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Lemon yield and fruit quality affected by NPK fertilization

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Abstract

A field trial with Sicilian lemon on Volkameriana rootstock was carried out, during 7 years, in a sandy and low fertility oxisol in the State of São Paulo, Brazil, in order to determine quantitative relationships of lemon yield and fruit quality with NPK fertilization. The experiment was set up in an incomplete factorial design of the (1/2) 4^3 type, summing up 32 treatments, with yearly rates of N (30, 100, 170, and 240 kg ha^{-1}), P (9, 27, 62 and 79.0 kg ha^{-1}), and K (24, 91, 158, and 225 kg ha^{-1}), split in three applications from early spring to late summer. Mathematical models of the type $Y = b_0 + b_{11}\mathrm{N} + b_{12}\mathrm{N}^2 + b_{21}\mathrm{P} + b_{22}\mathrm{P}^2 + b_{31}\mathrm{K} + b_{32}\mathrm{K}^2 + b_{12}\mathrm{NP} + b_{13}\mathrm{NK} + b_{23}\mathrm{PK}$ were adjusted to selected variables related to fruit yield and quality, soil, and leaf analyses. The maximum fruit yield, averaged over six harvests, was reached with the rates calculated with the response curve as N = 220 kg ha^{-1}, P = 20 kg ha^{-1} and K = 310 kg ha^{-1}. For K the optimum rate was much higher than the highest rate applied. The effects of nitrogen and potassium on fruit yield were, respectively, quadratic and linear. The response of lemon to phosphorus, in the first 4 years was linear up to the highest P rate applied, which increased the average yield over 15%. In the fifth year, there was no response to P and in the sixth year, a negative response was observed. These results might be related to P accumulation in the top layer of soil, mainly for the highest rates of P, as shown by the results of soil testing within the years. Leaf analyses for N, P and K, related with maximum yield, were respectively, 15–18, 1.8–2.2 and 15–20 g kg^{-1}, for samples taken from fruit bearing terminals. Fruit quality characteristics were affected by nutrient rates only after the second year of fertilizer application. Phosphorus and potassium were the most effective nutrients to increase fruit size. Negative effects of N and K were observed on the essential oil content of fruits, whereas P promoted a positive trend. The effect of P application on oil concentration was closely related to its effect on peel thickness.

Keywords: Lemon; NPK fertilization; Fruit quality

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1. Introduction

Lemon production is destined to either fresh fruit markets or processing of pectin, juice and essential oil. Fruit size and peel color are important fruit characteristics for fresh market, while for processing, soluble solids, juice, pectin, and essential oil content are important.

The available information on nutrient requirements to improve lemon yield and fruit quality is small, compared with oranges. For this reason, lemon growers normally apply the production practices used for orange, including fertilizer programs. The study of Koo (1963) showed that potassium requirement for lemon was higher than that for orange and recommended rates of potassium 25% higher than those for nitrogen, for optimal lemon yield.

Koo et al. (1973, 1974) conducted, in a sandy soil in Florida, USA, an N $\times$ K factorial experiment with young bearing lemon trees, during four harvests. The most profitable nitrogen rate was close to 200 kg ha^{-1}, which is very close to the results reported by Jones et al. (1970) in California, USA. The nitrogen rates significantly affected fruit quality: decreased fruit size and acid content in the juice; increased peel oil and percentage of green fruits. The higher rates of nitrogen accounted for lower marketable production. Potassium had no significant effect on yield, but increased acid content in juice. The highest lemon yield, along the four harvests, was 28 t ha^{-1}, which is considered low for lemon and might explain the absence of response to potassium. A linear relation between yield and leaf-N was observed in annual leaf sampling. The results suggested the range from 22 to 26 g kg^{-1} as adequate for lemon leaves taken from 2- to 4-month-old non-bearing twigs.

In South Africa, lemon response to NPK fertilization was studied by Du Plessis et al. (1975) and the results showed that higher yields were obtained with the rates around 160 and 150 kg ha^{-1}, respectively, for N and K. No response was observed for P. Optimal yields were associated with nutrient contents of N, P and K in the leaves, respectively, of 23, 1.1 and 9.0 g kg^{-1}. The optimal value for leaf-N is in agreement with, whereas leaf-K is lower than those proposed by Koo et al. (1974).

Lemon fruit traits are affected by high nitrogen rates, as observed by Singh and Singh (1984). Increasing rates of N linearly decreased peel thickness, juice and ascorbic acid contents in fruits. On the other hand, total soluble solids and acid content increased with N rates.

The results of Aso et al. (1987), obtained in Tucuman, Argentina, suggested that lemon trees efficiently use nitrogen; they obtained fruit yield higher than 480 kg per tree with a rate of 600 g of N per tree, corresponding to an efficiency of 68 kg of lemons per 1 kg of applied N.

Cantarella et al. (1992) reported the results of a network of NPK factorial experiments, adjusting response surfaces to yield of several sweet orange varieties, including the first two harvests of this present study. Maximum yield of both oranges and lemons was reached with N rate close to 220 kg ha^{-1}. In the same way, the response for P was similar for both orange and lemon, and was closely related to the availability of nutrients in the soil. However, lemon requirement for K was much higher than for oranges.

This paper reports a long-term study of the effects of NPK fertilization on lemon yield and fruit quality with the objective of establishing criteria for fertilizer recommendations based on soil test and leaf analyses.

2. Materials and methods

The experiment was carried out for 8 years in a commercial grove near Botucatu, State of São Paulo, Brazil. The soil is a sandy, well-drained and very low fertility oxisol, with the following initial chemical characteristics: pH in $CaCl_2 = 4.5$; P-resin = 4 mg dm^{-3}; and exchangeable cations, expressed in mmol$_c$ dm^{-3}, Ca = 13; Mg = 4 and K = 0.7 and soil base saturation (*V*, %) of 32%. Prior to the application of the treatments the soil was limed to increase by *V* (%) to 70% of the cation exchange capacity and re-limed when necessary, according to soil analyses.

The lemon trees (*Citrus limon* L.), Sicilian variety, on *Citrus volkamerina* as rootstock, were planted in 1982, spaced 8 m $\times$ 6 m, corresponding to 208 plants/h. Each plot consisted of 4 rows with 5 trees each (20 trees). The six centrally-located trees were used for sampling and the others as guard trees.

The treatments were set up in an incomplete factorial design of the (1/2) 4^3 type, summing up 32 treatments, according to Andrade and Noleto (1986) and are described in Table 1. Yearly rates of N (30, 100, 170, and 240 kg ha^{-1}) as nitrochalk, P (9, 27, 62 and 79 kg ha^{-1}) as triple superphosphate and K (24, 91, 158, and 225 kg ha^{-1}) as KCl, were split in three applications, from early spring to late summer. Micronutrients were applied twice a year spraying a solution with the following composition: urea 3.0 g l^{-1}, zinc sulfate 2.5 g l^{-1}, boric acid 1.5 g l^{-1} and manganese sulfate 2.0 g l^{-1}.

Yields were obtained by summing up the fruits harvested from two blooms, developed from spring and summer flushes. Fruit quality was evaluated in samples of 15 fruits, developed from spring flush, which represent normally 85% of the annual production.

The experiment was monitored every 2 years with soil and leaf analyses. Soil samples were taken from both 0–20 and 20–40 cm layers and analyzed according to the methods developed by van Raij et al. (1986). Leaf samples were collected from 4- to 6-month-old fruiting terminals and analyzed for total concentration of nutrients, according to the methods described by Bataglia et al. (1983).

The statistical analyses was based on variance analyses and on a mathematical model of the type $Y = b_0 + b_{11}\mathrm{N} + b_{12}\mathrm{N}^2 + b_{21}\mathrm{P} + b_{22}\mathrm{P}^2 + b_{31}\mathrm{K} + b_{32}\mathrm{K}^2 + b_{12}\mathrm{NP} +_{13} \mathrm{NK} + b_{23}\mathrm{PK}$ adjusted using a specially developed computer program.

3. Results and discussion

3.1. NPK fertilization and lemon yield

The treatments were applied beginning in 1988, when the trees were 6 years old, and continued until 1995. The harvest of 1989 season was not measured due to its dependence on a previous fertilizer program. The general average of lemon yield along six harvests was above 40 t ha^{-1}, which can be considered high for a non-irrigated grove. In 1993 the trees were severely affected by blossom blight disease and the average yield decreased to 17.2 t ha^{-1}, limiting the effect of the treatments in this season.

The effects of N, P and K on lemon yield were additive, because no significant nutrient interaction was observed in any year. Potassium effects on lemon yield were very

Table 1
Treatments within a factorial, experiment and their effects on lemon yield in six successive harvests

Annual rates ($kg\ ha^{-1}$) of			Harvests ($t\ ha^{-1}$)						Mean of treatments
N	P	K	1990	1991	1992	1993	1994	1995	
30	79	24	48.4	36.3	65.1	18.0	40.6	12.0	36.7
240	79	225	64.4	49.4	74.6	20.1	72.1	50.4	55.2
240	27	91	59.1	47.6	60.4	13.1	49.0	20.3	41.6
170	62	225	52.5	45.8	67.1	20.3	70.1	36.9	48.8
170	9	91	45.3	34.4	54.3	10.2	63.5	48.4	42.7
100	9	158	55.5	38.2	62.9	11.9	65.8	30.1	44.1
240	62	158	54.9	50.4	60.6	23.0	62.9	43.3	49.2
170	79	158	63.9	47.8	64.6	19.6	75.1	42.8	52.3
30	62	91	53.7	40.7	62.0	15.4	48.0	27.4	41.2
240	9	24	41.2	26.5	47.5	15.0	37.4	17.1	30.8
30	9	225	51.3	34.7	68.2	17.0	66.2	36.4	45.6
100	27	225	60.0	37.1	73.3	18.5	66.3	49.4	50.8
100	79	91	55.7	43.2	63.2	24.5	52.6	26.2	44.2
30	27	158	56.4	34.5	71.4	11.8	57.1	30.3	43.6
170	27	24	52.3	46.9	52.1	21.6	40.3	15.8	38.2
100	62	24	47.8	39.3	51.6	10.3	45.3	19.3	35.6
240	9	225	52.6	44.8	63.7	15.1	60.0	57.4	48.9
30	79	225	58.2	48.0	70.9	18.2	49.8	39.1	47.4
30	62	158	49.7	37.4	70.4	18.3	38.7	19.3	39.0
100	79	158	64.6	51.6	67.5	22.0	61.9	38.2	51.0
170	62	24	56.3	36.5	47.5	18.4	36.1	18.7	35.6
240	79	24	56.5	40.6	51.8	19.0	31.2	13.7	35.5
240	62	91	64.7	44.5	59.2	16.0	53.7	33.2	45.2
170	79	91	59.7	51.8	55.6	21.5	45.4	20.9	42.5
240	27	158	63.1	44.7	61.5	18.0	65.4	48.8	50.3
170	27	225	67.4	47.7	67.8	20.5	66.3	59.8	54.9
30	27	91	48.7	29.1	51.7	18.9	38.1	13.3	33.3
170	9	158	57.6	45.9	64.4	17.1	55.2	34.8	45.8
100	27	24	47.2	30.4	43.4	16.1	40.9	18.8	32.8
100	9	91	60.8	43.9	63.4	14.0	54.2	17.8	42.4
100	62	225	55.9	47.5	62.8	18.7	62.3	43.7	48.5
30	9	24	45.5	33.4	43.7	9.3	27.6	12.1	28.6
Annual average ($t\ ha^{-1}$)			55.3	41.6	60.8	17.2	53.1	31.1	43.2
Analyses of variance[a]			NL**	NL**	N ns[b]	N ns[b]	NQ**	NL**	NQ**
			PL**	PL**	PL*	PL*	P ns[b]	PL*	PL**
			KL**	KL**	KL**	K ns[b]	KL**	KL**	KL**
Coefficient of variation (%)			8.3	12.5	7.3	19.6	10.2	25.9	6.0

[a] L and Q are respectively the linear and quadratic trends.
[b] Not significant.
* $P < 0.05$.
** $P < 0.01$.

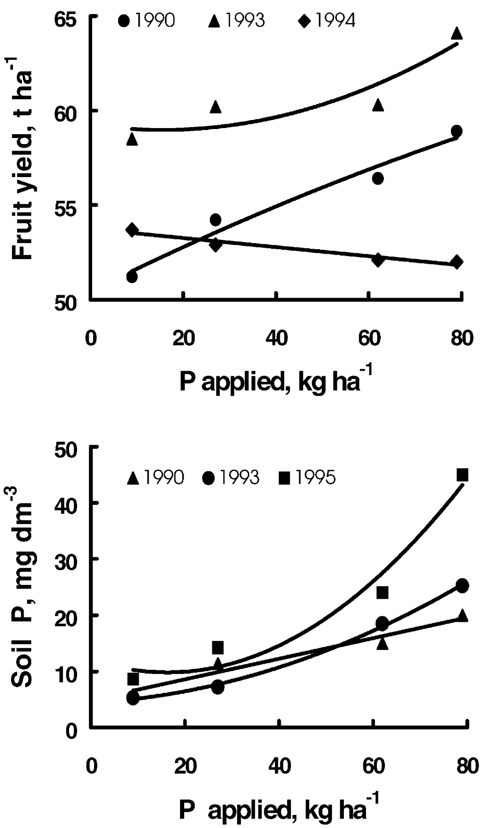

Fig. 1. Three years of lemon yield and soil-P extractable by anion exchange resin in response to P application.

consistent and linear along the 6 years and also in the average of all harvests. Nitrogen response was not as consistent as that for potassium. In the first 2 years, the effects were linear whereas a quadratic trend was observed on the yield results averaged in overall harvests (Table 1). A quadratic trend for the response of N rates was also reported by Jones et al. (1970), who found that N rates higher than 200 kg ha^{-1} decreased lemon yield.

The effect of phosphorus rates on lemon yield was very pronounced at the beginning of the experiment. As P accumulated in the soil, its effect on yield decreased along the years and no response was observed in the sixth year, when the sum of the lowest rate of P applied amounted to 54 kg ha^{-1} of P and increased soil-P from 4 to 12 mg dm^{-3}. In the last harvest a linear and negative effect of this nutrient on lemon yield was observed (Fig. 1). The results of soil analyses showed that the highest rate of P, applied in seven successive years, increased soil-P to above 40 mg dm^{-3} (Fig. 1), which is the lower limit of the very high class for citrus according to Quaggio et al. (1998). Therefore, the effect of P on yield, averaged along six harvests, was linear but less pronounced than for K and N (Table 1).

A response function to N, P, and K rates and combinations was adjusted to the results of lemon yield averaged over all harvests (Table 2). Solving this equation by differential

Table 2
Response functions for lemon yield and for fruit quality characteristics[a]

Dependent variables	Surface coefficients										R^2
	B_0	N	NQ	P	PQ	K	KQ	NP	NK	PK	
Yield (t ha^{-1})	5.8	0.1430	−0.000491	0.0200	−0.00007	0.1490	−0.000242	0.000175	−0.000010	−0.000006	87.5
Fruit weight (g)	167.0	0.1500	−0.000867	0.1340	−0.00152	0.5720	−0.001030	0.000985	−0.000424	−0.000626	70.5
Juice (%)	43.7	−0.0230	−0.000020	0.0494	−0.00034	−0.0770	0.000155	0.000087	0.000136	−0.000036	39.9
Total acidity (%)	4.7	0.0019	−0.000003	0.0036	−0.00003	0.0060	−0.000012	0.000001	−0.000003	−0.000001	74.9
Soluble solids (%)	7.7	0.0029	−0.000001	0.0092	−0.00005	0.0041	−0.000009	−0.000015	−0.000010	0.000003	22.2
Peel oil (kg t^{-1})	6.0	0.0015	−0.000008	−0.0005	−0.00001	−0.0042	0.000005	−0.000010	0.000000	0.000019	54.6
Peel oil (kg ha^{-1})	32.8	0.8970	−0.003050	0.1240	−0.00046	0.8160	−0.001440	−0.000460	0.000796	0.000450	85.2

[a] Data are average of 6 years. Rates of N, P, and K are expressed in kg ha^{-1}.

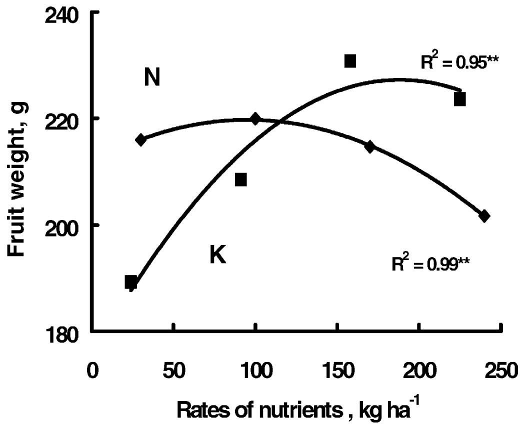

Fig. 2. Nitrogen and potassium rates affecting lemon fruit size.

calculus, the rates of N = 220 kg ha^{-1}, P = 20 kg ha^{-1}, and K = 310 kg ha^{-1} were calculated as optimal to attain maximum lemon yield. For K the optimum rate was about 38% higher than the highest rate of K applied (225 kg ha^{-1} K). Those results demonstrated that potassium is the nutrient to which lemon yield responds the greatest. In this soil very low in exchangeable K, rates of K 40% higher than those for nitrogen were necessary to reach maximum lemon yield, confirming previous results reported by Koo (1963). The optimal N rate is close to that obtained by Jones et al. (1970) and Koo et al. (1973, 1974), respectively, in California and Florida, USA, and lower than that suggested by Du Plessis et al. (1975) in South Africa. The annual P rate of 40 kg ha^{-1}, calculated with the average yields of six harvests, should be considered optimal for soils medium in available P, because at the beginning of the experiment, when the soil was very low in P, the response to P was linear up to the highest rate of 79 kg ha^{-1}, and decreased along the years due to P accumulation in the soil.

3.2. Fertilization and fruit quality

The effects of nutrients on fruit quality were evaluated during the last three harvests. Response functions were adjusted to nutrient rates and fruit quality characteristics, as presented in Table 2. The regression coefficients demonstrated that nutrient rates affected significantly the measured fruit quality parameters, except for total soluble solids in juice, which was not affected by any treatment.

Fruit size was significantly affected by rates of potassium and nitrogen, as shown in Fig. 2. As reported in previous papers (Du Plessis and Koen, 1989; Koo et al., 1974), potassium presented a positive effect whereas nitrogen decreased fruit weight. Phosphorus did not affect significantly the average values of fruit size in the last three harvests. However, in the 1995 harvest, a quadratic effect of P rates on fruit size (data not shown) and peel thickness was observed, which reflected in the same way, on the oil content of the fruit (Fig. 3). The depressive effect of the highest P rate on peel oil in this season might be related to excessive accumulation of P in the soil, revealed by soil analyses, and agrees with

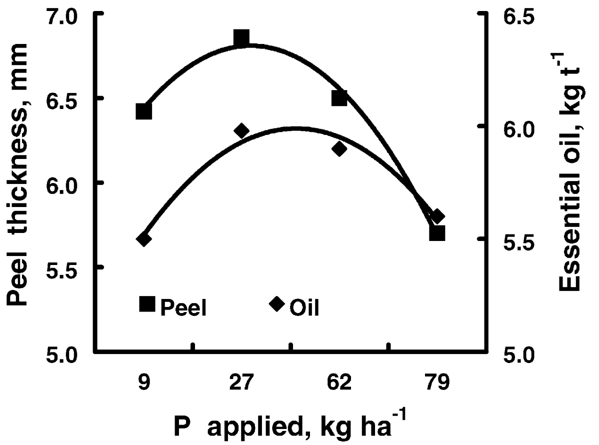

Fig. 3. Effects of P on peel thickness and on essential oil content.

the results found by Du Plessis and Koen (1992) that rates too low or too high in either P or K, decrease lemon fruit size.

The effect of N and K on the average values of the last three evaluations of peel oil content is presented in Fig. 4. Rates of nitrogen higher than 100 kg ha^{-1} caused a sharp decrease in peel oil in relation to the lowest rate of 20 kg ha^{-1}. The effect of potassium was also depressive on peel oil; however, it was less pronounced than that for nitrogen (Fig. 4). Similar results were observed by Kesterson et al. (1977) with pineapple orange in Florida. Despite the negative effect of these nutrients on peel oil per ton of fruit, the total production of essential oil per area, the most important variable for lemon growers, increased with the application of nitrogen and potassium (Fig. 4). Potassium was more effective than nitrogen due to its higher effect on yield. In other conditions, Koo et al. (1973) observed that nitrogen caused a greater increase in lemon yield, thus oil per hectare, than did potassium.

A mathematical model adjusted for NPK rates and their interactions explained 85% of observed variation in the average values of total oil production (Table 2). This model shows that the rates of N, P and K to optimize oil production were, respectively, $N = 228$ kg ha^{-1}, $P = 18$ kg ha^{-1} and $K = 310$ kg ha^{-1}, thus very close to those calculated for maximum yield. In the same way as for fruit yield, the optimum rate for K was much higher than that applied.

3.3. Leaf analyses as a diagnostic tool for lemon fertilization

The studies on nutritional status of lemon and lime, based on leaf analyses, have shown that generally leaf analyses standards, proposed for oranges by Embleton et al. (1973), can be used for lemons, except for nitrogen, which for lemons should be lower than for oranges (Jones et al., 1970; Koo et al., 1974; Du Plessis et al., 1975; Intrigolo and Intelisano, 1997). These studies were based on leaf sampling of non-fruiting terminals from the spring flushes. In Brazil, leaf samples for citrus are taken from fruiting terminals, developed from

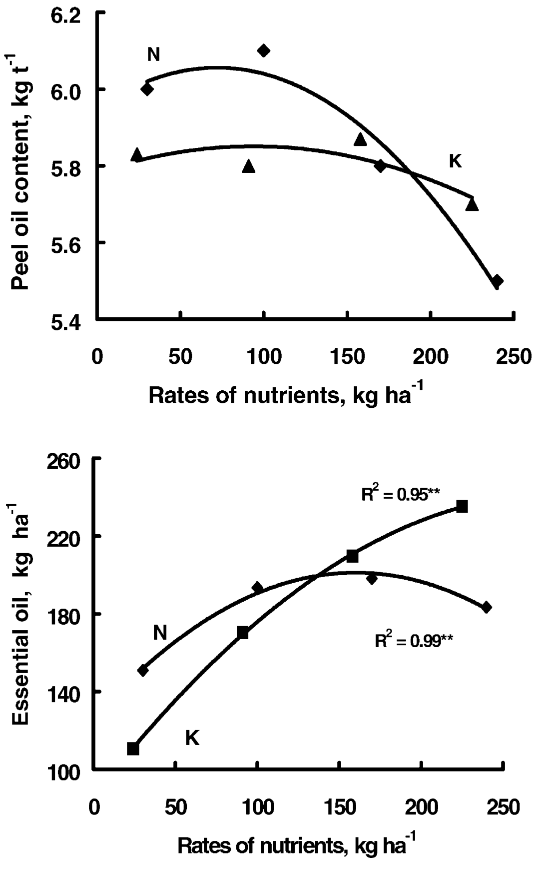

Fig. 4. Effects of N and K on peel oil and on total oil production of lemon.

spring flushes, due to ease of identifying the correct leaf and also because leaves from fruiting terminals are more sensitive to a sink effect or nutrient redistribution from leaves to fruits.

Fig. 5 presents the calibration curves for interpreting leaf analyses, established with N, P, and K contents of lemon leaves in the 1993 and 1994 harvests, and the corresponding yield response to applied rates of these nutrients, expressed as relative yield.

The calibrating curve for leaf-N showed a typical quadratic trend, demonstrating that excessive rates of nitrogen resulted in diminished lemon yield, in agreement with the results of Du Plessis et al. (1975) and Intrigolo and Intelisano (1997). The optimum range for leaf-N found was 15–18 g kg^{-1} which is much lower than that for oranges as proposed by Embleton et al. (1973). In comparison with the results of previous papers with lemon and lime (Jones et al., 1970; Koo et al., 1974; Du Plessis et al., 1975 and Intrigolo and Intelisano, 1997) this optimum range is lower due to the sampling in fruiting terminals, where the a sink effect is more accentuated. However, Du Plessis and Koen (1992), reinterpreting the results of leaf analyses from three fertilizing trials with lemons, in which

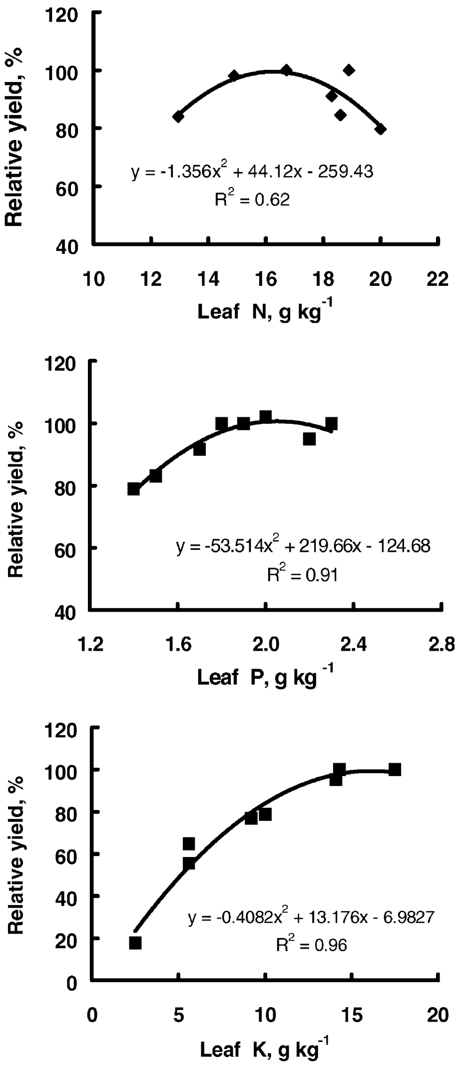

Fig. 5. Calibrations curves for leaf analyses interpretation for lemon.

fully expanded leaves were taken behind fruits of 40–45 mm, found 17–21 g kg^{-1} to be the optimal range for N, closer to the range obtained in the present paper.

Leaf-P presented a narrow optimum range from 1.8 to 2.2 g kg^{-1}, confirming the results of previous paper of Quaggio et al. (1998) that leaf-P is not as sensitive an index of phosphorus availability in the soil as is soil testing. The determined optimum range for leaf-P was slightly higher than for oranges (Embleton et al., 1973) and higher than the range proposed by Du Plessis and Koen (1992).

Leaf-K was closely related to relative yield of lemon (Fig. 5) and presented a close correlation with exchangeable potassium in the soil ($R^2 = 0.95^{**}$, data not shown). The scale of the calibrating curve demonstrated that leaf-K is as sensitive a diagnostic procedure as soil-K to determine potassium availability in the soil to lemon trees. The scale of leaf-K for lemons was wider than that obtained by Quaggio et al. (1998) for oranges. Besides, maximum lemon yield was attained with leaf-K close to 16 g kg^{-1}, therefore higher than the normal range for oranges (Embleton et al., 1973), confirming the higher potassium requirement of lemons compared to oranges.

4. Conclusions

Potassium requirement for lemon trees is higher than for nitrogen. In a soil with very low K, maximum lemon yield averaged over six harvests, was attained with the rates of $N = 220$ kg ha^{-1}, $P = 20$ kg ha^{-1} and $K > 225$ kg ha^{-1}. Fruit size increased with increasing rates of K and decreasing rates of N; rates of P too low or too high decreased fruit size. Essential oil concentration was related to peel thickness and decreased with high rates of either nitrogen or potassium. Suggested optimal ranges for leaf analyses, expressed in g kg^{-1} were: N = 15–18; P = 1.8–2.2 and K = 15–20.

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