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Citrus fruit yield response to nitrogen and potassium fertilization depends on nutrient-water management system

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ABSTRACT

The objectives of the present study were to investigate the influence of water supply combined with different rates and methods of nitrogen (N) and potassium (K) application on fruit yield and nutrient use efficiency (NutUE) of citrus by monitoring plant nutritional status and soil solution dynamic. The experiment was carried out with 4-yr-old Natal sweet orange trees on Rangpur lime over 4 consecutive growing seasons. Treatments were composed of 2 rates of N and K (NK): 50% and 100% of the recommended rates for maximum yield in rain-fed environments and 3 nutrient-water management systems: non-irrigation + broadcast granular fertilizer, irrigation + broadcast granular fertilizer and fertilizer application via irrigation (fertigation). Fruit yield was maximum under fertigation with application of 50% of the NK rate, and fertigation improved NutUE by 22% compared to non-irrigated trees. However, no difference in productivity and NutUE occurred across nutrient-water management systems under 100% of the NK rate. Differences in plant nutritional were not consistent across treatments and did not contribute to explain variations in fruit yield and NutUE. Soil solution analysis of fertigated trees receiving 100% of the NK rate revealed the lowest pH value and the highest concentration of N-NH_4. It is concluded that fruit yield responses of citrus trees treated with established NK rates for rain-fed environments might be limited by soil solution acidification and N-NH_4 toxicity when fertilizers are applied via fertigation, being necessary further adjustments on fertilization management of fertigated citrus groves.

1. Introduction

As a result of more frequent occurrence of irregular rainfall distribution during the growing seasons and subsequent reduction on the potential productivity of citrus groves due to drought stress events, the adoption of irrigation and/or fertigation by growers has increased rapidly in the Brazilian citrus industry. However, nutrient management in these areas remains an open question since the current fertilizer guidelines for irrigated and fertigated citrus trees are mostly based on previous studies developed under rain-fed conditions (Quaggio et al., 1998). The claims regarding the need to reevaluate the recommended fertilizer rates are supported by the current view concerning the importance of the simultaneous optimization of water and fertilizer inputs for more sustainable production in agricultural areas (Qin et al., 2016). Furthermore, whereas additional water supply to the trees via irrigation and/or fertigation might benefit nutrient use efficiency (NutUE, kg fruit per kg of applied nutrient) by alleviating drought stress and maximizing nutrient uptake in the root zone there is an increase in nutrient demand due to augmented tree growth and fruit yield (Schumann et al., 2003; Bryla and Machado, 2011).

More specifically, in the case of fertigation, gains in NutUE that are achieved in comparison to the more traditional nutrient-water management in the field (i.e., broadcast granular fertilizer application combined with irrigation) might also be the consequence of both the synchronized supply of nutrients with tree demand and the reduction of nutrients losses through leaching (Kusakabe et al., 2006; Alva et al., 2008). However, the application of fertilizers via irrigation increases the potential of soil acidification in the root zone and alters the dynamic of nutrient availability to the plants (Neilsen et al., 1993; Souza and Quaggio, 2006; Souza et al., 2015). In fact, although such a response attained with fertigation might be beneficial for enhancing nutrient availability in neutral to alkaline soils, i.e., metallic micronutrients (He et al., 1999), it has been demonstrated that soil acidification is a limiting factor for the long-term sustainability of fertigation in tropical acid

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soils since it leads to nutritional imbalances and concomitant reductions in fruit yield and NutUE (Quaggio et al., 2014). Accordingly, there is an urgent need to conduct more studies that aim to improve the current understanding of the major mechanisms driving the performance of citrus trees experiencing fertigation in low fertility acid soils, offering hence, novel strategies related to fertilizer management that could contribute to promote gains in fruit yield and NutUE.

Herein, it is proposed that a comprehensive evaluation of nutrient dynamics in the soil-plant system is a suitable alternative to refine fertilization management programs in irrigated and fertigated citrus groves in tropical soils. Therefore, a long-term field study was carried out to investigate the effects of the nitrogen (N) and potassium (K) rates that were previously defined under rain-fed environments for maximum fruit yield and distinct nutrient-water management systems (i.e., broadcast solid fertilizer application combined with irrigation and/or fertigation) on the dynamics of the soil solution (total nutrient concentrations and free-form activities), plant nutritional status, fruit yield and NutUE of citrus trees over 4 growing seasons.

2. Materials and methods

The experimental field was located in the central-south region of São Paulo State, Brazil, in the city of Pirajuí (21°59′ S and 49°27′ W). According to Köppen climate classification, the climate in the region is a Cwa mesothermic type with a dry winter (Fig. 1). The trial was set up in 2005 in udic, "hapl" Ultisols, with 4-yr-old Natal sweet orange trees [*Citrus sinensis* (L.) Osbeck] on Rangpur lime rootstock [*Citrus limon* (L.) Osbeck], and the experiment was carried out for 4 consecutive growing seasons (from 2005 to 2008). The plots were formed in 3 rows, with 12 trees in each, and trees were spaced at 7.0 m × 3.0 m (476 trees ha^{-1}). All the evaluations during the experimental period were performed on the 10 central trees, and treatments were distributed in a completely randomized block design with 4 replications.

The treatments consisted of the combination of 3 nutrient-water management systems and 2 rates of N and K (referred to as NK hereafter). Nutrient-water management systems corresponded to the following: (i) broadcast fertilizer application under rain-fed condition (non-irrigated), broadcast fertilizer application combined with supplementary water supply (irrigated) and (iii) fertilizer application via irrigation water (fertigated). The nutrient rates were 50% (NK50%) and 100% (NK100%) of those amounts recommended for maximum fruit yield under rain-fed environments. Accordingly, there were 6 treatments in total: non-irrigated + NK50%, non-irrigated + NK100%, irrigated + NK50%, irrigated + NK100%, fertigated + NK50% and fertigated + NK100%.

The 100% recommended NK rate corresponded to 240 kg N ha^{-1} yr^{-1} and 160 kg K_2O ha^{-1} yr^{-1}. The solid fertilizers were broadcast under the tree canopy and split into 3 applications per year (early

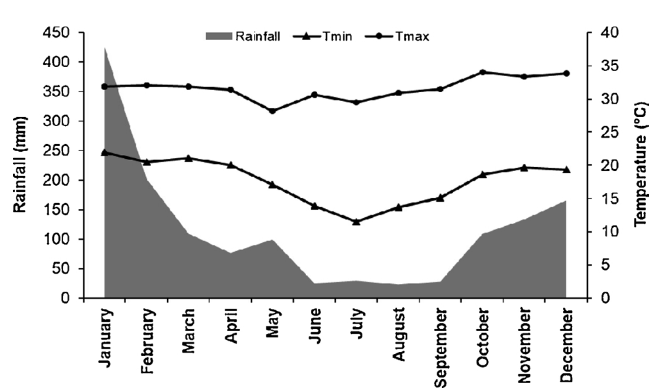

Fig. 1. Mean values of rainfall and air temperatures (minimum, Tmin and maximum, Tmax) across the 4 growing seasons (2005–2008) in which the experiment was conducted.

spring, summer and early autumn), while fertigation was applied weekly from early spring to early autumn, summing up to 32 fertigation events per year. Ammonium nitrate and potassium chlorine were used as sources of N and K, respectively, for all treatments. The P was also broadcast under the tree canopy as monoammonium phosphate at 40 kg P_2O_5 ha^{-1} yr^{-1} in a single application during early spring in all plots. Irrigation and fertigation were made through double lines of drip emitters (3.5 L h^{-1}), which formed a wetted bulb of approximately 0.8 m in width per emitter line. Therefore, the wetting coverage area was estimated to be approximately 23% of the total area of the experiment. The irrigation and fertigation management was based on estimated evapotranspiration from a class A tank and crop coefficient (Allen et al., 1998).

The composition of soil solution was monitored monthly from 2005 to 2008 during the period of the year in which irrigation and fertigation were performed. After each week with fertigation events, soil solution samples were obtained with vacuum soil solution extractors located at a depth of 30 cm, and samples were storage in plastic flasks and kept in a refrigerator. Samples taken during consecutives 4 weeks were homogenized to create the monthly soil solution samples. During the dry season (June to August), it was not possible to collect samples from non-irrigated plots. As such, despite there being 32 fertigation events per year, only 18 samples across the 4 growing seasons were used to evaluate the effects of treatments on the soil solution dynamic. The decision to use only 18 samples was made after obtaining soil solution samples from the non-irrigated plots subsequent to the occurrence of rain. Electrical conductivity and total concentrations of N (N-NO_3 and N-NH_4), K, P, Ca, Mg, S and Cl were determined according to the methods described by van Raij et al. (2011). The soil solution ionic strength (I) and the free-form activities of the nutrients were calculated using the GEOCHEM computer program.

Six-month-old leaves were sampled from fruiting terminal branches and analyzed for mineral composition (Bataglia et al., 1983; Quaggio et al., 2005). Productivity (ton of fruit ha^{-1}) was determined by weighing the fruits collected from the 10 central trees in each plot. The NutUE (kg of fruit per kg of applied nutrient) was calculated for N (NUE) and K (KUE) as the ratio between the fruit yield and their respective rates (kg N ha^{-1} or kg K_2O ha^{-1}).

The data were subjected to analysis of variance (ANOVA) using pooled values across the evaluated growing seasons (2005–2008) for fruit yield, NutUE, plant nutritional status, total nutrient concentration and free-form ion activities in the soil solution. Except for the latter, in which the standard error was used as the criterion to separate the means, the effects of the tested treatments on other parameters were compared by using Tukey's test at $p < 0.05$.

3. Results

The composition of the soil solution was influenced by NK rates and nutrient-water management systems. For instance, whereas non-irrigated and irrigated treatments exhibited similar pH of the soil solution, the lowest value for this parameter was observed under fertigation, except for the comparison between non-irrigated + NK100% and fertigated + NK50% (Table 1). Total concentrations of P, N-NO_3, Cl, K and N-NH_4 were highest under fertigation with both NK rates, whereas the difference between non-irrigated and irrigated plots were not consistent and varied with the nutrient. Regarding Ca and Mg, the lowest concentrations of these elements occurred for both irrigated treatments, and in the case of S, its lowest values were observed under fertigation (Table 1).

Under fertigation, free-form activity of P, N-NO_3, K and N-NH_4 were higher than in the non-irrigated and irrigated conditions (Table 2). In relation to the free-form activity of Ca and Mg, the highest values were found in soil solution samples from the fertigated + NK100%. However, the lowest and highest values of free-form activity of S were determined under fertigation and non-irrigation, respectively, regardless

Table 1
Values of pH and total concentration of anions and cations in soil solution as a function of NK rates and nutrient-water management systems over 4 growing seasons (2005–2008).

Treatments	pH	P $mmol_c\,L^{-1}$	S	N-NO_3	Cl	K	Ca	Mg	N-NH_4
Non-irrigated + NK50%	6.3	0.007	0.47	1.14	0.43	0.30	0.82	0.69	0.04
Non-irrigated + NK100%	5.7	0.027	0.62	1.65	0.67	0.80	0.92	0.79	0.11
Irrigated + NK50%	6.4	0.025	0.23	0.53	0.16	0.25	0.56	0.39	0.04
Irrigated + NK100%	6.1	0.031	0.27	0.90	0.22	0.40	0.59	0.40	0.27
Fertigated + NK50%	5.5	0.060	0.11	2.37	1.13	1.09	0.97	0.55	0.79
Fertigated + NK100%	4.9	0.058	0.12	3.32	1.81	1.33	1.21	0.95	1.12
F test									
Treatment	***	***	***	***	***	***	***	***	***
LSD	0.5	0.024	0.08	0.39	0.29	0.21	0.21	0.20	0.23

NK50% and NK100% correspond to 50% (N = 120 kg N ha^{-1} and K = 80 kg K_2O ha^{-1}) and 100% (N = 240 kg N ha^{-1} and K = 160 kg K_2O ha^{-1}), respectively, of the recommended NK for maximum fruit yield under rain-fed conditions. Non-irrigated and irrigated treatments were combined with broadcast fertilizer application; in the fertigated treatment fertilizer application occurred via irrigation water. ***significant at $p < 0.001$. LSD = least significant difference by Tukey's test ($p < 0.05$). The means represent the average of 18 samples across the 4 growing seasons.

of the amount of NK applied (Table 2).

Leaf concentrations of N, Ca, Cu and Mn were influenced by NK rates and nutrient-water management systems, whereas no variation was observed for K, P, Mg, B, Fe and Zn (Table 3). The use of fertigation promoted greater leaf concentrations of N compared to those found in the trees with non-irrigation; however, when comparing irrigation and fertigation, no consistent variation in plant nutritional status was observed. Leaf concentration of Ca showed the greatest difference for the comparison between non-irrigated + NK100% trees and those under fertigation. In the case of Cu, difference in leaf concentration was only detected between irrigated + NK50% and both non-irrigated treatments. Furthermore, variation in leaf Mn concentration occurred for the comparison between irrigated treatments with both non-irrigated + NK100% and fertigated + NK100%.

Over the average of the 4 growing seasons, the lowest and the highest fruit yields were obtained in the non-irrigated + NK50% and fertigated + NK50%, respectively (Fig. 2). The remaining treatments exhibited an intermediary response between them, reflecting that increasing the NK supply to 100% of the recommended rate resulted in a greater fruit yield in only the non-irrigated condition. Accordingly, NUE and KUE in the treatments receiving 50% of the recommended NK rate increased by 12% and 22% under irrigation and fertigation, respectively, compared to the non-irrigated trees (Fig. 3). However, no variation occurred for NUE and KUE under NK100% and their averaged values corresponded to around 48% of those obtained with the application of half of NK rate (data not shown).

4. Discussion

Our results suggest that fertilization strategies in citrus groves that use irrigation and/or fertigation might be significantly distinct from those previously established under rain-fed conditions. For instance, it was demonstrated that with NK50%, the following ranking was observed for fruit yield: fertigation > irrigation > non-irrigation (Fig. 2). However, no difference in productivity of the trees among nutrient-water management systems was detected with NK100%. Moreover, with the adoption of irrigation, both NK50% and NK100% presented similar fruit yields, whereas for non-irrigation and fertigation conditions, the relative yield of trees receiving 50% of the NK rate was 90% and 106%, respectively, of those receiving the higher rate. In the present study, improved tree growth was the main factor driving these positive fruit yield responses under irrigation and fertigation relatively to the rain-fed treatments at 50% of the NK, as no significant variation in yield efficiency (ton of fruit produced per m^3 of canopy) was found across all treatments (data not shown). These observed gains in productivity of the trees subjected to irrigation and fertigation resulted

Table 2
Ionic strength (I) and free-form activity of nutrients in the soil solution as a function of NK rates and nutrient-water management systems over 4 growing seasons (2005–2008).

Treatments	I	P $mmol\,L^{-1}$	S	N-NO_3
Non-irrigated + NK50%	0.0047 ± (0.0002)	0.005 ± (0.001)	0.298 ± (0.013)	1.060 ± (0.132)
Non-irrigated + NK100%	0.0058 ± (0.0002)	0.023 ± (0.008)	0.376 ± (0.010)	1.520 ± (0.075)
Irrigated + NK50%	0.0028 ± (0.0001)	0.020 ± (0.005)	0.163 ± (0.018)	0.407 ± (0.053)
Irrigated + NK100%	0.0034 ± (0.0002)	0.026 ± (0.002)	0.183 ± (0.011)	0.890 ± (0.046)
Fertigated + NK50%	0.0060 ± (0.0003)	0.057 ± (0.007)	0.069 ± (0.003)	2.172 ± (0.094)
Fertigated + NK100%	0.0084 ± (0.0002)	0.050 ± (0.003)	0.066 ± (0.008)	3.010 ± (0.103)

Treatments	K $mmol\,L^{-1}$	Ca	Mg	N-NH_4
Non-irrigated + NK50%	0.279 ± (0.039)	0.578 ± (0.039)	0.492 ± (0.040)	0.039 ± (0.004)
Non-irrigated + NK100%	0.820 ± (0.081)	0.621 ± (0.027)	0.541 ± (0.018)	0.102 ± (0.008)
Irrigated + NK50%	0.233 ± (0.007)	0.434 ± (0.010)	0.305 ± (0.023)	0.039 ± (0.004)
Irrigated + NK100%	0.379 ± (0.020)	0.440 ± (0.031)	0.305 ± (0.015)	0.252 ± (0.026)
Fertigated + NK50%	1.000 ± (0.084)	0.681 ± (0.042)	0.392 ± (0.048)	0.731 ± (0.068)
Fertigated + NK100%	1.209 ± (0.050)	0.809 ± (0.039)	0.639 ± (0.066)	1.021 ± (0.097)

NK50% and NK100% correspond to 50% (N = 120 kg N ha^{-1} and K = 80 kg K_2O ha^{-1}) and 100% (N = 240 kg N ha^{-1} and K = 160 kg K_2O ha^{-1}), respectively, of the recommended NK for maximum fruit yield under rain-fed conditions. Non-irrigated and irrigated treatments were combined with broadcast fertilizer application; in the fertigated treatment fertilizer application occurred via irrigation water. The means represent the average of 18 samples across the 4 growing seasons and the values between parentheses are standard errors (n = 4).

Table 3
Leaf nutrient concentrations of citrus trees as a function of NK rates and nutrient-water management systems over 4 growing seasons (2005–2008).

Treatments	N $g\,kg^{-1}$	K	P	Ca	Mg	B $mg\,kg^{-1}$	Cu	Fe	Mn	Zn
Non-irrigated + NK50%	25.8	11.9	1.3	37.8	5.2	163	134	148	140	64
Non-irrigated + NK100%	26.0	11.9	1.3	39.0	5.4	160	121	148	156	58
Irrigated + NK50%	26.5	12.4	1.3	37.3	5.3	172	183	157	115	67
Irrigated + NK100%	28.0	12.5	1.3	35.4	5.5	170	141	146	115	56
Fertigated + NK50%	29.0	12.3	1.3	35.2	5.3	170	157	144	140	65
Fertigated + NK100%	28.6	13.5	1.2	34.0	5.1	173	163	156	148	64
F test										
Treatment	***	ns	ns	***	ns	ns	**	ns	***	ns
LSD	1.6	1.8	0.1	3.3	0.7	15	45	23	27	12

NK50% and NK100% correspond to 50% (N = 120 kg N ha^{-1} and K = 80 kg K_2O ha^{-1}) and 100% (N = 240 kg N ha^{-1} and K = 160 kg K_2O ha^{-1}), respectively, of the recommended NK for maximum fruit yield under rain-fed conditions. Non-irrigated and irrigated treatments were combined with broadcast fertilizer application; in the fertigated treatment fertilizer application occurred via irrigation water. ns = non-significant; **significant at $p < 0.01$ and ***significant at $p < 0.001$. LSD = least significant difference by Tukey's test ($p < 0.05$). The values represent the average of the 4 growing seasons.

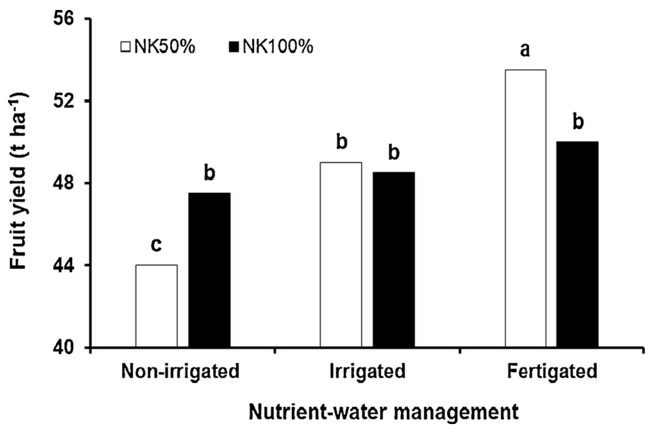

Fig. 2. Citrus fruit yield as a function of nitrogen and potassium (NK) rates and nutrient-water management systems. NK50% and NK100% correspond to 50% (N = 120 kg N ha^{-1} and K = 80 kg K_2O ha^{-1}) and 100% (N = 240 kg N ha^{-1} and K = 160 kg K_2O ha^{-1}), respectively, of the recommended NK for maximum fruit yield under rain-fed conditions. Non-irrigated and irrigated treatments were combined with broadcast fertilizer application; in the fertigated treatment fertilizer application occurred via irrigation water. The values are the averages across the 4 growing seasons (2005–2008). Different letters on the top of the columns represent significant differences by Tukey's test ($p < 0.05$).

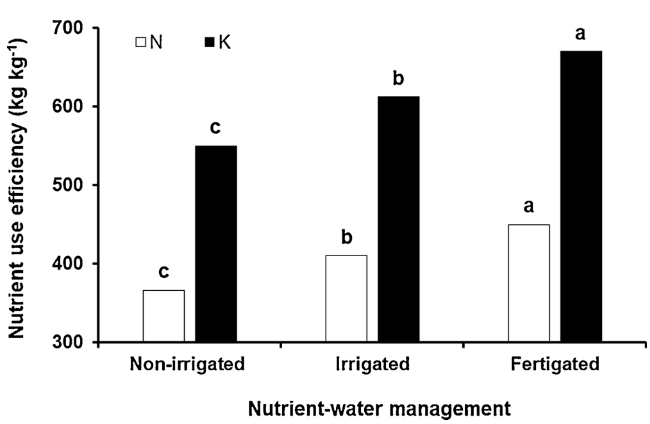

Fig. 3. Nitrogen (N) and potassium (K) use efficiencies (kg fruit kg^{-1} N or K_2O, respectively) for the 50% NK rate (N = 120 kg N ha^{-1} and K = 80 kg K_2O ha^{-1}) under different nutrient-water management systems. Non-irrigated and irrigated treatments were combined with broadcast fertilizer application; in the fertigated treatment fertilizer application occurred via irrigation water. The values are the averages across the 4 growing seasons (2005–2008). Different letters on the top of the columns represent significant differences by Tukey's test ($p < 0.05$) for each nutrient separately.

consequently in greater fruit yield per unit of applied nutrient (Fig. 3). Such gains in NUE and KUE through a supplementary water supply might have further positive effects on citrus production sustainability because it reduces both risks of environmental pollution and costs with overuse of fertilizers (Liu et al., 2017; Wolff et al., 2017).

The improved fruit yield and subsequent NutUE under supplementary water supply could be primarily attributed to the amelioration of the effects of drought stress events on the physiological processes sustaining canopy formation (Swietlik, 1992; Panigrahi et al., 2012). In addition, a more specific comparison between irrigation and fertigation allowed us to separate the effects of supplementary water application from those of nutrient management (broadcast granular fertilizer application versus nutrient application via irrigation). Based on this, it was revealed that the positive effects on fruit yield achieved with fertigation could not be solely attributed to additional water supply to the trees, since with NK50% greater fruit yield and NutUE were obtained with fertigation than with the two irrigated treatments (Figs. 2 and 3). This result might be explained by increased nutrient availability in the soil solution of the fertigated trees, which was a result of the more frequent application and close placement of the nutrients to the root zone (Dasberg et al., 1984; Boman, 1996). In fact, such an idea of augmented nutrient supply to the trees is supported by higher values of total concentration and free-form activity of $N\text{-}NO_3$, P, K, Ca and Mg in the fertigated + NK50% relatively to the irrigated + NK50% (Tables 1 and 2).

Despite the observed differences in total concentration and free-form activity of nutrients in the soil solution (Tables 1 and 2), no consistent variation was found in plant nutritional status that could be directly related to the bioavailability of nutrients or explain the differences in fruit yield. For instance, leaf concentrations of K, P and Mg were similar across treatments, and even with variation in the concentrations of N and Ca, all trees had sufficient amounts of these nutrients (Table 3; Quaggio et al., 2005). One plausible explanation for the lack of a consistent association between nutrient availability in the soil solution and plant nutritional status is the occurrence of nutrient dilution in tree biomass, which can be caused by both higher tree growth and fruit yield. Herein, the most noticeable response of the plants in terms of nutritional status corresponded to the results of leaf Mn concentrations, which were considered to be excessive for citrus-bearing trees in all treatments (Table 3; Quaggio et al., 2005). In fact, it has been argued that Mn toxicity is a critical factor driving contrasting responses of citrus trees to nutrient-water management systems (Neilsen et al., 1993) and N fertilizer sources used for fertigation (Quaggio et al., 2014). However, no consistent relationship was established between leaf Mn concentration and fruit yield in the present study, revealing the need for further researches to better elucidate the critical level of Mn toxicity for citrus trees in the field.

In contrast to the results observed in treatments with 50% of the recommended NK rate, under NK100%, no variation in either fruit yield was detected among nutrient-water management systems; additionally, while the 100% NK rate promoted greater fruit yield than the 50% NK rate under non-irrigation, a decline in productivity occurred when the higher rate was applied with fertigation (Fig. 2). Such a decrease observed in fertigated + NK100% might be explained by the occurrence of N-NH_4 toxicity since the concentration of this N form in the soil solution (Table 1) were very close to those values found in fertigated citrus trees with ammonium nitrate and that exhibited reduction in fruit yield (Quaggio et al., 2014). The presence of this constraint might be explained by the fact that a more concentrated supply of nutrients close to the root zone, compared to broadcast granular fertilizer applications, increases the potential of soil acidification (Souza et al., 2015; Messiga et al., 2018). This condition of elevated acidity, in turn, inhibits the process of nitrification and contributes to N-NH_4 accumulation and toxicity, leading to further reductions in the potential responses of the citrus trees to higher N rates supplied via fertigation (Dasberg et al., 1988; Weinert et al., 2002).

In conclusion, the results of this long-term study have practical implications for a more sustainable citrus production in low fertility acidic soils since we were able to consistently demonstrate that maximum fruit yield under fertigation might be achieved with lower NK rates than those currently recommended for rain-fed environments. Moreover, despite the positive effects found in fruit yield and NutUE with the use of fertigation, the long-term sustainability of these citrus groves in tropical soils requires some further adjustments in management practices in order to minimize the intensity of acidification and N-NH_4 accumulation in the soil solution, i.e. use of less acidifying fertilizer sources.

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