



## Fruit yield of Valencia sweet orange fertilized with different N sources and the loss of applied N

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### Abstract

Nutrient management recommendations are needed to increase nitrogen uptake efficiency, minimize nutrient losses and reduce adverse effects on the environment. A study of the effects of nitrogen fertilization on N losses and fruit yield of 6-yr-old Valencia sweet orange (*Citrus sinensis* (L.) Osb.) on Rangpur lime rootstock (*C. limonia* Osb.) grove was conducted in an Alfisol in Brazil from 1996 to 2001. Urea (UR) or ammonium nitrate (AN) fertilizers were surface-applied annually at rates of 20, 100, 180, and 260 kg N ha<sup>-1</sup> split into three applications from mid-spring to early fall. A semi-open trapping system, using H<sub>3</sub>PO<sub>4</sub> + glycerol-soaked plastic foams, was used for selected treatments in the field to evaluate NH<sub>3</sub> volatilized from applied N fertilizers. Ammonia volatilization reached 26 to 44% of the N applied as UR at the highest rate of N used. Ammonia volatilization losses with AN were lower (4% of the N applied). On the other hand, AN resulted in greater nitrate leaching and greater soil acidification than UR. A marked effect of AN fertilizer on soil pH (CaCl<sub>2</sub>) in the 0–20 cm depth layer was observed with a decrease of up to 1.7 pH units at the highest N rate. Acidification was followed by a decrease in exchangeable Ca and Mg; consequently, after 5 yr of fertilization with AN, soil base saturation dropped from 77% in the plots treated with 20 kg N ha<sup>-1</sup> per year, to 24% in those that received 260 kg N ha<sup>-1</sup> per year. The effect of N sources on fruit yield varied from year to year. In 2001, for a calculated N application rate of 150 kg ha<sup>-1</sup>, the fertilizer efficiency index of UR was 75% of that of AN.

### Introduction

Fruit yield of citrus trees depends largely on nitrogen fertilization, because this element plays an important role in vegetative and reproductive growth (Jackson et al. 1995). Nitrogen removal by fruit harvest is about 1.9 kg N ton<sup>-1</sup> fresh weight (Bataglia et al. 1977), which is similar to that of potassium but much higher than those of other nutrients. Recommended N rates for citrus in Brazil are based on the fruit yield and the N status of trees, as assessed by leaf analysis, and range from 40 to 260 kg N ha<sup>-1</sup> (Quaggio et al. 1996). Since modern agriculture is facing considerable environmental challenges to minimize the impact of agricultural products on soils, water, and air quality, there is a clear need to fine tune recommended

rates for maximum fertilizer efficiency, and to investigate losses of nutrients in the field that may contribute to adverse effects.

Urea is the most common N fertilizer used for various crops. Gaseous loss of ammonia following urea fertilizer application may account for up to 75% of total N applied (Fenn and Miyamoto 1981), whereas N volatilization from other forms of nitrogen fertilizer is less, especially in acid soils (Havlin et al. 1999).

Studies on N volatilization have been carried out under laboratory, greenhouse, and field conditions. However, the soil-atmosphere conditions in the laboratory and greenhouse may differ greatly from those in the field. Hargrove and Kissel (1979) found that NH<sub>3</sub> losses from urea fertilizer applied to Coastal

bermudagrass sod were lower under field conditions (0 to 9%) than under laboratory conditions (13 to 31%). Freney et al. (1992) observed significant ammonia losses from urea applied to sugarcane in Australia over a period of six weeks. In dry climatic conditions ammonia loss was 39% of the applied N, but decreased to 17% in a wet zone, indicating that the rate and extent of ammonia losses were controlled by the availability of water in the soil system. Surface-applied urea to a permanent orchardgrass sod resulted in  $\text{NH}_3$  losses of up to 42% within 8 d (Lightener et al. 1990). Ammonia volatilization loss may be related to soil cation exchange capacity (CEC). Keller and Mengel (1986) reported that gaseous losses of N in 5 d from surface-applied urea to a no-till corn field were 30% and 11% from a Mollisol and an Alfisol with CEC values of 67 and 123  $\text{mmol}_c \text{ kg}^{-1}$ , respectively.

Losses of ammonia from urea are high when applied to a soil surface covered with plant material. Urban et al. (1987) found that  $\text{NH}_3$  losses from urea measured in growth chamber experiments ranged from 15 to 32% of the applied N on a bare soil, and 68 to 82% on a mulched soil. The effects of plant residue mulch on  $\text{NH}_3$  volatilization were related to (i) a physical barrier between the N source and the soil by the crop residue, (ii) maintenance of soil in moist condition over a prolonged period, and (iii) a relatively high urease activity of the plant residue. Citrus orchard management is changing to minimize weed competition and enhance early fruit production. Herbicide is commonly applied in a band of about 1.5 m on both sides of the tree row, and the grass in the middle row is periodically mowed and spread under trees, where the fertilizer is generally broadcast. Soil incorporation of fertilizers in citrus groves is often difficult due to chances of plant injury.

Different methods are used to measure N gaseous losses from soils (Marshall and Debell 1980). Nömmik (1973), Kissel et al. (1977), Ferguson et al. (1988) and Sherlock et al. (1989) used a semi-open system, which permitted exchange with the atmosphere via diffusion and allowed continuous measurement of  $\text{NH}_3$  volatilization. Another method involved the measurement of  $\text{NH}_3$  volatilization by computing the vertical and horizontal fluxes of atmospheric  $\text{NH}_3$  concentration and wind speed in large circular plots (mass balance micrometeorological method) (Wilson et al. 1983; Black et al. 1985a; Leuning et al. 1985; Wood et al. 2000). However, the applicability of this method to areas grown with trees is more difficult, because of the non-uniform distribution of trees in rows and inter-rows as compared to pasture areas.

Excess of nitrate not used by trees is subject to leaching losses below the rooting zone of citrus (McNeal et al. 1995). This downward movement reduces the efficiency of applied fertilizer and may cause the contamination of groundwater. Water quality concerns have been raised in the Florida citrus industry, because of increasing levels of nitrate concentration in groundwater near major citrus producing regions (Graham and Alva 1996).

The field evaluation of N fertilization is therefore important to estimate the efficiency of applied fertilizer. The objective of this research was to determine the  $\text{NH}_3$  volatilization and changes in selected soil characteristics and fruit yield in response to urea and ammonium nitrate applied on the surface of an Alfisol grown with citrus trees.

## Material and methods

### *Characteristics of the study area and experimental design*

A field experiment was conducted in a commercial citrus grove of Valencia sweet orange trees (*Citrus sinensis* (L.) Osb.) on Rangpur lime rootstock (*C. limonia* Osb.), which was established in 1990 in an Alfisol in Matão, a traditional citrus-growing area of the São Paulo State in southwestern Brazil. Selected physical and chemical characteristics of the soil are presented in Table 1. The trees were planted in a 7.5 m  $\times$  4.2 m spacing and treated as a commercial grove until the experiment was initiated in 1995. Insects, diseases and weeds were controlled as needed. Herbicides were applied in a band 1.5 to 2.0 m wide on both sides of the tree row; the grass in the middle was mechanically mowed. Therefore, the fertilized area was usually covered with plant residues. The fertilizer experiment was a randomized block design with four replications of rates of urea (45% N) and ammonium nitrate (33% N). The annual N rates used were 20, 100, 180, and 260  $\text{kg N ha}^{-1}$ , split into three applications in October, January, and April, corresponding to the warm and rainy season in the Southern Hemisphere. The fertilizer was hand-applied to the soil surface, in 1.5 m wide bands on both sides of the tree line. About 65% of the fertilizer was applied under the tree canopy. Dolomite lime (2.8  $\text{t ha}^{-1}$  in 1998 and 1.4  $\text{t ha}^{-1}$  in 1999) was broadcasted on all plots to partially compensate for the soil acidification due to N fertilization.

Table 1. Selected physical and chemical characteristics of the soil.

Depth (cm)	OM (g dm <sup>-3</sup> )	pH <sup>a</sup>	Ca (mmol <sub>c</sub> dm <sup>-3</sup> )	CEC (mmol <sub>c</sub> dm <sup>-3</sup> )	BS <sup>b</sup> (%)	Clay (g kg <sup>-1</sup> )	Sand (g kg <sup>-1</sup> )
0–20	20	5.4	29	66	67	131	804
20–40	12	5.4	25	58	70	166	769
40–60	9	5.4	24	60	69	226	726

<sup>a</sup>Soil to 0.01 mol L<sup>-1</sup> CaCl<sub>2</sub> solution ratio = 1:2.5 (v/v). <sup>b</sup>Soil base saturation.

### Field evaluations and laboratory analysis

Fruits were harvested between 1997 and 2001. Soil was sampled (12 holes per plot) to the depth of 60 cm, in 20 cm layer increments, from 1997 to 2000 and analyzed for pH in 0.01 mol L<sup>-1</sup> CaCl<sub>2</sub> solution (soil:solution ratio 1:2.5 v/v), resin extractable Ca, Mg, and K (Van Raij et al. 1986), and 2 mol L<sup>-1</sup> KCl-extractable inorganic N (NH<sub>4</sub><sup>+</sup> + NO<sub>3</sub><sup>-</sup>) (Bremner 1965). Semi-open chambers to trap NH<sub>3</sub> were used to measure the gaseous loss of N fertilizer, following the model described by Nõmmik (1973). The trapping device was a PVC cylinder, 35 cm long and 20 cm in diameter with an inverted plastic plate as cover, which allowed air exchange with the outside environment. Two discs of polyurethane plastic foam (density: 0.03 g cm<sup>-3</sup>; thickness: 2 cm; and circular area: 314 cm<sup>2</sup>) soaked in 2.25 mol L<sup>-1</sup> H<sub>3</sub>PO<sub>4</sub> plus 4.0% (v/v) glycerol solution were placed inside the cylinder at 10 and 20 cm from the top. Each disc retained 100 to 120 mL of the acid–glycerol solution. The disc placed in the top position was used to trap potential contamination of the atmospheric NH<sub>3</sub>. The lower position disc trapped the NH<sub>3</sub> volatilized from the soil and was used to measure the losses.

For each NH<sub>3</sub> trap, four PVC bases (cylinders 0.195 m in diameter and 0.10 m high) were partially inserted into the soil of the fertilized area of selected treatments (UR: 20, 100, and 260; and AN: 20 and 260 kg N ha<sup>-1</sup>), leaving about 0.05 m above the soil surface onto which the NH<sub>3</sub> chambers would fit. These bases received the amount of the fertilizer treatment corresponding to the rates applied to the rest of the plot. The chambers were set up immediately after the third annual split application of the N treatments on April 9, 1996, April 16, 1997, and April 20, 1999. After 2 to 5 days exposure, the NH<sub>3</sub> trapping discs were replaced by new discs. The chambers were relocated to adjacent bases in the same plot after the replacement of the exposed discs in order to minimize the effect of the chamber on the soil–fertilizer reactions. Discs collected in the field were sealed in plastic bags and stored in a refrigerator at 5 °C. Ammonia trapped by the plastic foam discs at the

lower position in the cylinder was extracted by leaching, followed by squeezing five consecutive portions of 100 mL of 1.0 mol L<sup>-1</sup> KCl solution. The extract was transferred to a 500 mL volumetric flask and made to the volume. An aliquot of KCl extract was steam-distilled with 10 mL of 5.0 mol L<sup>-1</sup> NaOH solution, and then titrated with 0.025 mol L<sup>-1</sup> H<sub>2</sub>SO<sub>4</sub> for N-NH<sub>4</sub><sup>+</sup> determination (Bremner 1965).

Daily precipitation on the area of the experiment was recorded during the course of the experiment.

### Data analysis

Data were tested for significant differences among treatments in a randomized block ANOVA with four replications using the GLM procedure of the SAS® system (SAS Institute 1996). The fertilizer efficiency index (FEI) of urea compared to that of ammonium nitrate was estimated as:

$$FEI = \frac{Y_{UR} - Y_0}{Y_{AN} - Y_0} \times 100$$

where Y<sub>0</sub> is the fruit yield obtained with the lowest N rate (20 kg ha<sup>-1</sup> N); Y<sub>UR</sub> and Y<sub>AN</sub> are the yields obtained with 150 kg ha<sup>-1</sup> of N as urea and AN, respectively. Fruit yield data were estimated by response curves adjusted to experimental data. The rate of 150 kg ha<sup>-1</sup> N was chosen because it represents the average rate used for citrus in Brazil.

## Results and discussion

### Ammonia volatilization from soil applied N fertilizers

The peaks of NH<sub>3</sub> losses occurred within 3 d after fertilizer application for urea and with less intensity for AN (Figure 1). Black et al. (1985a) also reported low volatilization losses during the first 24 h due to the slow hydrolysis of urea, and they found that most of the volatilization losses were completed during the 6 d following fertilizer application, which accounted

for 24 to 30% of the total N applied. Under dry conditions, dissolution and hydrolysis of fertilizer granules were dependent on the addition of small amounts of water through dew, and maximum daily losses occurred on the third day (Black et al. 1985b; Keller and Mengel 1986). In an experiment on orchardgrass sod with surface application of 200 kg N ha<sup>-1</sup> as urea, measurable NH<sub>3</sub> losses occurred within 12 to 24 h, with a maximum rate on the third day (Lightener et al. 1990). The NH<sub>3</sub> volatilization from surface-applied N fertilizers to an Alfisol (pH 7.9) under laboratory conditions followed a Langmuir kinetic model, i.e., an initial rapid reaction followed by a slow reaction (He et al. 1999a).

The cumulative amount of NH<sub>3</sub> volatilized from the unfertilized citrus grove was negligible during all the three years. The ammonia loss from AN was only 0.7 kg ha<sup>-1</sup> N in 1997 (Figure 1B) and 3.2 kg ha<sup>-1</sup> N in 1999 (Figure 1C), which corresponded to about 10% of the N applied at the 6.7 kg N ha<sup>-1</sup> rate. In urea treatments cumulative ammonia losses during different years varied from 17 to 26%, 15 to 31%, and 17 to 44% of the N applied at the rates of 6.7, 33.3, and 86.7 kg N ha<sup>-1</sup>, respectively (Figure 1). The mean NH<sub>3</sub> volatilization losses across three years from soil-applied urea were 20, 24, and 31% with application of 6.7, 33.3, and 86.7 kg N ha<sup>-1</sup>, respectively. These results agree with those reported by Keller and Mengel (1986), Lightener et al. (1990) and Black et al. (1985b). Differences in the total ammonia losses from applied AN or urea are usually positively related to the maximum soil surface pH produced by each of the fertilizers after dissolution and hydrolysis (Black et al. 1985b; Fan and Mackenzie 1993; Zia et al. 1999).

The presence on the soil surface of plant residues from herbicide or mechanical control of weed may have contributed to enhance urea hydrolysis and NH<sub>3</sub> volatilization losses. Black et al. (1985b) reported that the percentage N volatilization from urea broadcasted on a pasture in New Zealand increased with increasing N application rates. Considerable overlapping of urea granules would occur at higher rates and the surface soil pH would depend in part on the degree of urea diffusing into the microsites of acid soils (Peoples et al. 1995). Weather is an important factor in determining the rate and extent of NH<sub>3</sub> losses from soils following surface application of urea. Ammonia volatilization was measured at the end of the rainy season. In the first and third assays (Figure 1A and 1C) soils were relatively moist due to rainfall in the

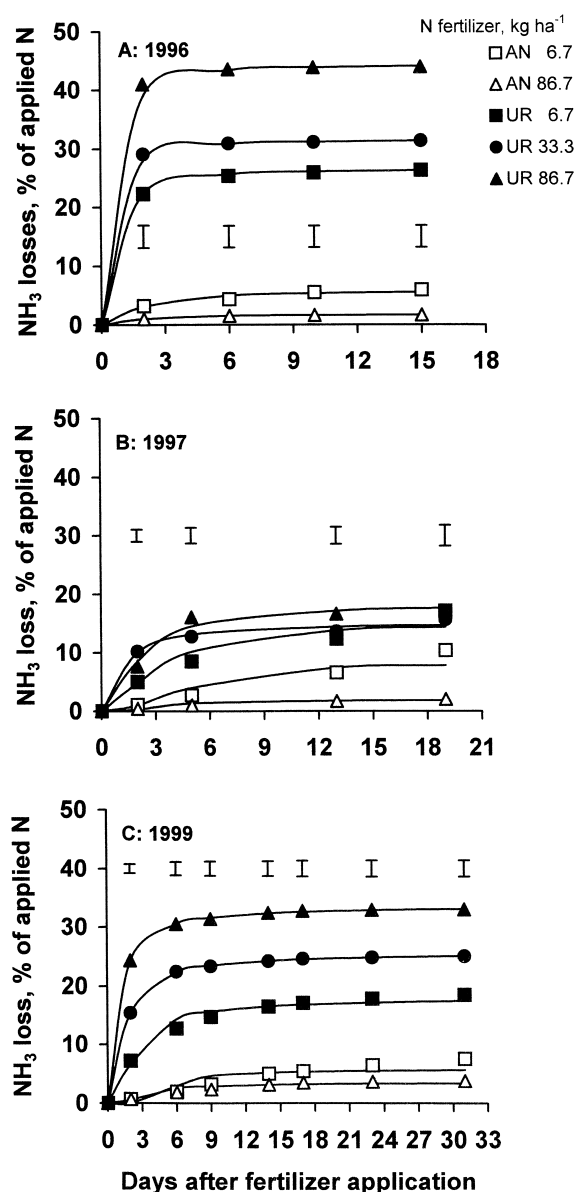


Figure 1. Cumulative NH<sub>3</sub> volatilization from surface-applied N fertilizers. Vertical bars indicate the least significance difference (LSD;  $p \leq 0.05$ ) for each time of measurement of NH<sub>3</sub> volatilization. AN: ammonium nitrate; UR: urea. Numbers following symbols refer to rates of N per application (3 per year) in kg ha<sup>-1</sup>.

weeks prior to the fertilizer application, which helped to hydrolyze the urea and thus caused high gaseous losses of NH<sub>3</sub>. In 1996 (Figure 1A), 10 mm of rain fell on the second day and caused a decrease in the rate of volatilization thereafter, since the cumulative losses tended to level off. In 1999 urea was applied to a very humid soil, but the following rain (30 mm)

occurred only 18 d later, which explains the high losses and the longer period in which they occurred (Figure 1C). On the other hand, in 1997 the soil surface was dry when the fertilizer was applied, causing a much lower rate of losses; on the sixth day, a 41-mm rain practically stopped the  $\text{NH}_3$  volatilization and the overall losses were smaller than observed for other years. Keller and Mengel (1986) observed that a 25-mm rain effectively stopped volatilization of ammonia from granular urea applied ( $168 \text{ kg N ha}^{-1}$ ) to a Mollisol 50 h after fertilization. A similar effect was reported by Ferguson et al. (1988); i.e., 28 mm rain slowed the  $\text{NH}_3$  loss from urea solution applied ( $120 \text{ kg N ha}^{-1}$ ) to a Mollisol. In this latter study, the cumulative losses of ammonia were less than 10% of applied N.

Lara-Cabezas et al. (1999), using  $^{15}\text{N}$  mass balance, estimated that the efficiency factor of a similar semi-open static chamber was lower than 1, suggesting that not all  $\text{NH}_3$  volatilized could be trapped in the chamber. Therefore, the losses estimated in the present study could be lower than the actual values.

The rates and amounts of  $\text{NH}_3$  losses depend on weather conditions, as is evident from data obtained in 1996, 1997, and 1999 (Figure 1). Although the measurements of  $\text{NH}_3$  volatilization were done in April, the results would probably apply to fertilizations carried out at other times because of high temperatures throughout the growing season and the occurrence of short time changes of weather con-

ditions. The chances of rain occurring within a 1- to 3-day interval in that region are as great in April, when  $\text{NH}_3$  volatilization was evaluated, as in the summer. Weather conditions during the first three days after fertilizer application seem to be critical for  $\text{NH}_3$  losses from soils covered with plant residues (Cantarella et al. 2001).

#### *Nitrogen leaching and soil acidification*

High N application rates resulted in high amounts of inorganic N in the soil at the 20 to 60 cm depth for both N sources (Table 2). Syvertsen and Smith (1996) found similar results in a study conducted with 4-yr-old grapefruit trees grown in lysimeters and fertilized at three N rates, in which N recovered from drainage water accounted for up to 42% of that applied.

Some of the inorganic N found in the 20–60 cm depth layer (Table 2) will be taken up by the citrus roots, although most of the rooting system is concentrated in the 0–20 cm layer. Deep soil sampling is a difficult operation and could not be done every year. Nitrate data from the beginning and the end of a growing season are available only for 1998–1999 (samplings of October 1998 and April 1999). The inorganic N, mainly nitrate, found in the 20–60 cm soil layer in the plots treated with the higher rates of fertilizer was inversely related to the amount of rain in the season preceding the sampling. At the end of the rainy season (April–May) only small amounts of N

Table 2. Inorganic nitrogen content in the 20 to 60 cm soil depth layer and rainfall in the season prior to soil sampling in groves treated with different sources and rates of N fertilizer.

Fertilizer source	Annual application rate (kg ha <sup>-1</sup> N)	Date of sampling <sup>1</sup>				
		April 1997	October 1998	April 1999	August 2000	Mean
kg ha <sup>-1</sup> (NH <sub>4</sub> <sup>+</sup> +NO <sub>3</sub> <sup>-</sup> )-N						
Urea	20	26a <sup>2</sup>	24a	23	35	27a
	100	18a	22a	18	32	23a
	180	32a	34a	24	59	37a
	260	32a	32a	24	50	35a
Ammonium nitrate	20	20a	26a	21	32	25a
	100	30a	37a	22	56	36b
	180	79b	40a	20	83	55b
	260	59b	79b	22	63	56b
Rainfall in the season preceding soil sampling <sup>3</sup> (mm)						
		Oct 96–Apr 97	May 98–Sep 98	Oct 98–Apr 99	May 00–Aug 00	
		1071	292	1483	107	

<sup>1</sup>April samples were collected on the day before the last N application of the rainy season, about 2.5 months after the previous fertilization; October or August samples were collected after the dry period, before a new cycle of N fertilization started. <sup>2</sup>Values followed by the same letter, comparing N sources with the same application rate within the columns, are not significantly different (Tukey  $p \leq 0.05$ ). <sup>3</sup>Rainy season: October–April; dry season: May–September.

were detected in 1999, a year with above-average rainfall, compared with 1997 (Table 2). At the end of the dry season (August–October) the treatments with high amounts of N applied still had some residual inorganic N, especially in the year 2000 with a dry winter, when 63 to 83 kg/ha of N had accumulated in the 20–60 cm soil depth (Table 2). This amount is liable to leaching during the following rainy season.

Greater amounts of leached N were observed with application of AN than with UR (Table 2). For example, the mean value of inorganic nitrogen found in the 20 to 60 cm layer of plots with 260 kg N ha<sup>-1</sup> applied as AN was 56 kg ha<sup>-1</sup> (NH<sub>4</sub><sup>+</sup> + NO<sub>3</sub><sup>-</sup>)-N, which was 60% more than the corresponding mean value observed for the UR treatment. These differences suggested that less nitrate was leached with UR because of greater losses of NH<sub>3</sub> by volatilization, reducing inorganic N accumulation in the soil. Paramasivam and Alva (1997) attributed the lower recovery of N in the leachate from a soil amended with urea to the gaseous losses by NH<sub>3</sub> volatilization and/or denitrification, in an experiment carried out in the laboratory to evaluate leaching of N from different N fertilizers.

High rates of nitrogen application caused acidification at the 0–20 and 20–40 cm soil depths after 5 yr of treatment (Table 3). The acidifying effect of the N fertilizations was much smaller in the 20–40 cm layer

and was negligible in the 40–60 cm layer. This acidification was related to the N rates applied but was more pronounced in the AN than in the UR treatment, although UR is considered a more acidifying fertilizer than AN (Pierre et al. 1970). The greater losses of N through NH<sub>3</sub> volatilization from UR may explain this difference between the two fertilizer sources. Soil acidification is also associated with the depletion of the basic cations due to NO<sub>3</sub><sup>-</sup> leaching (Bouman et al. 1995) which occurred in both N sources, but more so with AN. The loss of base cations decreased base saturation in the surface layer by about 20% for UR and 53% for AN when applied at the rate of 260 kg N ha<sup>-1</sup> compared with 20 kg N ha<sup>-1</sup>. He et al. (1999b) found that N fertilizer applied in a Florida Entisol with 26-yr-old white Marsh grapefruit resulted in a decrease of the soil pH (water/soil ratio, 2:1 v/w) by 0.7 to 1.7 units after 4 yr of fertilization. The marked acidifying effect of N fertilization on the Alfisol of the present study can probably be attributed to the low buffering capacity of the soil. It should be considered that all plots were limed with dolomite lime in 1998 and 1999 to minimize the effect of acidification due to the treatments with higher rates of N.

Magnesium and calcium were the cations most depleted from the upper layer following N application. About 25 to 43% less Ca and Mg were present in the 0–20 cm layer in the treatment with 260 kg N

Table 3. Results of soil chemical analysis of samples collected 5 yr after first application of different rates of nitrogen as urea or ammonium nitrate (AN).

Application rate (kg ha <sup>-1</sup> N)	pH (CaCl <sub>2</sub> )		Ca <sup>2+</sup> + Mg <sup>2+</sup> + K <sup>+</sup> (mmol <sub>c</sub> dm <sup>-3</sup> )		Soil base saturation (%)	
	Urea	AN	Urea	AN	Urea	AN
<i>Sampling depth 0–20 cm</i>						
20	5.6a <sup>1</sup>	5.8a	47b	64a	67a	77a
100	5.5a	4.9b	40a	40a	65a	51a
180	4.9a	4.4b	45a	28b	58a	38b
260	4.7a	4.1b	33a	19b	47a	24b
Rate effect <sup>2</sup>	L	L	L	L	L	L
<i>Sampling depth 20–40 cm</i>						
20	5.3a	5.6a	27a	36a	55b	68a
100	5.8a	5.3b	35a	37a	69a	64a
180	5.5a	5.1a	40a	32a	67a	59a
260	5.3a	4.8b	33a	27a	62a	48b
Rate effect	ns	L	ns	ns	ns	L
<i>Sampling depth 40–60 cm</i>						
20	5.5a	5.7a	32a	33a	65a	66a
100	5.7a	5.4a	37a	31a	67a	61a
180	5.4a	5.6a	36a	35a	63a	65a
260	5.4a	5.4a	27a	28a	57a	59a
Rate effect	ns	ns	ns	ns	ns	ns

<sup>1</sup>Values followed by the same letter, comparing N sources with the same application rate (paired values in the line), are not significantly different (Tukey  $p \leq 0.05$ ). <sup>2</sup>L and ns: linear and non-significant effect of rates of N application ( $p \leq 0.05$ ) in the column.

$\text{ha}^{-1}$  as urea compared with the plots that received only  $20 \text{ kg N ha}^{-1}$ . The corresponding losses for the plots treated with AN were around 70%. However, exchangeable K concentration decreased only 17 to 23% due to N fertilization. In the treatments with 180 and  $260 \text{ kg ha}^{-1} \text{ N}$  the concentration of Mg was below  $8 \text{ mmol}_c \text{ dm}^{-3}$ , which is considered the limit for an adequate supply for citrus production in Brazil (Quaggio et al. 1998). Even though the Ca concentration decreased substantially due to the acidifying effect of N and leaching, it did not reach limiting values. The concentration of exchangeable K remained in the range of 1.7 to  $2.4 \text{ mmol}_c \text{ dm}^{-3}$ , regardless of the N treatment, because of regular K application.

### Fruit yield

In 1997 average yields were high (around  $80 \text{ t/ha}$ ) but in 1998, with below-average rainfall in the 1997–1998 growing season, fruit yields ranged from 40 to  $46 \text{ t/ha}$ . In both years no yield response to N rates or sources was observed, probably due to the potential of soil N mineralization in the experimental area as well as to the past N fertilization of the grove, which may have resulted in high N reserves in tree biomass. Cantarella et al. (1992), in field experiments carried out under similar soil conditions in the State of São Paulo, observed that well fertilized groves may take two to three years to start responding to N rates. Dou et al. (1997) estimated the contribution of N from mineralization of leaf residues under the citrus tree canopy as 40 to  $150 \text{ kg N ha}^{-1} \text{ yr}^{-1}$ , depending on the soil type and tree age. In addition, citrus trees store large quantities of N within various plant components (Mattos 2000), which will be mobilized for tree growth and fruit yield in subsequent seasons.

Fruit yields in 2000 and 2001 showed high response ( $p < 0.05$ ) to N application (Figure 2). In 2000, maximum fruit yield ( $58 \text{ t ha}^{-1}$ ) was attained with a rate of  $150 \text{ kg N ha}^{-1}$  for both UR and AN treatments (Figure 2A) and there were no significant differences between the N sources. After the high yields of 2000, N reserves of the plants were probably depleted and responses to N fertilization were higher in 2001 (Figure 2B). Maximum fruit yields were attained with annual application of  $200 \text{ kg ha}^{-1} \text{ N}$  of AN, in agreement with the data obtained in other orange groves of São Paulo State by Cantarella et al. (1992) and Quaggio et al. (1998). Fruit yields were higher

with AN than with urea. The fertilizer efficiency index of urea, estimated for a rate of application of  $150 \text{ kg ha}^{-1} \text{ N}$ , which is frequently recommended for high yield orchards, was 75% of that of the AN.

The results obtained in this paper confirm other data from the literature on N losses by  $\text{NH}_3$  volatilization of surface-applied urea and show that this product is less effective than AN for citrus fertilization with the present soil and crop management practices. It is unlikely that farmers will mechanically incorporate N fertilizer into the soil because of the extra cost, but they may consider the use of other N sources not subject to high  $\text{NH}_3$  losses.

Urea is the most widely used granular N fertilizer for citrus in Brazil because of greater market availability. Production of AN in Brazil is limited and increasing safety restrictions on this fertilizer make it unlikely that this will change. The 20 to 30% lower price of urea per unit N compared with AN may partially or totally compensate for the  $\text{NH}_3$  volatilization losses, but farmers feel uneasy about a fertilizer prone to high losses. As  $\text{NH}_3$  losses increase with an

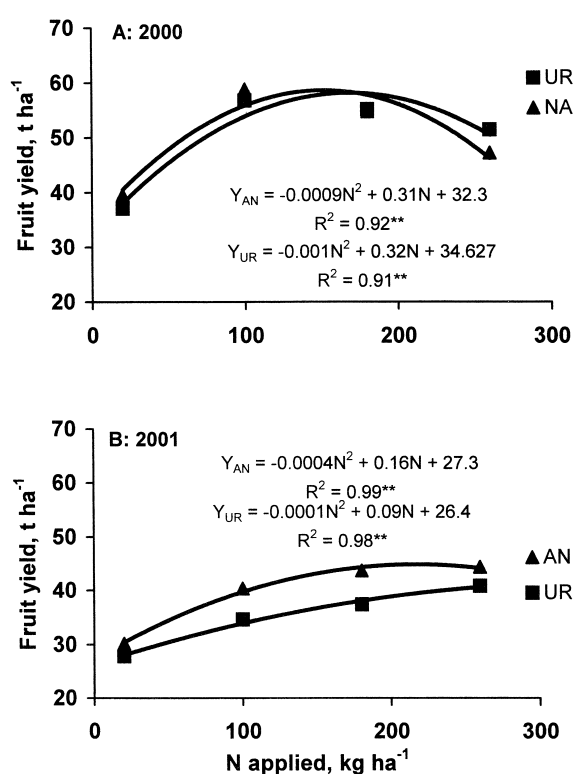


Figure 2. Fruit yield response of Valencia orange to rates of N fertilizer applied as urea (UR) or ammonium nitrate (AN). Data from harvests of year 2000 (A) and 2001 (B).

increase in the rate of fertilizer application, the use of lower rates of urea and a larger number of split applications may provide an alternative way of improving urea-N efficiency.

## Conclusions

Losses of N following application of dry granular fertilizers on the soil surface without incorporation in citrus groves are important in magnitude. Ammonia volatilization accounted for up to 44% of applied N as urea at 86.7 kg N ha<sup>-1</sup>. Since less N was lost from ammonium nitrate, it may be a preferred N source for broadcast application when NH<sub>3</sub> volatilization is a concern, or alternatively more frequent application of urea in small amounts may prove to be a better practice.

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