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Plant growth and nutrient accumulation in two tomato hybrids under tropical conditions

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Abstract

An adequate nutrient supply can reduce production costs, improve tomato quality, and increase yield. Understanding the nutritional needs of tomato plants is thus fundamental to its successful cultivation. This study characterised plant growth and nutrient accumulation and export in 'Gault' and 'Pomerano' hybrid tomatoes cultivated under tropical conditions in Brazil. The experimental design was randomised blocks with four replicates. Leaf number, tissue dry weights, and nutrient accumulation were evaluated throughout the growing cycle. Plant growth was slow at the beginning of the cycle, but total accumulation of dry matter began to increase faster when 'Gault' and 'Pomerano' had 29 and 28 leaves, peaking at 767.6 and 712.5 g plant^{-1}, respectively, by the end of the cycle. Fruit yields were 148.5 and 122.6 t ha^{-1} for 'Gault' and 'Pomerano', respectively. The maximum nutrient accumulation for both hybrids at the end of the cycle was in the order K > N > Ca > S > Mg > P > Mn > Fe > Cu > Zn > B. The amounts of N, P, and K were highest in the fruit, and the amounts of Ca, Mg, and S were highest in the vegetative tissues, for both hybrids.

Keywords: *Solanum lycopersicum* L., nutrient uptake, plant nutrition, fertilisation, phenology, sustainability.
Abbreviations: AC_amount of nutrients accumulated; DAT_days after transplantation; DM_dry matter; DP_duration of the period of highest accumulation; EP_export of nutrients; ET_extraction of nutrients; NL_number of leaves; NAT_amount of nutrients required per tonne of fruit produced; PC_{max}_maximum point of curve; PC_{min}_minimum point of curve; TA_total accumulation.

Introduction

Tomato is one of the most economically and socially important vegetables in the world. Global production was approximately 170 million t in 2014, with approximately 4.3 million t (2.5%) produced in Brazil (FAO, 2014). The cost of fertilisers in Brazil accounted for 23% of total production costs in 2014, following only by labour costs (ABCSEM, 2014). Obtaining high yields at the lowest possible cost is therefore necessary for tomato cultivation to be economically viable, which depends on a rational application of fertilisers, amongst other factors (Diógenes, 2016). Tomato productivity and quality depend highly on an adequate nutrient supply and reduced costs (Bastos et al., 2013), so knowing the nutritional needs of the plants is fundamental to successful cultivation.

Tomato production in Brazil has greatly transformed in the last two decades, with a substantial increase in average yield from 43 to 67 t ha^{-1} between 1994 and 2014 (FAO, 2014). Growers can currently attain yields >100 t ha^{-1}, such as 131.5 t ha^{-1} for the 'Sahel' hybrid (Shiragihe et al., 2010) and 131.9 and 158.7 t ha^{-1} for the 'Dominador' and 'Serato' hybrids, respectively (Purquerio et al., 2016). This increase in yield was largely due to the use of hybrids with greater resistance to pests and diseases and adapted to specific climatic conditions and to a better use of available inputs. The higher production of vegetal mass by the new hybrids has therefore affected their nutritional needs (Furlani and Purquerio, 2010).

Phenological and nutritional characterisation by studying nutrient absorption during the growing cycle is a useful tool for updating fertilisation programmes to provide adequate nutrition (Moraes et al., 2016). Plotting these data for an entire growing cycle allows us to identify the periods of higher nutritional requirements and dry-matter production for determining the best times for the application of fertilisers, avoiding possible deficiencies or superfluous consumption of some nutrients (Haag and Minami, 1988; Furlani and Purquerio, 2010). This type of study also provides information about the amount of nutrients accumulated, removed, and exported in the harvested tissues of the plants. Such information is important, especially for short-cycle crops and intensive fertilisation, as for the tomato (Omaña and Peña, 2015).

Pioneer studies in Brazil by Gargantini and Blanco (1963), Fernandes et al. (1975), and Haag et al. (1978); subsequent studies by Fayad et al (2002), Rodrigues et al. (2002), Prado et al. (2011), and Lucena et al. (2013); and a more recent

study by Purquerio et al. (2016) have all reported differences in the quantities of nutrients absorbed and in yield. Such differences can be due to the genotypic variations of each cultivar, including its typology, to variations in growing conditions, and mainly to mass production (Haag and Minami, 1988). Studies of nutrient uptake by tomato plants should therefore continue to help us understand the specific nutritional requirements of new hybrids and to obtain supply data that will help us to refine current fertilisation recommendations. The aim of this study was thus to characterise the growth and nutrient accumulation and export for two hybrid tomatoes, 'Gault' and 'Pomerano', cultivated under tropical field conditions.

Results

Number of leaves and dry-matter accumulation throughout the growing cycle

The number of leaves increased at the beginning of the growing cycle until 52 days after transplantation (DAT) for 'Gault' and 55 DAT for 'Pomerano' and then stabilised at a mean of 37 leaves plant^{-1} until the end of the cycle (140 DAT) for both hybrids (Fig. 1). The accumulation of total dry matter (DM) (leaves, stems, and fruit) for 'Gault' and 'Pomerano' was 13 and 13% by 44 and 45 DAT and 82 and 81% (626.3 and 579.5 g plant^{-1}) by 127 and 126 DAT of the totals of 767.6 and 712.5 g plant^{-1}, respectively (Fig. 1). The leaves and stems accumulated most of their DM from 28 to 71 DAT for 'Gault' and from 29 to 77 DAT for 'Pomerano'. These accumulations were 77% (161.9 and 184.6 g plant^{-1}) of the estimated totals of 210.4 and 240.4 g plant^{-1} for 'Gault' and 'Pomerano', respectively (Fig. 1). The 'Gault' and 'Pomerano' fruit had accumulated only 13% of their total DM by 63 and 70 DAT, respectively. Most of the DM had accumulated by 130 and 126 DAT, totalling 82% (456.9 g plant^{-1}) and 80% (372.8 g plant^{-1}) of the totals estimated at 556.0 and 468.5 g plant^{-1} for 'Gault' and 'Pomerano', respectively. Yield at the end of the growing cycle was 148.5 t ha^{-1} for 'Gault' and 122.6 t ha^{-1} for 'Pomerano'.

Nutrient accumulation throughout the growing cycle

Nutrient accumulation was low during the beginning of the growing cycle, followed by a period of larger accumulation and a late tendency to stabilise (Fig. 2), fitting a non-linear sigmoidal model. Nutrient accumulation for both hybrids was highest at the end of the growing cycle (Table 1). K was the most accumulated macronutrient for both hybrids, followed by N, Ca, S, Mg, and P. Mn was the most accumulated micronutrient, followed by Fe, Cu, Zn, and B. The minimum curve point (PC_{min}) and maximum curve point (PC_{max}) for 'Gault' were between 23 and 42 DAT and between 60 and 134 DAT, depending on the nutrient. PC_{min} for 'Pomerano' was between 25 and 48 DAT, depending on the nutrient. PC_{max} was earlier for 'Pomerano' (48-123 DAT) than 'Gault' (Table 2). The period of highest accumulation (DP) and the accumulated amount (AC) were variable amongst the nutrients. The longest period was 100 d for K, when 25.5 g plant^{-1} were accumulated, in contrast with 27 d for Zn, with an accumulation of 20.3 mg plant^{-1}. The amount accumulated relative to the total amount accumulated during the cycle (AC/AT) varied by <11% amongst the nutrients, regardless of the duration of the period of highest accumulation. K and Zn were the extremes, with a 73 d difference in the period of highest accumulation, but AC/AT was only 8% (84 and 76%, respectively) (Table 2).

Nutrient extraction and export at the end of the growing cycle

The amounts of nutrients extracted by 'Gault' and 'Pomerano' planted at 13 333 plants ha^{-1} by 140 DAT are shown in Table 3. The orders of extraction of macro- and micronutrients for both hybrids were K > N > Ca > S > Mg > P and Mn > Fe > Cu > Zn > B, respectively. Some of the extracted nutrients were returned to the soil by the decomposition of leaves and stems, and some were removed in the harvested fruit (export). The orders of export were K > N > Ca > P > S > Mg > Fe > B > Mn > Zn > Cu for 'Gault' and K > N > P > Ca > S > Mg > Fe > B > Zn > Mn > Cu for 'Pomerano'.

The amounts of nutrients exported relative to the amounts extracted varied between the hybrids and nutrients (Table 3). 'Pomerano' required more nutrients than 'Gault' for each tonne of fruit produced.

Discussion

The beginning of the increase in total DM accumulation occurred when 'Gault' had 29 leaves and 'Pomerano' had 28 leaves. We thus inferred that the 'Gault' and 'Pomerano' plants needed a canopy containing 78 and 76% of the total leaves at the end of the growing cycle, respectively, before they could accumulate DM at the highest rate. Number of leaves is a phenological characteristic that can be used to monitor the development of a plant over time. It could thus be used to plan nutrient distribution during growing seasons and in regions where environmental conditions affect the duration of the growing cycle (Moraes et al., 2016).

Most of the period with the highest accumulation of total DM occurred during the highest accumulation of fruit DM, likely because of the draining effect that fruit has on plants (Betancourt and Pierre, 2013). The stabilisation of DM accumulation in leaves and stems occurred when fruit DM accumulation intensified. Carbohydrates and other photoassimilates are translocated from leaves to fruit due to the predominance of the reproductive phase over the vegetative phase (Marschner, 2012).

Fruit accounted for 72 and 66% of total DM at the end of the growing cycle for 'Gault' and 'Pomerano', respectively. These values were slightly higher than the 51% for 'Santa Clara' reported by Fayad et al. (2002) and the 54 and 62% for 'Dominador' and 'Serato', respectively, reported by Purquerio et al. (2016). The distribution of DM amongst plant organs plays a fundamental role in production, because the performance of a crop depends on the capacity to accumulate biomass in organs destined for harvesting (Peil and Gálvez, 2005). The nutrient accumulation of the hybrids followed the curve for total DM accumulation, depending on the amount accumulated and on the demand. Nutrient accumulation for 'Gault' and 'Pomerano' was very low until 34 DAT, on average. The highest demand began only with the increase in the vegetative canopy at 28 and 29 DAT for 'Gault' and

Table 1. Maximum nutrient accumulation for 'Gault' and 'Pomerano' at the end of the growing cycle.

Hybrid	N	P	K	Ca	Mg	S	B	Cu	Fe	Mn	Zn
	----------		g plant^{-1}		----------		----------		mg plant^{-1}		----------
'Gault'	16.1	2.0	30.2	10.2	3.0	3.9	22.6	45.9	61.8	72.9	26.6
'Pomerano'	15.6	2.2	29.8	8.6	2.3	3.2	20.9	40.1	79.1	88.7	35.1

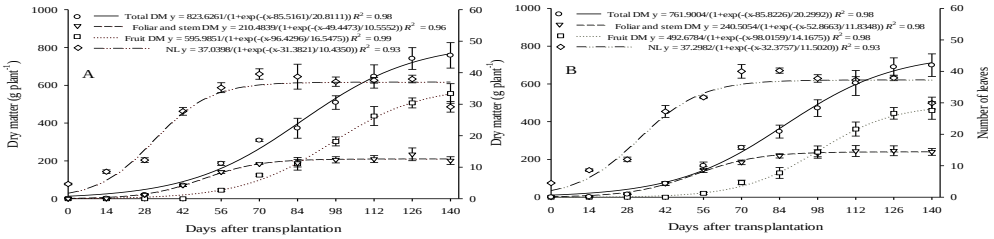

Fig 1. Total and tissue dry-matter (DM) accumulation and number of leaves (NL) for 'Gault' (A) and 'Pomerano' (B) plants during the growing cycle.

Table 2. Initial (PC_{min}), final (PC_{max}), and duration of the period of highest accumulation (DP), amount of nutrients accumulated during the period (AC), and relationship between AC and total accumulation (TA) at the end of the growing cycle for 'Gault' and 'Pomerano'.

	'Gault'					'Pomerano'				
	PC_{min}[1]	PC_{max}[2]	DP[3]	AC	AC/TA	PC_{min}	PC_{max}	DP	AC	AC/TA
	---- DAT ----		(d[4])	g plant^{-1}	%	---- DAT ----		(d)	g plant^{-1}	%
N	35	107	72	12.5	78	33	103	70	12.1	77
P	30	88	58	1.6	77	29	110	81	1.8	79
K	34	134	100	25.5	84	41	123	82	24.0	80
Ca	36	119	83	8.2	80	33	111	78	6.8	79
Mg	36	131	95	2.5	83	30	121	91	1.8	81
S	35	108	73	3.0	78	31	94	63	2.5	77
	---- DAT ----		(d)	mg plant^{-1}	%	---- DAT ----		(d)	mg plant^{-1}	%
B	33	113	80	17.9	79	33	104	71	16.2	78
Cu	23	72	49	35.2	77	35	48	13	30.9	77
Fe	38	129	91	52.4	85	48	140	92	66.2	84
Mn	42	99	57	55.7	76	40	95	55	68.2	77
Zn	33	60	27	20.3	76	25	80	55	26.9	77

[1]Minimum curve point (PC_{min} = x0-2b).
[2]Maximum curve point (PC_{max} = x0+2b) calculated using the parameters of the sigmoidal equation used to adjust the nutrient accumulation data.
[3]DP = PC_{max}-PC_{min}.
[4](d) = days.

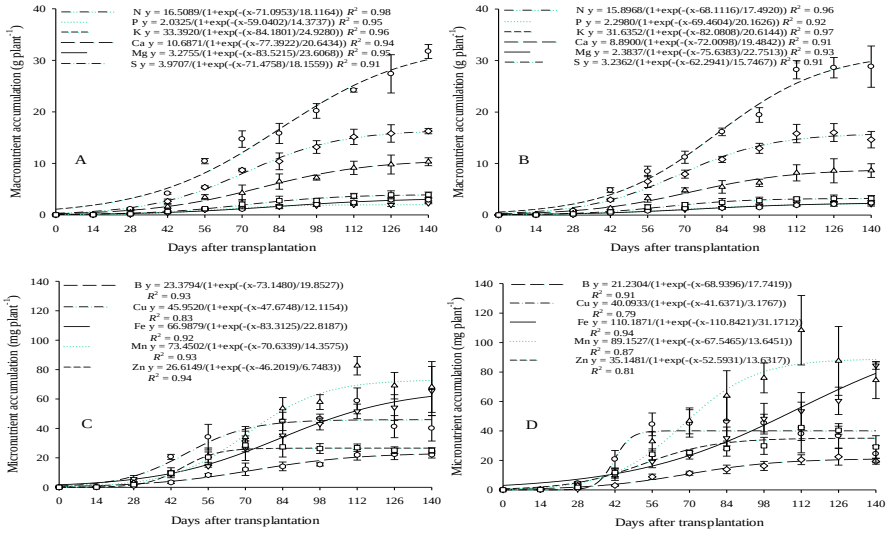

Fig 2. Macronutrient (A and B) and micronutrient (C and D) accumulation by 'Gault' (A and C) and 'Pomerano' (B and D) plants during the growing cycle.

Table 3. Extraction of nutrients by plants (ET), export in fruit (EP), ratio of export to extraction (EP/ET), and amount of nutrients required per tonne of fruit produced (NAT) by 'Gault' and 'Pomerano' at the end of the growing cycle (140 DAT).

	'Gault'				'Pomerano'			
	ET	EP	EP/ET	NAT	ET	EP	EP/ET	NAT
	------- kg ha^{-1} -------		%	kg t^{-1}	----- kg ha^{-1} ------		%	kg t^{-1}
N	215.3	153.7	71	1.5	208.5	137.3	66	1.7
P	27.0	24.4	90	0.2	29.7	20.2	68	0.2
K	402.3	286.9	71	2.7	397.8	227.6	57	3.2
Ca	135.9	27.1	20	0.9	115.0	19.6	17	0.9
Mg	40.0	13.0	32	0.3	30.0	8.8	29	0.2
S	51.8	16.1	31	0.3	42.8	13.6	32	0.3
	----- g ha^{-1} -----		%	g t^{-1}	----- g ha^{-1} -----		%	g t^{-1}
B	301.3	149.9	50	2.0	278.0	124.9	45	2.3
Cu	612.4	69.4	11	4.1	534.6	56.2	11	4.4
Fe	824.4	282.2	34	5.6	1055.1	278.7	26	8.6
Mn	971.6	116.4	12	6.5	1182.8	108.0	9	9.6
Zn	354.9	115.8	33	2.4	467.9	110.8	24	3.8

'Pomerano', respectively, when the highest foliar and stem DM accumulation began.

(K). Potassium (30.2 and 29.8 g plant^{-1}), N (16.1 and 15.6 g plant^{-1}), and Ca (10.2 and 8.6 g plant^{-1}) were the most accumulated nutrients for 'Gault' and 'Pomerano', respectively, similar to the sequences reported by Fayad et al (2002), Prado et al (2011), Lucena et al (2013), Betancourt and Pierre (2013), and Purquerio et al (2016). The amounts of the nutrients, however, differed amongst these studies.

The demand for K was highest at 71 and 59% of the growing cycle for 'Gault' and 'Pomerano', respectively (Table 2). K is involved in physiological processes that control plant growth, flowering, fruiting, and fruit quality (Cecílio Filho and Nowaki, 2016). K was in demand over a long period during the growing cycle, so the application of K fertiliser in instalments, depending on the demand, is important.

Most of the period of highest demand for N occurred during the increase in foliar and stem DM (Table 2, Fig. 1). This nutrient is important for the formation of the photosynthetic canopy of tomato plants, and an adequate availability during vegetative development contributes later to an increase in yield (Bastos et al., 2013). N was also in demand during fruit DM accumulation, when N provides benefits for the maintenance of the photosynthetic canopy, in enzymatic and proteinaceous complexes, and for relationships with other nutrients, especially P and K (Cecílio Filho and Nowaki, 2016).

The demand for Ca was highest during foliar and stem DM accumulation and during most of fruit DM accumulation (Table 2, Fig. 1). Ca must be available to hybrids from approximately the first 25% of the growing cycle until the end of the cycle. Ca has important functions in enzymatic activity. It promotes the development of the root system, photosynthetic phosphorylation, and the germination of pollen grains and affects pollen-tube growth and cell-wall formation (Bastos et al., 2013).

Macronutrients S (3.9 and 3.2 g plant^{-1}), Mg (3.0 and 2.3 g plant^{-1}), and P (2.0 and 2.2 g plant^{-1}) were accumulated less for 'Gault' and 'Pomerano', respectively, and in the same order, as also reported by Purquerio et al (2016) for 'Dominador' and 'Serato' and by Fayad et al (2002) for the EF-50 hybrid in greenhouse cultivation. The amounts, however, differed amongst these studies. This order differed from that reported by Fayad et al (2002) for 'Santa Clara' cultivated in the field and by Prado et al. (2011) for 'Raisa' cultivated in a hydroponic system, thus highlighting the importance of studying nutrient accumulation throughout the growing cycle for different genotypes, production systems, and locations.

The period with the highest demand for S was similar to that for N, differing in only one day for 'Gault' and seven days for 'Pomerano' (Table 2), but the amounts of S accumulated were approximately four- and five-fold lower than for N, respectively. S is present in other sources of nutrients used for fertilisation, so this nutrient is often neglected in fertilisation programmes and studies of absorption efficiency. S in our study, however, was the fourth most absorbed nutrient quantitatively. It is fundamental to crops because it is a constituent of the amino acids methionine and cysteine and of cysteine's oxidised dimer, cystine. Cysteine, in turn, is a precursor of the biosynthesis of lycopene, a substance that destroys free radicals and is responsible for the reddish coloration of the fruit (Alvarenga and Coelho, 2013).

Mg is a constituent of chlorophyll and an activator of enzymes. It is also associated with fruit coloration (Minami and Haag, 1980). Its availability is thus fundamental during the vegetative and reproductive phases. Mg demand was the second highest for both hybrids (Table 2). 'Gault', however, needed this nutrient later than 'Pomerano'.

P demand was highest in distinct periods in the hybrids. This period for 'Gault' was the shortest amongst all macronutrients, with a higher participation during highest foliar and stem DM accumulation. This period for 'Pomerano' lasted until the beginning of highest fruit DM accumulation (Table 2, Fig. 1). The duration of the periods of highest P demand differed by 23 days between the two hybrids, but the amount of P accumulated during these periods was similar, indicating a need for differential management, depending on the genotype.

The order of micronutrient accumulation differed from published orders. Fayad et al (2002) reported an order (mg plant^{-1}) for 'Santa Clara' grown in the field of Cu (171.0) > Mn (108.6) > Fe (98.4) > Zn (25.0). Prado et al. (2011) reported an order (mg plant^{-1}) for 'Raísa' cultivated in a hydroponic system of Fe = Zn (12.7) > Mn (8.0) > B (6.0) > Cu (3.2). Purquerio et al. (2016) reported an order (mg plant^{-1}) for 'Dominador' and 'Serato' of Cu (119.0 and 118.6) > Mn

(91.1 and 78.5) > Fe (74.7 and 50.8) > Zn (33.9 and 32.6) > B (20.1 and 17.6), respectively. In addition to the genotypic variations amongst these materials, micronutrient accumulation is influenced by factors such as the abundance of the elements in nature, soil pH, organic-matter content, oxides, primary and secondary minerals, stage of development, yield and type of crop (Abreu et al., 2007).

Mn was the most accumulated micronutrient (72.9 and 88.7 mg plant^{-1} for 'Gault' and 'Pomerano', respectively). Mn demand was highest at approximately 40% of the 'Gault' and 'Pomerano' cycles (Table 2, Fig. 1).

The duration of the period of the highest Fe demand was very similar between the hybrids. Fe was the second highest accumulated micronutrient (Table 2), but the amount accumulated during the highest demand differed between the hybrids (61.8 and 79.1 mg plant^{-1} for 'Gault' and 'Pomerano', respectively). The dynamics of accumulation also differed. Accumulation was constant until the end of the cycle for 'Pomerano' but tended to stabilise for 'Gault' (Table 2, Fig. 2).

Cu was the third most accumulated micronutrient for both hybrids (45.9 and 40.1 mg plant^{-1} for 'Gault' and 'Pomerano', respectively). The pattern of accumulation throughout the cycle, however, differed between the hybrids. The period of highest demand was 35% of the growing cycle for 'Gault' but only 9% for 'Pomerano' (Table 2). In contrast, the quantities accumulated during this period by both hybrids were similar (35.2 and 30.9 mg plant^{-1} for 'Gault' and 'Pomerano', respectively), indicating a faster accumulation of Cu by 'Pomerano'.

The increase in Zn accumulation (26.6 and 35.1 mg plant^{-1}) over the cycle was more gradual for 'Pomerano' than 'Gault' (Fig. 2), covering part of the phases with the highest accumulation of foliar, stem, and fruit DM. This period for 'Gault' occurred only during highest foliar and stem DM accumulation (Table 2).

B was the least most accumulated micronutrient (22.6 and 20.9 mg plant^{-1} for 'Gault' and 'Pomerano', respectively). B demand was highest at approximately 57 and 50% of the growing cycle for 'Gault' and 'Pomerano', respectively (Table 2). B accumulation increased during the highest foliar, stem, and fruit DM accumulation (Table 2, Fig. 1). The pattern and amount of B accumulation throughout the cycle was similar between the hybrids (Fig. 2).

Despite the differences in the duration of the periods of highest demand amongst the nutrients, the accumulated quantities at the end of these periods increased approximately seven-fold relative to the amounts at the beginning of the periods (Table 2, Fig. 2) for both hybrids, except for Fe and Cu for 'Pomerano', which increased six- and eight-fold, respectively. All nutrients also increased seven-fold for 'Dominador' and 'Serato' (Purquerio et al., 2016). This information may help the design of fertilisation programmes to supply nutrients to plants in adequate quantities when most needed.

The export (EP) of nutrients depended on their extraction (ET) (Table 3). The quantities exported varied with hybrid, function, and translocation of nutrients to fruit. P was the least extracted macronutrient (ET) (27.0 and 29.7 kg ha^{-1} for 'Gault' and 'Pomerano', respectively) for both hybrids but was fourth and third in the EP order (24.4 and 20.2 kg ha^{-1} for 'Gault' and 'Pomerano', respectively). EP/ET, however, was highest for P, at 90 and 68% for 'Gault' and 'Pomerano', respectively. Similar results were reported by Diogenes (2016) and Purquerio et al. (2016) for 'Caeté', 'Dominador', and 'Serato', in which P was the least extracted, but the second, third, and fourth in EP order, respectively. The amounts of redistributed N, P, and K were highest in fruit, and the amounts of redistributed Ca, Mg, and S were highest in the vegetative tissues of both hybrids (Table 3).

Iron was the most exported micronutrient (282.2 and 278.7 g ha^{-1} for 'Gault' and 'Pomerano', respectively) (Table 3) and for 'Santa Clara' and EF-50 (Fayad et al., 2002) and 'Dominator' and 'Serato' (Purquerio et al., 2016). B was the least extracted micronutrient (301.3 and 278.0 g ha^{-1}) but was second in export order (149.9 and 124.9 g ha^{-1}), surpassing Mn (116.4 and 108.0 g ha^{-1}), Zn (115.8 and 110.8 g ha^{-1}), and Cu (69.4 and 56.2 g ha^{-1}) for 'Gault' and 'Pomerano', respectively. B, Fe, and Zn had the highest micronutrient EP/ET ratios, but none was translocated at >50% of the extracted amount. Little Cu and Mn were exported.

The nutrient amounts per tonne of fruit produced (NAT) (Table 3) indicated the nutritional requirements of the plants, independent of productivity and duration of the growing cycle. 'Pomerano' thus needed more (kg t^{-1}) N (1.7), K (3.2), B (2.3), Cu (4.4), Fe (8.6), Mn (9.6), and Zn (3.8) to produce one tonne of fruit. For P (0.2), Ca (0.9) and S (0.3), the NAT ratio was identical for both hybrids, although the extracted amounts differed at the end of the cycle.

Materials and Methods

Two independent and simultaneous experiments were carried out near the city of Santo Antônio de Posse, São Paulo (SP) (22°18'00"S, 47°00'00"W; 585 m a.s.l.) from 22 March to 10 August 2011. The maximum, mean, and minimum air temperatures during this period were 26.1, 17.7, and 11.0 °C, respectively. Total rainfall was 206.2 mm.

Soil chemical and physical characterisation

The soil (0-0.2 m) chemical properties were: 18 g dm^{-3} organic matter, pH 5.8, 84.3 mg P dm^{-3}, 4.2 mmol$_c$ K dm^{-3}, 28 mmol$_c$ Ca dm^{-3}, 12 mmol$_c$ Mg dm^{-3}, 20 mmol$_c$ H+Al dm^{-3} and a cation exchange capacity of 64.2. The soil contained 20% coarse sand, 18% fine sand, 9% silt, and 53% clay.

Experimental design

The experimental design was randomised blocks with four replicates. Each block constituted a plot containing 120 plants (double rows containing 60 plants each). Two additional beds were prepared as borders along the length of the plots. The treatments were evaluation periods 0, 14, 28, 42, 56, 70, 84, 98, 112, 126, and 140 days after transplantation (DAT). Seedlings of both hybrids were grown in trays with 200 cells. Soil preparation consisted of ploughing, harrowing, and the preparation of beds.

Fertilisation

Basal fertilisation consisted of 30.0 kg N ha^{-1} (ammonium sulphate, 20% N), 600.0 kg P_2O_5 ha^{-1} (single superphosphate, 18% P_2O_5), 200.0 kg K_2O ha^{-1} (potassium chloride, 58% K_2O), and 2.0 kg boric acid ha^{-1} based on the soil analysis and the

recommendation for the state of São Paulo (Trani and Raij, 1997); 8000.0 kg ha^{-1} of Fertium Phós HF (3% N, 16% P_2O_5, 6% K_2O, 1.5% Mg, 3% S, 0.1% B, and 0.15% Zn) were also applied. Side dressings were applied daily at 227 kg N ha^{-1}, 197 kg P_2O_5 ha^{-1}, 410 kg K_2O ha^{-1}, and 111 kg Ca ha^{-1} as monoammonium phosphate (10% N, 48% P_2O_5), monopotassium phosphate (52% P_2O_5, 34% K_2O), potassium nitrate (12% N, 45% K_2O), calcium nitrate (15% N, 19% Ca), and formulated fertilisers (13-40-30, 17-6-18, and 15-5-30 N-P_2O_5-K_2O).

Plant material

'Gault' and 'Pomerano' (Agristar) hybrid tomatoes were used. Both are indeterminate, salad varieties resistant to *Fusarium oxysporum* f. sp. lycopersici race 3, *F. oxysporum* f. sp. radicis-lycopersici, Tomato mosaic tobamovirus, *Verticillium albo-atrum*, and *V. dahliae.*

Experimental procedure

The seedlings were transplanted on 22 March 2011 at the three leaf stage at a plant and row spacing of 0.50 × 070 m with 1.5 m between double rows (13 333 plants ha^{-1}). The plants were watered by drip irrigation with one line (30 cm between emitters) per tomato row. Weeds were controlled and moisture levels were maintained by mulching using double-sided (black/white) plastic film. Phytosanitation controlled for pests (*Bemisia tabaci*, *Bemisia argentifolli*, *Tuta absoluta*, and *Thrips tabaci*) and diseases (*Alternaria solani* Sorauer and *Phytophthora infestans* (Mont.) de Bary).

Characteristics assessed

Samples were collected at intervals of 14 days. The seedlings constituted the samples at 0 DAT. The number of leaves and stems, foliar and fruit DM, nutrient accumulation in the plant, and yield were evaluated. Three plants were collected per plot at each evaluation, leaving at least four plants as a border for the subsequent collection. The last samples were collected at 140 DAT. The collected plants were washed with water and detergent and separated into stems, leaves, and fruit, which were then dried in a forced-air circulation oven at 60 °C to a constant dry weight. The dry material was weighed and chemically analysed to determine the nutrient content of the tissues (stems, leaves, and fruit). Nutrient accumulation was calculated by multiplying the content of each nutrient in each plant tissue by the amount of DM of each tissue. The total accumulation of each nutrient in the plant was determined by the sum of the accumulation in the tissues. The times of maximum accumulation of dry mass and nutrients were determined by the minimum (PC_{min}) and maximum (PC_{max}) points of curves in sigmoid models calculated using the method described by Venegas et al. (1998). The export of nutrients was calculated by multiplying the nutrient accumulations in the fruit by the total number of plants ha^{-1}. The amount of nutrients needed to produce one tonne of fruit was calculated by dividing export values of each nutrient by the productivity at the end of the cycle.

Data analysis

The data for nutrient accumulation were analysed using a non-linear three-parameter regression model defined by the best statistical fit (*F* test) and the coefficient of determination (R^2). SigmaPlot 12.5 (Systat Software, USA) was used for the analyses.

Conclusion

Plant growth was slow at the beginning of the growing cycle. 'Gault' and 'Pomerano' maximised total dry-matter accumulation after the first third of the growing cycle (44 and 45 DAT, recpectively) when fruiting began. 'Gault' and 'Pomerano' accumulated macro- and micronutrients in the order K > N > Ca > S > Mg > P > Mn > Fe > Cu > Zn > B. The amounts of N, P, and K were highest in the fruit, and the amounts of Ca, Mg, and S were highest in the vegetative tissues, for both hybrids. Quantification of nutrient accumulation throughout the growing cycle of tomato hybrids may be helpful in planning top dressing and fertigation. The high R^2 values for the non-linear sigmoid regressions indicated their suitability for estimating both DM and nutrient accumulation in the tomato hybrids as functions of days after transplantion.

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