca, and 6.9% Mg.

The topdressing fertilization consisted of monthly application of 55.0 mL of biofertilizer from 30 DAP up to March 2018. This frequency was due to the need for control cortical lesions in pineapple fruit peels, a typical problem of ´Turiaçu` pineapple. These lesions can be caused by boron deficiency and the biofertilizer can be a source of this micronutrient (AMORIM et al., 2013; CHITARRA and CHITARRA, 1990; SIEBENEICHLER et al., 2008). The biofertilizer (10 mL per liter of water) was applied using a backpack sprayer. Solid calcium carbide (CaC_2) was applied on the apex of the stem of the plants (1.0 g per plant) at 13 and 15 months after planting for floral induction in the pineapple plants. However, the crop under organic fertilization in São Luís required a third application at 16 months after planting, because of absence of flowering in plants.

The biofertilizer was produced by the State University of Maranhão and has potential for pest and disease control (MONDEGO et al., 2018; MONDEGO et al., 2019). This biofertilizer was prepared by an anaerobic fermentation process, with the following formulation for 10 L: 2.00 kg of bovine manure, 0.20 kg of ground sugarcane, 0.10 kg of ash, 0.10 kg of ground phosphate rock, 0.05 kg of boric acid, 0.04 kg of zinc sulfate, and 0.20 L of bovine milk. The biofertilizer was dried in a forced-air circulation oven at 65.0 °C until constant weight for the analysis. The dry matter content in the liquid part of the biofertilizer was determined (MARROCOS et al., 2012).

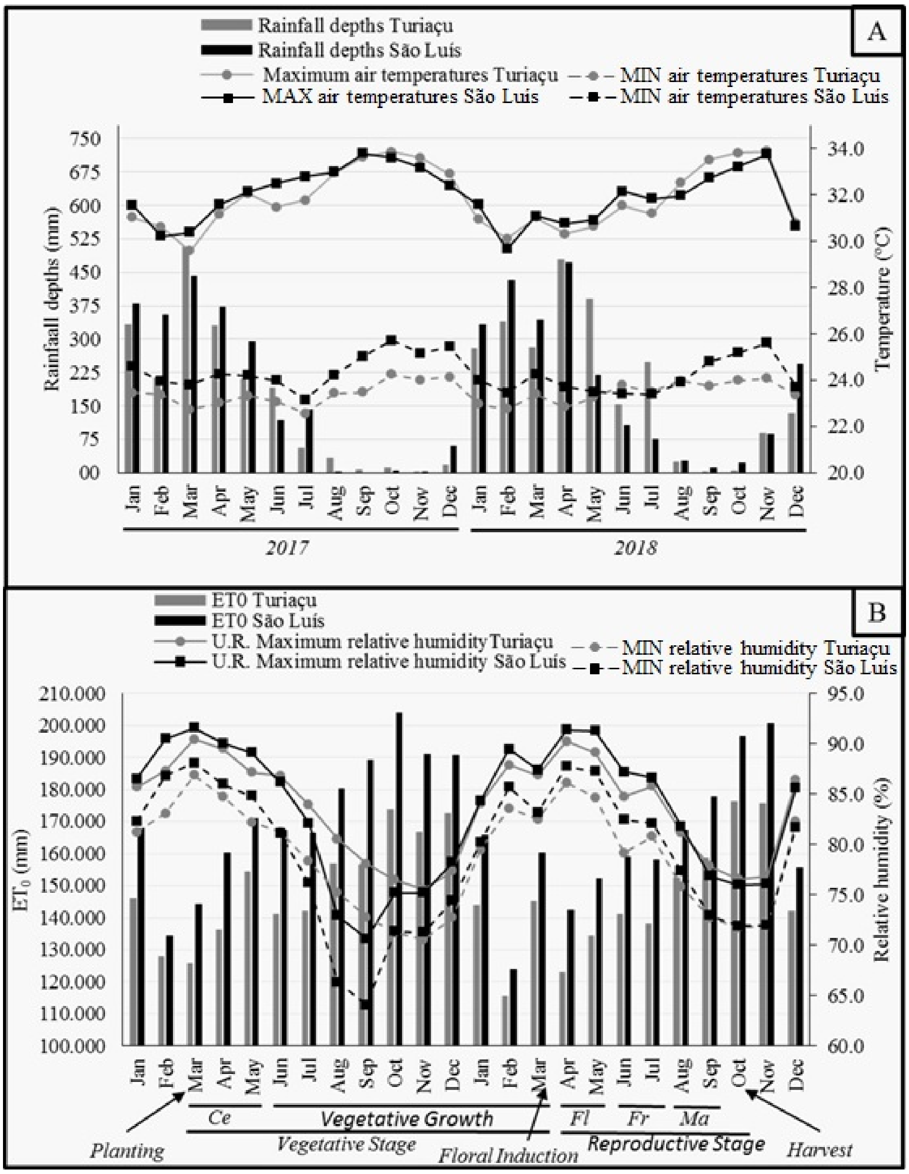

Figure 1 - Meteorological data from January 2017 to December 2018 in the municipalities of Turiaçu and São Luís, MA, Brazil, including rainfall depths, minimum and maximum air temperatures (A), reference evapotranspiration (ET_0) and minimum and maximum air relative humidity (B) (Inmet, 2019). Ecophysiological evaluation times at the vegetative (*) and reproductive (**) stages.

The nutrient concentrations were determined in each sample of biofertilizer using extracts obtained by sulfuric acid digestion; they were determined according to TEDESCO et al. (1995). The biofertilizer presented the following chemical composition: N = 0.37 g L^{-1}; P= 0.32 g L^{-1}; K = 2.69 g L^{-1}; Ca = 0.25 g L^{-1}; Na = 0.60 g L^{-1}; Mg = 0.17 g L^{-1}; Fe = 0.06 g L^{-1}; Al = 0.016 g L^{-1}; Co = 0.001 g L^{-1}; Ni = 0.002 g L^{-1}; Pb = 0.06 g L^{-1}; Zn = 0.09 g L^{-1}; and Mo = 0.003 g L^{-1}.

Determination of ecophysiological variables

The ecophysiology of the pineapple plants was evaluated in the D leaf (located in the middle third of each branch; bigger leaf with a 45º angle), which was selected because it is the most metabolically active leaf of the plant (REINHARDT et al., 2002). Two ecophysiological evaluations were done in each phenological stage (vegetative and reproductive).

Table 1 - Soil chemical and physical atributes of samples collected from the 0-20 cm layer in São Luís and Turiaçu, MA, Brazil.

Chemical analysis										
Experimental Unity	OM ($g\ dm^{-3}$)	pH	P ($mg\ dm^{-3}$)	Ca	Mg	K	H+Al	SB	CEC	BS
				($mmol_c\ dm^{-3}$)						
São Luís	21	5.4	118	38	9	2.6	22	49.6	71.6	69
Turiaçu	13	4.2	1	9	9	2.1	32	20.1	52.1	39
Physical analysis										
Experimental Unity	Granulometric composition				Texture					
	Coarse sand	Fine sand	Silt	Clay						
	$g\ Kg^{-1}$									
São Luís	18	54	12	16	Sandy loam					
Turiaçu	9	45	30	16	Sandy loam					

OM = organic matter; SB = sum of bases; H+Al = potential acidity; CEC = cation exchange capacity; BS = base saturation.

The evaluations in the D leaf of each plant were done always at 8:00 a.m., using 20 plants per type of fertilization and crop location, as follows: plants at vegetative stage in the dry season (November 2017; 8 months after planting) and in the rainy season (January 2018; 10 months after planting); and those at reproductive stage, at flowering (May 2018; 14 months after planting; rainy season) and maturation (August 2018; 17 months after planting; dry season).

Gas exchange was evaluated using an infrared gas analyzer (LI-6400XT, LI-COR, Lincoln, USA), including evaluations of CO_2 photosynthetic assimilation (*A*); instantaneous transpiration (*E*); stomatal conductance (*gs*); vapor-pressure deficit between the leaf and the atmosphere (VPD), and CO_2 internal concentration (Ci). The water use efficiency was calculated by the *A* to *E* ratio.

The chlorophyll *a* fluorescence was measured using a non-modulated portable fluorometer (Pocket-PEA, Hansatech Instruments Ltd., King's Lynn, UK), with the aid of tweezers provided by the manufacturer to adapt the leaf tissue to the dark for 30 minutes. The following variables were evaluated: maximum quantum efficiency of photosystem II (Fv/Fm) and photosynthetic index (PI). Chlorophyll index was estimated using a portable SPAD chlorophyll meter, model 502, MINOLTA (1989).

Plant height and fruit yield

The following variables were evaluated after harvest (19 months after planting): plant height (from the ground surface up to the fruit base) and fruit yield. Three plants were randomly chosen in each plot for evaluation of plant height, using a tape measurer. Fruit yield was estimated through the product between fruit weights and plant densities per hectare.

Statistical analysis

The data were subjected to the Lilliefors normality and to the homogeneity of variances tests, the means of the treatments were compared by the F test (Anova) in joint analysis of growth environment (crop location and type of soil fertilization) for each season, at 5% probability. The program R was used for the statistical analysis. Fruit yield was evaluated with missing data imputation, because of the lack of flowering in the organic crop in São Luis.

RESULTS

Vegetative stage

Chlorophyll index and maximum quantum efficiency of photosystem II (Fv/Fm) of the pineapple plants evaluated were affected by the crop location and type of soil fertilization. There was significant interaction for the dry and rainy seasons. The pineapple plants grown in São Luís in both seasons and under organic fertilization presented the lowest Chlorophyll index and Fv/Fm, whereas plants with mineral fertilization grown in Turiaçu presented always the highest mean Chlorophyll index and Fv/Fm (Table 2).

The pineapple plants grown with mineral fertilization presented higher Chlorophyll index than those grown with organic fertilization.

The plants grown in São Luís presented higher degradation of photosynthetic pigments than those grown in Turiaçu in the dry season, indicated by low values of Chlorophyll index.

Table 2 - Chlorophyll index and maximum quantum efficiency of photosystem II (Fv/Fm) in D leaves of plants of Turiaçu pineapple at vegetative stage grown in two locations and under two types of fertilization, evaluated in the dry and rainy seasons.

---chlorophyll index---					
Variable		---Dry season---		---Rainy season---	
		Turiaçu	São Luís	Turiaçu	São Luís
SPAD	Mineral Fertilization	46.05 aA	39.22 bA	65.47 aA	43.85bA
	Organic Fertilization	42.16 aB	30.71 bB	55.18aB	42.57bB
CV (%)		3.15	6.22	6.60	3.87
---Photochemical efficiency---					
Variable		---Dry season---		---Rainy season---	
		Turiaçu	São Luís	Turiaçu	São Luís
Fv/Fm	Mineral Fertilization	0.81 aA	0.68 bA	0.82 aA	0.78 bA
	Organic Fertilization	0.77 aB	0.42 bB	0.80 aB	0.75 aB
CV (%)		9.56	6.22	3.03	6.11

Means followed by the same lowercase letter in the rows or uppercase letter in the columns, within each season, are not different by the F test at 5% probability ($P \leq 0.05$); CV (%) = Coefficient of variation.

No plants presented damages in PSII (Fv/Fm ≥ 0.75 and ≤ 0.85) in the rainy season, regardless of the location and fertilization. However, the organic soil fertilizer used were not adequate for the cultivar ´Turiaçu`, as detected by their lower Chlorophyll index.

The pineapple plants grown in both locations and under both fertilizations presented no interaction for photosynthetic index (PI), either in the dry or in the rainy season. The plants grown in São Luís in the dry and rainy seasons presented lower stomatal conductance and, consequently, lower CO_2 photosynthetic assimilation when compared to those grown in Turiaçu.

The interaction between the crop location and type of fertilization was significant in the dry and rainy seasons for the CO_2 photosynthetic assimilation (A; $P < 0.0001$; $P < 0.0001$); stomatal conductance (gs; $P < 0.0001$; $P < 0.0001$); instantaneous transpiration (E; $P < 0.0001$; $P < 0.0001$); vapor-pressure deficit between the leaf and the atmosphere (VPD; $P < 0.0001$; $P<0.0001$); and water use efficiency (WUE; $P < 0.0001$; $P < 0.0001$) (Table 3). However, the leaf CO_2 internal concentration (Ci) presented no interaction, either in the dry or rainy season.

The plants grown in São Luís had lower gas exchange than those grown in Turiaçu, regardless of the fertilization and season (Table 3).

The plants grown in São Luís had lower *gs* than those grown in Turiaçu, regardless of the season and type of soil fertilization (up to 90.0% lower in the dry, and up to 66.6% lower in the rainy season); higher VPD, regardless of the season and type of fertilization (up to 53.4% higher in the dry, and up to 48.4% higher in the rainy season); and the lower WUE, regardless of the season and type of fertilization (up to 72.6% lower in the dry, and up to 32.0% lower in the rainy season).

The less favorable climate conditions in São Luís, regardless of the seasons, resulted in plants with lower stomatal conductance (up to 90.0% lower in the dry, and up to 66.6% lower in the rainy season) and lower transpiration (up to 70.1% lower in the dry, and up to 53.7% lower in the rainy season) when compared to those grown in Turiaçu.

The plants grown under organic fertilization (regardless of the location and season) presented lower stomatal conductance and lower transpiration than those grown under mineral fertilization.

The plants grown in São Luís presented higher VPD than those grown in Turiaçu.

The crop location had no effect on WUE of plants in the rainy season ($P = 0.2624$), but the type of fertilization affected the pineapple plants grown under organic fertilization (regardless of the season), since they were not as efficient as those under mineral fertilization (32.0% lower, $P = 0.2724$ in the rainy season; and 72.6% lower, $P=0.2379$ in the dry season).

Reproductive stage

The plants presented interaction in the parameters chlorophyll index, maximum quantum efficiency of photosystem II (Fv/Fm), and photosynthetic index (PI) for the dry ($P < 0.0001$; $P < 0.0001$; $P < 0.0001$; respectively) and rainy

Table 3 - Gas exchange in D leaves of Turiaçu pineapple plants at vegetative stage grown in two locations and under two types of fertilization, evaluated in the dry and rainy seasons.

----------Gas exchange----------					
Variable		-----Dry season-----		-----Rainy season-----	
		Turiaçu	São Luís	Turiaçu	São Luís
A	Mineral Fertilization	1.89 aA	1.48 bA	6.62 aA	3.14 bA
	Organic Fertilization	1.05 aB	0.39 bB	1.55 aB	1.17 bA
CV (%)		9.86	15.32	24.20	18.88
gs	Mineral Fertilization	0.10 aA	0.05 bA	0.06 aA	0.04 aA
	Organic Fertilization	0.03 aB	0.01 aB	0.03 aB	0.02 bB
CV (%)		34.87	35.38	21.63	27.61
E	Mineral Fertilization	1.37 aA	1.27 bA	2.44 aA	2.53 bA
	Organic Fertilization	0.94 aB	0.41 bB	1.16 aB	1.13 bA
CV (%)		10.25	15.54	10.09	5.54
VPD	Mineral Fertilization	2.62 bB	2.72 aB	0.95 bB	1.08 aB
	Organic Fertilization	2.97 bA	4.02 aA	1.27 bA	1.41 aA
CV (%)		15.14	12.14	25.43	9.03
WUE	Mineral Fertilization	1.35 aA	1.16 bA	1.00 aA	1.01 aA
	Organic Fertilization	1.18 aB	0.37 bB	0.88 aB	0.68 aB
CV (%)		9.00	17.33	20.53	25.64

Means followed by the same uppercase letter in the rows or lowercase letter in the columns, within each season, are not different by the F test at 5% probability ($P \leq 0.05$); CV (%) = Coefficient of variation. CO_2 photosynthetic assimilation (A; µmol m^{-2} s^{-1}); stomatal conductance (gs; mol m^{-2} s^{-1}); instantaneous transpiration (E; mmol m^{-2} s^{-1}); vapor-pressure deficit between the leaf and the atmosphere (VPD; KPa); CO_2 internal concentration (Ci; mg dm^{-3}), and water use efficiency (WUE; µmol $mmol^{-1}$).

(P=0.0009; P < 0.0001; P = 0.0431; respectively) seasons. The pineapple plants grown in São Luís and under organic fertilization (dry season) presented the lowest Chlorophyll indexes, Fv/Fm, and PI (Table 4).

The climate conditions during the reproductive stage were less favorable in São Luís than in Turiaçu, regardless of the season. São Luís presented lower rainfall than Turiaçu during the flowering (20.32% lower) and fruiting (54.46% lower) stages of the plants, but in the ripening stage both locations presented rainfall lower than 150 mm.

Plants grown under the climate of São Luís and under organic fertilization presented lower photochemical efficiency (Fv/Fm and PI) and Chlorophyll index in the dry season.

The organic fertilization aggravated the negative effects of the less favorable climate conditions of São Luís. This fertilization and climate resulted in lower Chlorophyll index, Fv/Fm, and PI in both seasons (rainy and dry).

The plants grown in São Luís presented lower *A*, *E*, *gs,* and WUE, and higher VPD (rainy season and dry) than those grown in Turiaçu, regardless of the type of fertilization. There was interaction between crop location and type of fertilization for CO_2 photosynthetic assimilation (*A*; P < 0.0001; P<0.0001); stomatal conductance (*gs*; P < 0.0001; P < 0.0001)); transpiration (*E*; P < 0.0001; P < 0.0001); vapor-pressure deficit between the leaf and the atmosphere (VPD; P < 0.0001; P < 0.0001); and water use efficiency (WUE; P < 0.0001; P < 0.0001), in the dry and rainy seasons, respectively (Table 5). The leaf CO_2 internal concentration (Ci) presented no interaction, either in the dry or rainy season.

The plants grown in São Luís presented 58.5% and 98.0% lower *gs* in the rainy and dry seasons, respectively; and lower transpiration (29.3% and 90.7% in the rainy and dry seasons, respectively) than those grown in Turiaçu (Table 3).

The pineapple plants grown in São Luís presented higher VPD in both seasons than the plants grown in Turiaçu (Table 3). The water use efficiency of plants grown in São Luís was 39.4% lower in the rainy season, and 38.3% lower in the dry season than those of plants grown in Turiaçu (Table 3).

Plant height and fruit yield

Plant height and fruit yield were affected by the crop location and type of fertilization (P = 0.0584; 0.0024 respectively). Plants grown in Turiaçu

Table 4 - Chlorophyll index and maximum quantum efficiency of photosystem II (Fv/Fm) in D leaves of Turiaçu pineapple plants at reproductive stage grown in two locations and under two types of fertilization, evaluated in the dry and rainy seasons.

Variable		Dry season		Rainy season	
Chlorophyll index					
		Turiaçu	São Luís	Turiaçu	São Luís
SPAD	Mineral Fertilization	54.49 aA	45.05 bA	62.05 aA	54.43 bA
	Organic Fertilization	41.94aB	33.09 bB	52.14 aB	42.84 bB
CV (%)		3.08	6.91	4.36	0.85
Photochemical efficiency					
		Turiaçu	São Luís	Turiaçu	São Luís
Fv/Fm	Mineral Fertilization	0.82 aA	0.78 bA	0.84 aA	0.80 bA
	Organic Fertilization	0.75 aB	0.71 bB	0.78 aB	0.75 bB
CV (%)		1.61	3.51	1.33	0.85
PI	Mineral Fertilization	2.77 aA	1.85 bA	4.25 aA	3.87 bA
	Organic Fertilization	1.73 aB	0.81 bB	2.36 aB	2.19 bB
CV (%)		21.14	21.63	28.30	27.84

Means followed by the same lowercase letter in the rows or uppercase letter in the columns, within each season, are not different by the F test at 5% probability ($P \leq 0.05$); CV (%) = Coefficient of variation. Fv/Fm = maximum quantum efficiency of photosystem II; PI = Photosynthetic index.

presented 8.91% higher plant heights in the treatments with mineral fertilization, and 10.26% higher in the treatments with organic fertilization, presenting 76.90% higher fruit yield under mineral fertilization, and 91.80% higher fruit yield under organic fertilization, when compared with those plants grown in São Luís (Table 6).

The organic fertilization affected negatively plant height and fruit yield; the plants grown in Turiaçu presented 8.51% lower plant height and 54.39% lower fruit yield, whereas the plants grown in São Luís had 9.62 % lower plant height and 57.93% lower fruit yield when subjected to this fertilization (Table 6). The nutritional unbalanced of the organic fertilization used affected the flowering of the plants grown in São Luís.

DISCUSSION

Vegetative stage

The plants grown in São Luís presented lower Chlorophyll index and Fv/Fm, indicating that this location presented less favorable climate conditions for the photosynthetic activity than Turiaçu, such as higher minimum temperature, higher atmospheric demand, and lower maximum relative air humidity (BRITO et al., 2017; RAINHA et al., 2016; WILLIAMS et al., 2017). This was probably due to the climate conditions of São Luís, since the soil in São Luís was more fertile than that in Turiaçu according to soil chemical characteristics of the municipalities (Table 1). These less favorable conditions probably affect negatively and directly the Chlorophyll index and Fv/Fm.

The plants grown in São Luís presented higher degradation of photosynthetic pigments than those grown in Turiaçu in the dry season. Low water availability hinders the maintenance of turgidity and other biochemical processes in the leaf. Chlorophyll degradation results in loss of green color of leaves (LONG et al., 1994; TAIZ et al., 2017).

LEONARDO et al. (2013) evaluated pineapple plants of the Vitória cultivar under organic fertilization and reported that lower Chlorophyll indexes are related to nitrogen concentration in the plants. However, water availability was more important than nitrogen availability for the ´Turiaçu` pineapple plants evaluated, since the plants in São Luís always presented lower Chlorophyll index.

The plants grown in São Luís in the dry season presented lower development due to a possible phytotoxicity caused by the organic fertilization and aggravated by water stress. This is confirmed by their lower Chlorophyll index, Fv/Fm, plant height, and fruit yield. These stresses decrease the photosynthetic capacity and can damage the photosynthetic apparatus

Table 5 - Gas exchange in D leaves of Turiaçu pineapple plants at reproductive stage grown in two locations and under two types of fertilization, evaluated in the dry and rainy seasons.

Gas exchange					
Parameter		Dry season		Rainy season	
		Turiaçu	São Luís	Turiaçu	São Luís
A	Mineral Fertilization	5.43 aA	4.00 bA	6.13 aA	5.11 bA
	Organic Fertilization	3.44 aB	2.76 bB	5.98 aB	4.83 bB
CV (%)		5.90	9.33	10.08	13.20
gs	Mineral Fertilization	0.87 aA	0.04 bA	0.89 aA	0.75 bA
	Organic Fertilization	0.81 aB	0.02 bB	0.75 aB	0.73 bB
CV (%)		4.62	7.32	1.57	1.93
E	Mineral Fertilization	1.74 aA	1.51 bA	2.98 aA	2.10 bA
	Organic Fertilization	1.28 aB	1.20 bB	3.20 aB	2.00 bB
CV (%)		8.43	9.03	6.44	5.67
VPD	Mineral Fertilization	0.90 bB	2.64 aB	0.95 bB	0.97 aB
	Organic Fertilization	1.00 bA	2.76 aA	0.99 bA	1.09 aA
CV (%)		6.97	11.33	9.46	5.38
WUE	Mineral Fertilization	3.11 aA	2.64 bA	2.06 aA	2.53 bA
	Organic Fertilization	2.31 aB	2.30 bB	1.87 aB	2.41 bB
CV (%)		12.00	11.03	7.34	5.90

Means followed by the same uppercase letter in the rows or lowercase letter in the columns, within each season, are not different by the F test at 5% probability ($P \leq 0.05$); CV (%) = Coefficient of variation. CO_2 photosynthetic assimilation (A; µmol m^{-2} s^{-1}); stomatal conductance (gs; mol m^{-2} s^{-1}); instantaneous transpiration (E; mmol m^{-2} s^{-1}); vapor-pressure deficit between the leaf and the atmosphere (VPD; KPa); CO_2 internal concentration (Ci; mg dm^{-3}), and water use efficiency (WUE; µmol $mmol^{-1}$).

(LAWSON AND BLATT, 2014). Plants with healthy photosynthetic apparatus present Fv/Fm between 0.75 and 0.85 (BOLHÀR-NORDENKAMPF et al., 1989; CARVALHO et al., 2018; SILVA et al., 2015). The plants grown in Turiaçu in the dry season were the only ones that presented no damages in the photosynthetic apparatus, regardless of the type of fertilization.

The less favorable climate conditions of São Luís combined with the organic fertilization may have caused decreases in chlorophyll concentrations (lower Chlorophyll index). Chlorophyll is affected negatively by environmental (water availability) and nutritional (possible phytotoxicity) conditions; the more unfavorable these conditions, the lower the chlorophyll contents (MAIA JÚNIOR et al., 2017; WILLADINO et al., 2011).

Photosynthetic index (PI) is used to interpret responses of plants subjected to stress conditions: a PI lower than 1.0 represents a critical point (OLIVEIRA et al., 2015). This variable considers structural and functional events that occur in the PSI and PSII (GONÇALVES et al., 2005).

Table 6 - Plant height and fruit yield of Turiaçu pineapple plants grown in two locations and under two types of fertilization, evaluated in the dry and rainy seasons.

		Fertilization		Probability
		Mineral	Organic	Pr> (Type of fertilization within Location)
Plant height (cm)	Turiaçu	61.1	55.9	<0.0001
	São Luís	56.1	50.7	<0.0001
Pr> (Location within Type of fertilization)				
		<0.0001	<0.0001	
Fruit yield (Mg ha^{-1})	Turiaçu	51.3	23.4	<0.0001
	São Luís	29.0	12.2	<0.0001
Pr> (Location within Type of fertilization)				
		<0.0001	<0.0001	

Thus, the plants in the present work had no damages in PSI, even in the dry season, and could revert the stress, which was denoted by the Fv/Fm results.

The plants grown in São Luís had lower gas exchange than those grown in Turiaçu, regardless of the fertilization and season. This was probably because of stomatal and non-stomatal factors. This response can be explained by the lower *gs* caused by the increase in VPD (stomatal factor), and by possible damages caused to photochemical processes, such as degradation of the PSII and alteration in the electron transport (non-stomatal factor) (HUVE et al. 2019; TAIZ et al., 2017).

The plants grown in São Luís had lower *gs* than those grown in Turiaçu, regardless of the season and type of soil fertilization (up to 90.0% lower in the dry, and up to 66.6% lower in the rainy season); higher VPD, regardless of the season and type of fertilization (up to 53.4% higher in the dry, and up to 48.4% higher in the rainy season); and the lower WUE, regardless of the season and type of fertilization (up to 72.6% lower in the dry, and up to 32.0% lower in the rainy season).

These results confirm that the decrease in photosynthesis was caused by a stomatal factor. The non-stomatal factor probably occurred in the dry season in São Luís (under organic fertilization), since the Fv/Fm was below 0.75 (BOLHÀR-NORDENKAMPF et al., 1989; CARVALHO et al., 2018; SILVA et al., 2015), and the CO_2 internal concentration presented no significant difference between organic and mineral fertilizations in this location and season (P= 0.6421).

The less favorable climate conditions in São Luís, regardless of the seasons, resulted in plants with lower stomatal conductance (up to 90.0% lower in the dry, and up to 66.6% lower in the rainy season) and lower transpiration (up to 70.1% lower in the dry, and up to 53.7% lower in the rainy season) when compared to those grown in Turiaçu. Decreases in stomatal conductance and increases in resistance to gas exchange are the first responses of plants to water deficit conditions, since they reduce the opening of stomata, reducing water loss by transpiration (LAWSON & BLATT, 2014; RAINHA et al., 2016; TAIZ et al., 2017).

The plants grown under organic fertilization (regardless of the location and season) presented lower stomatal conductance and lower transpiration than those grown under mineral fertilization. This result is probably related to nutritional unbalance caused by the organic fertilization. In addition, ´Turiaçu` pineapple plants under this type of fertilization showed less development and leaf chlorosis, which are phytotoxicity symptoms (CAKMAK, 2005; KERBAUY, 2008); however, leaf analyzes would be necessary to confirm it. Moreover, phytotoxicity caused by nutrients can decrease the photosynthetic process by compromising stomatal opening (CAKMAK, 2005; KERBAUY, 2008), which was also observed.

The plants grown in São Luís presented higher VPD than those grown in Turiaçu. This was related to the higher ET_0 found in São Luís. High VPD causes stomatal closure and can decrease photosynthesis and gas exchange (EL-SHARKAWY & COCK, 1984). The increase in VPD decreased the CO_2 photosynthetic assimilation, as found by JIAO et al. (2019).

The crop location had no effect on WUE of plants in the rainy season (P= 0.2624), but the type of fertilization affected the pineapple plants grown under organic fertilization (regardless of the season), since they were not as efficient as those under mineral fertilization (32.0% lower, P=0.2724 in the rainy season; and 72.6% lower, P=0.2379 in the dry season). This confirms that the organic fertilization used or its application management was a source of stress for the ´Turiaçu` pineapple plants. The less favorable the climate conditions for the pineapple, the lower the WUE (RAINHA et al., 2016). This was confirmed by the results of plants grown under organic fertilization in São Luís.

Reproductive stage

São Luís presented lower rainfall than Turiaçu during the flowering (20.32% lower) and fruiting (54.46% lower) stages of the plants, but in the ripening stage both locations presented rainfall lower than 150 mm. This rainfall is lower than the ideal one for this crop (approximately 150 mm $month^{-1}$) (BRITO et al., 2017; CUNHA, 2005; WILLIAMS, 2017).

São Luís presented unfavorable relative air humidity, lower than 75 %, and minimum temperature, above than 26 ºC (CUNHA, 2005; WILLIAMS, 2017), during the vegetative stage of the plants, but not in the reproductive stage; the atmospheric demand was always higher in this municipality, as shown by its ET_0 (Figure 1).

Another result visualized, but not confirmed through the analysis, was the presence of significant amount of dew water in the plants in Turiaçu, even in the dry season. The dew can be an important source of water to the soil-plant system (JIA et al., 2019; LEV-YADUN et al., 2017;

WANG et al., 2017). This peculiarity may have contributed to the favorable results of this cultivar in its origin location.

Plants grown under the climate of São Luís and under organic fertilization presented lower photochemical efficiency (Fv/Fm and PI) and Chlorophyll index in the dry season. Abiotic factors affected negatively these parameters by decreasing the chlorophyll concentration and damaging the photosynthetic apparatus (PSII and PSI) (BOLHÀR-NORDENKAMPF et al., 1989; CARVALHO et al., 2018; DUTRA, 2015; MAIA JÚNIOR et al., 2017). The photosynthetic apparatus of plants grown in São Luís under organic fertilization was damaged, presenting Fv/Fm lower than 0.75 and PI lower than 1.0 because of the stress caused by the dry season combined with the organic fertilization used.

The organic fertilization aggravated the negative effects of the less favorable climate conditions of São Luís. This fertilization and climate resulted in lower Chlorophyll index, Fv/Fm, and PI in both seasons (rainy and dry). This indicates problems in the organic fertilization, which are probable related to its concentration or management. This unbalance has been considered responsible for causing stresses and reducing the photosynthetic capacity of plants (GONÇALVES et al., 2005; MONOSTORI et al., 2016; RAINHA et al., 2016; WILLADINO et al., 2011).

CONCLUSIONS

The ecophysiology of Turiaçu pineapple plants grown in São Luís were worse than that of plants grown in their place of origin. The plants were more affected by water availability than by soil fertility. The less favorable climate conditions of São Luís disfavored the grown of plants at vegetative and reproductive stages. The plants showed limitations in photochemical efficiency, gas exchange, and fruit yield when not grown in its origin location, regardless of the type of soil fertilization.

The organic fertilization used were not adequate for the Turiaçu pineapple crops evaluated, and aggravated the negative effects of the unfavorable climate conditions of São Luís, MA, Brazil, causing even problems for floral induction of the plants.

ACKNOWLEDGMENTS

We would like to thank Fundação de Amparo à Pesquisa e ao Desenvolvimento Científico e Tecnológico do Maranhão, Brazil, for the financial support. Process number: 1498/16.

DECLARATION OF CONFLICT OF INTEREST

The authors declare no conflict of interest. The founding sponsors had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, and in the decision to publish the results.

AUTHORS' CONTRIBUTIONS

All authors contributed equally for the conception and writing of the manuscript. All authors 18 critically revised the manuscript and approved of the final version.

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