Nitrogen fertilizer leaching in an Oxisol cultivated with sugarcane

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ABSTRACT: Nitrogen (N) leaching below the crop-rooting zone represents not only a valuable loss of nutrients for the plant, but also a potential pollution source of groundwater. The objective of this work was to quantify leaching losses of native N and that derived from fertilizer in an Oxisol that was cultivated with sugarcane (*Saccharum officinarum*) during the crop plant cycle. The sugarcane was planted and fertilized with urea in the planting furrow, with 120 kg ha^{-1} of N. In order to determine the fate of the fertilizer - N, four microplots with ^{15}N enriched fertilizer were installed. Input and output of N at the depth of 0.9 m were quantified from the flux density of water and the N concentration in soil solution. During the evaluation period the rainfall was 141 mm less than the historical average (1,315 mm), and the climate was drier than normal in January. The average concentration of mineral N in soil solution was 1.8 mg L^{-1}. The abundance of ^{15}N was very high at the beginning (first week) of the assessment period and remained approximately constant (0.453 atom% of ^{15}N) until the end of the period. The internal drainage was 91 mm of water and the N leaching loss was 1.1 kg ha^{-1} of N, with only 54 g ha^{-1} derived from fertilizer. Therefore, under high demand of N by the crop in a system without burning before planting, the leaching of N was not considerable, mainly because the surplus of water between the months of December and March was lower than expected and also because the extraction of nitrogen by the crop was high.
Key words: *Saccharum* spp., sustainability, solute transport, environmental quality, pollution

Nitrogênio lixiviado num Latossolo cultivado com cana-de-açúcar

RESUMO: A lixiviação de nitrogênio (N) abaixo da zona radicular representa uma valiosa perda do nutriente para as plantas e uma fonte potencial de poluição do lençol freático. Quantificaram-se as perdas de N por lixiviação num Latossolo Vermelho Amarelo cultivado com cana-de-açúcar (*Saccharum officinarum*) durante o ciclo agrícola de cana-planta. A cultura foi implantada e fertilizada no sulco com 120 kg ha^{-1} de N-uréia. Para conhecer o destino do fertilizante, foram instaladas quatro microparcelas onde o fertilizante era marcado com o isótopo ^{15}N. As entradas e saídas de N a 0,9 m de profundidade foram quantificadas diariamente pela densidade de fluxo de água e a concentração de N da solução no solo. No período de avaliação, a precipitação pluvial foi 141 mm menor que a média histórica (1.315 mm) sendo janeiro mais seco que o normal. A concentração de N mineral média foi 1,8 mg L^{-1}. A abundância de ^{15}N foi superior à abundância natural do isótopo, especialmente no início do período de avaliação, permanecendo logo constante (0,453% de ^{15}N). A drenagem interna foi de 91 mm de água e a perda por lixiviação foi 1,1 kg ha^{-1} de N com apenas 54 g ha^{-1} derivados do fertilizante. Portanto, com elevada demanda de nutrientes e elevada incorporação de restos culturais, não foram registradas perdas apreciáveis de N por lixiviação devido ao fato de o excedente de água entre os meses de dezembro e março ter sido menor que o esperado e pela elevada extração de N pela cana-de-açúcar.
Palavras-chave: *Saccharum* spp., sustentabilidade, transporte de solutos, qualidade ambiental, poluição

Introduction

Since the initiation of the Proalcohol program in Brazil in 1975, sugarcane (*Saccharum officinarum*) for producing ethanol for fuel has increased in cultivated area and productivity, mainly in the São Paulo State. The expansion of ethanol production from sugarcane generates discussions about social and environmental issues (Goldemberg et al., 2008; Hartemink, 2008; Uriarte et al., 2009), with emphasis in the agricultural sector on the use of management systems that avoid negative impacts on soil, water and biodiversity (Goldemberg et al., 2008; Hartemink, 2008; Martinelli and Filoso, 2008).

Under this context, fertilization with nitrogen (N) should be carefully assessed for sustainability because high N use efficiency is directly related to lower risk of groundwater and air pollution, smaller losses of nutrients by leaching and lower risk of soil acidification, besides the direct benefits of increased sugarcane productivity and decreased production costs. One of the main problems with nitrogen fertilization in sugarcane is the low N recovery by the crop (Hartemink, 2008), between 10 to 40% as measured in the field using ^{15}N tracer isotope (Chapman et al., 1994; Trivelin et al., 1995; Vallis et al., 1996). Thus, the portion of N not used by the crop may remain in the soil, be incorporated as organic matter, be lost to the atmosphere or leach below the root zone where crops effectively extract water and nutrients.

In São Paulo State, there are few studies on N leaching by means of direct monitoring in the field, especially with doses higher than normally used during the sugarcane crop plant cycle (30 to 90 kg ha^{-1} of N, Cantarella et al., 2007). We hypothesize that doses of N higher than those normally used will originate leaching of N. Considering that this is important to find explanatory variables for predicting or explaining N leaching, and to generate information that allows the planning of sustainable crop management practices, the objective of this study was to quantify the leaching loss of native nitrogen and that derived from fertilizer in an Oxisol of the State of São Paulo (Brazil) cultivated with sugarcane during the agricultural cycle of the crop plant.

Material and Methods

The experiment was carried out near Pirassununga, state of São Paulo, Brazil (21°55' S, 47°10' W, 650 m a.s.l.). The climate, according to the Köeppen classification, is of the Aw type: tropical of savanna. Based on 30 years of meteorological data from the location, the annual average temperature is 21.7°C and the annual average rainfall is 1,343 mm, with higher frequency between December and March (840 mm) (Sentelhas et al., 2008). By using the climatological water balance method of Thornthwaite and Mather (1955), rainfall exceeds potential evapotranspiration between December and March, producing a water excess of 381 mm. The soil is a Typic Eutrustox (Table 1 and 2) of sandy clay loam texture, with a water table over the depth of 10 m. The methodology used in this study was similar to that presented by Ghiberto et al. (2009).

Before sugarcane planting, 2 t ha^{-1} of dolomite limestone was applied over the entire experimental area. Then, the sugarcane (variety SP81-3250) was planted and fertilized with urea (120 kg ha^{-1} of N) in the planting furrow between February 21 and 24, 2005. In addition, 120

Table 1 – Chemical attributes of the soil.

Soil Horizon	Depth	pH			P	K	Ca	Mg	Al	H + Al	CEC
		H_2O	KCl	ΔpH							
	m				mg kg^{-1}	---------- mmol$_c$ kg^{-1} ----------					
A_p	0.20	7.2	6.2	-1	10	1.9	43	11	0	8	63.9
BA	0.44	6.5	6.1	-0.4	1	2.6	7	3	0	11	23.6
B_{w1}	0.81	6.9	6.2	-0.7	2	2.5	11	4	0	10	27.5
B_{w2}	0.81+	6.4	6.1	-0.3	1	1.8	18	7	0	11	37.8

pH_{H_2O}: pH in water, ratio 1:2.5; pH_{KCl}: pH in 1 M KCl ratio 1:2.5; $\Delta pH = pH_{KCl} - pH_{H2O}$; P: extraction by ionic exchanger resin and determination by colorimetry; K and Na: extraction by Mehlich1 solution and determination by flame photometry; Ca, Mg: extraction by ion exchanger resin and determination by spectrometry of atomic absorption; H+Al: determination by 0.5 M calcium acetate pH=7; Cation exchange capacity: CEC = Na + K + Ca + Mg + Al.

Table 2 – Particle size distribution, bulk density (ρ_b), particle density (ρ_p) and total porosity (TP) of the soil.

Depth	Particle size distribution			ρ_b	ρ_p	TP
	Sand	Silt	Clay			
m	---------- g kg^{-1} ----------			---------- kg m^{-3} ----------		%
0.1	733	52	215	1609	2681	40.0
0.2	720	60	220	1688	2673	36.7
0.3	705	55	240	1681	2682	37.3
0.4	678	77	245	1532	2685	43.0
0.5	695	50	255	1528	2693	43.3
0.6	658	73	270	1451	2694	46.1
0.7	673	48	280	1407	2692	55.6
0.8	635	80	285	1392	2694	48.3
0.9	675	40	285	1427	2695	47.1
1.0	635	78	288	1298	2695	51.8

Particle size distribution: pipette method; ρ_b: undisturbed soil samples in 0.05 × 0.05 m cores; ρ_p: helium pycnometer; TP= $(1-\rho_b/\rho_p)$.

kg ha^{-1} of K_2O and P_2O_5 with the sources potassium chloride (KCl) and triple superphosphate, respectively, were also applied. To determine the fate of the N-fertilizer, four microplots were installed. They consisted of 2.0 m of planting line, i.e., 2.0 m × 1.5 m since the spacing between the rows is 1.5 m (Trivelin et al., 1994), in which nitrogen fertilizer enriched to 5.04 ^{15}N At% was applied.

Input and output of N ions, at the 0.9 m depth, were evaluated from the flux densities of water and the ion concentrations; tensiometers, the soil water retention curve and soil solution extractors with porous cups were used for this purpose. The equipment was installed in the field at the end of August 2005, just after leveling of the soil between plant rows. Because it was not possible to install the equipments before leveling the soil between plant rows, there was the delay between fertilization and beginning of the measurements. For this it was assumed that the release of N was low because of the high incorporation of crop residues with a C/N of around 100, which facilitates the immobilization process (Oliveira et al., 1999). On other hand, near the town of Pirassununga, in the period without measurements, the climatological water balance is negative, which means that there is no surplus water to drain and transport solutes below the root-zone.

One tensiometer was installed at each of the depths of 0.8, 0.9 and 1.0 m, and a solution extractor was installed at the depth of 0.9 m in each microplot. The 0.9 m depth was adopted because in this region, most sugarcane root biomass is found close to the soil surface; in fact, 80% occurs within the top 0.6 m (Ball-Coelho et al., 1992; Smith et al., 2005). Ion movement was measured by integrating the daily ion flux density over the time period, as indicated in equation (1) for NO_3^-:

$$q_{NO_3^-} = \int_{t_0}^{t_f} q_w C_{NO_3^-} \, dt \qquad (1)$$

where $q_{NO_3^-}$ (kg ha^{-1}) is the flow of nitrate in the soil, q_w is the soil water flux density (m d^{-1}), and $C_{NO_3^-}$ is the concentration of nitrate in the soil solution (kg L^{-1}) at the moment of measurement. t_0 and t_f represent the initial time (equipment installation) and final time (harvest) of the experiment. The same procedure was carried out to estimate the flow of NO_2^- and NH_4^+.

The soil water flux density at the depth of 0.9 m was estimated from August/2005 (installation of equipment) until June/2006 (sugarcane harvest) using the Darcy-Buckingham equation (equation 2):

$$\theta_w = -K(\theta)\Delta(\psi_t)/L \qquad (2)$$

where K(θ) is the soil hydraulic conductivity (m d^{-1}) as a function of the volumetric water content (θ), or K(θ) function, and $\Delta\psi_t/L$ is the soil water total potential gradient, both at the depth of 0.9 m.

The volumetric soil water content, used to estimate K during the experiment, was obtained from daily readings of the tensiometers and the soil water retention curve at the depth of 0.9 m. The gradient (Dy_t/L) at the depth of 0.9 m was calculated by finite difference from daily readings of tensiometers at the depths of 0.8 m and 1.0 m. The K(θ) function was determined by the instantaneous profile method (Hillel et al., 1972) by means of equation (3):

$$K(\theta) = K_0 \exp\gamma\,(\theta - \theta_0) \qquad (3)$$

in which K_o = 443.3 mm d^{-1} (at time zero of soil water redistribution); γ = 52.232 and θ_o = 0.366 m^3 m^{-3} (at time zero of soil water redistribution).

Soil bulk density (r_b) was determined at depths of 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9 and 1.0 m using an Uhland sampler. Three soil cores (diameter of 0.05 m and height of 0.05 m) were taken per depth. The soil water retention curve at the 0.9 m depth was determined for the matric potentials -0.5, -1, -3, -5, -7 and -10 kPa by using porous plate funnels and, for -30, -50, 70 and -100 kPa, in Richard's pressure cells. Three soil cores were saturated and equilibrated at each potential, and then the gravimetric and volumetric soil water content was calculated using the soil bulk density. Finally, the data were adjusted to equation (4) (van Genuchten, 1980):

$$\theta = \theta_r + (\theta_s - \theta_r)\,[1 + (a|\,\psi_m|)^n]^{-m} \qquad (4)$$

where θ_s = 0.455 m^3 m^{-3} is the saturated soil water content; θ_r = 0.126 m^3 m^{-3} is the soil residual water content; α = 0.542 kPa, n = 5.0463 and m = 0.1668 are adjustment parameters; and y_m is the matric potential.

The solution taken from the soil was filtered (millipore cellulose filter paper 0.45 μm) and the concentration of the ions NH_4^+, NO_3^- and NO_2^- determined by ion chromatography (DIONEX ICS-90). The ^{15}N analyses to quantify the N in the soil solution derived from fertilizer were made by means of a mass spectrometer (ANCA-GSL by Secon). However, composite samples from each extractor were used in sequence to obtain reliable measurements on the mass spectrometer when the total mineral N content in the sample was less than 150 to 250 mg N. Thereafter, each sample was concentrated by distillation in alkaline medium with Devarda alloy (Cantarella and Trivelin, 2001). The percentage of nitrogen in the soil solution derived from the fertilizer (%NSSDF) was calculated by equation (5), adapted from Hauck et al. (1994):

$$\%NSSDF = [(Atom\%_{solution} - Atom\%_{soil})/(Atom\%_{fertilizer} - Atom\%_{soil})] \times 100 \qquad (5)$$

where Atom% is the ^{15}N abundance of the fertilizer (5.04%) and of the soil (0.367%).

The soil water storage (H) was determined by the gravimetric method in each replicate by sampling of the following soil layers: 0 - 0.15, 0.15 - 0.25, 0.25 - 0.35, 0.35 - 0.45, 0.45 - 0.55, 0.55 - 0.65, 0.65 - 0.75, 0.75 - 0.85, 0.85 - 0.95 and 0.95 - 1.05 m, approximately every 20 d. Each sample was placed in an aluminum can, hermetically sealed, and transported to the laboratory, where the gravimetric and volumetric soil water contents were determined using the soil bulk density of each depth and then calculating the soil water storage (Gardner, 1986).

Daily rainfalls were measured by means of a pluviometer installed at the experiment site and compared to the historical series of Pirassununga between 1939 and 2004, obtained from the pluviometric database of the State of São Paulo.

Results and Discussion

Rainfall between September 1, 2005 and May 31, 2006 amounted to 1,174 mm, which is 141 mm less than the historical average over the same period (1,315 mm) (Table 3). Even though January is the rainiest month of the year, rainfall was recorded to be 71 mm less than normal. On the other hand, February exceeded the average by 103 mm. According to Tollner (2002), the return period of an equal or greater event for February is seven years. The rainfall distribution was similar to the historical average in the remaining months of monitoring.

From December 5, 2005 to December 22, 2005, the soil water storage down to a depth of 0.9 m increased by 48 mm following an increase in the rainfall of 116 mm (Figure 1). After this period, the soil profile had a volumetric soil water content around the field capacity (FC) until January 10, 2006 (FC= 0.237 m^3 m^{-3} for ψ_m= -10 kPa). Next, during the phenological phase of maximum growth of sugarcane (Franco 2008), with high water demand by the crop and coinciding with a period of low precipitation, the soil water storage decreased (January, Table 3 and Figure 1). Then, with atypical rainfalls in late February, the storage of water was elevated in the period of February 21, 2006 to April 12, 2006.

The evolution of the volumetric soil water content at 0.9 m depth was similar to the storage of water in the soil profile during the monitoring period (Figure 1). The volumetric water content (θ), inferred from the tensiometer readings, was less than 0.15 m^3 m^{-3} from the beginning of the experiment to December 24, 2005. After that, there was an increase in θ, with the maximum value of 0.278 m^3 m^{-3} at January 5, 2006. According to the results, θ never reached saturation (θ_s = 0.455 m^3 m^{-3}, adjustment parameter of equation 4) or θ_o (parameter of the K(θ) function of equation 3), but exceeded in three circumstances the field capacity at the depth of 0.9 m.

It was possible to extract the soil solution only in the period between December 26, 2005 and April 28, 2006, when the soil water matric potential was higher than -40 kPa. The mean mineral N concentration during the experiment was 1.8 mg L^{-1} with a standard deviation of 2.2. At the beginning of the extraction period, the N concentration was higher than in the later period (Figure 2). The At% of ^{15}N was higher than the natural abundance of the isotope (0.367 At% of ^{15}N) from the beginning of the evaluation period, decreasing subsequently and remaining almost constant (0.453 At% of ^{15}N) from December 28, 2005 to February 15, 2006 (Figure 2).

Coinciding with the rain periods 3, 5 and 7, the volumetric soil water content exceeded field capacity and

Table 3 – Monthly average rainfall in Pirassununga in the period 1939-2004 and during the months of the experiment.

Year	Monthly rainfall distribution (mm)								
	Sep.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May
2005/2006	61	121	153	230	244	217	166	69	54
65 yr average	56	79	56	233	173	320	202	53	3

Table 4 – Rainfall, drained water and nitrogen flow in the soil at various periods; positive numbers indicate gains and negative numbers indicate losses of water and nitrogen at the depth of 0.9 m.

Period		Rainfall	Drainage	N leaching†				
N°	Date			N-TOTAL	N-NO_2-	N-NO_3-	N-NH_4+	^{15}N-Fert.
		mm		---------- kg ha^{-1} ----------				
1	08/24 - 11/30	191	0.1 (0.7)	0.0 (0.0)	0.000	0.014	0.001	0.004
2	12/01 - 12/14	61	-0.1 (0.0)	0.0 (0.0)	0.000	-0.006	-0.001	-0.002
3	12/15 - 01/08	326	-22.3 (11.4)	-0.4 (0.4)	-0.010	-0.226	-0.155	-0.043
4	01/09 - 01/31	19	-0.9 (1.1)	0.0 (0.0)	0.000	-0.001	-0.006	0.000
5	02/01 - 02/20	297	-49.4 (32.4)	-0.6 (0.3)	-0.087	-0.162	-0.354	-0.010
6	02/21 - 03/18	92	-4.1 (1.1)	0.0 (0.0)	-0.005	-0.007	-0.035	-0.001
7	03/19 - 03/29	131	-9.6 (12.2)	-0.1 (0.0)	-0.011	-0.023	-0.028	-0.001
8	03/30 - 05/31	58	-4.7 (2.0)	0.0 (0.0)	-0.010	-0.011	-0.027	-0.001
Total		1175	-91.0 (60.9)	-1.1 (0.7)	-0.123	-0.422	-0.605	-0.054

The numbers shown for each period represent the average of four repetitions, and the respective standard deviations. The number shown as the total of the cycle is the sum of each period and the respective standard deviation propagated. (†) In the experiment: 120 kg ha^{-1} of N; 120 kg ha^{-1} of K_2O and P_2O_5; and 2 t ha^{-1} of dolomite limestone were applied.

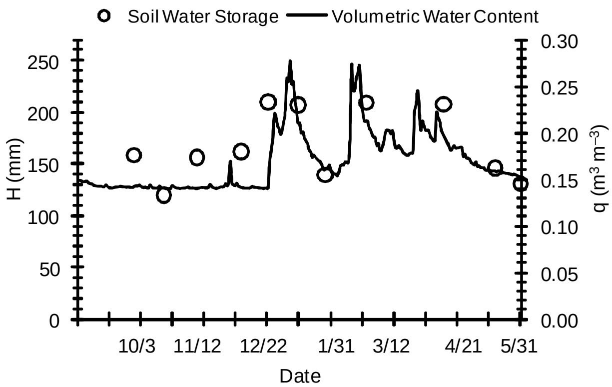

Figure 1 – Evolution of the volumetric water content (θ), average of four repetitions (full line) at 0.9 m of depth, and soil water storage (H) until 0.9 m depth during the months of monitoring.

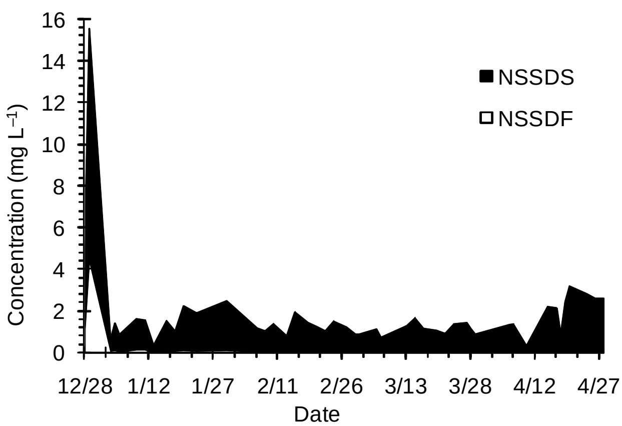

Figure 2 – Concentration of nitrogen in the soil solution derived from soil (NSSDS) and N derived from fertilizer (NSSDF) during the months of monitoring.

there was an increase of the water flux at the 0.9 m depth (Table 4). In the other periods, internal drainage was lower because θ was smaller than 0.236 m^3 m^{-3} (Figure 1), which corresponded to a K of 0.5 mm d^{-1} (equation 3). On average, 91 mm were drained during all cycles, which was 290 mm less than the surplus of 381 mm calculated by the climatological water balance method of Thornthwaite and Mather (1955), as described by Sentelhas et al. (2008). The capillary rise throughout the cycle was very low, about 1 mm (Brito et al., 2009).

Leaching N losses occurred mainly during periods 3 and 5 (Table 4), when the drainage was higher (Figure 3). The total amount of N loss was 1.1 kg ha^{-1}, of which 37% was as N-NO_3^-, 11% as N-NO_2^- and 52% as N-NH_4^+. From the analysis of the ^{15}N isotope in the soil solution, only 54 g ha^{-1} of nitrogen from the applied fertilizer (120 kg ha^{-1}) was leached during the crop plant cycle.

The amount of leached N, both native and derived from fertilizer, was low, as observed in other studies with sugarcane (Ng Kee Kwong and Deville, 1984; Southwick et al., 1995). In field studies, Oliveira et al. (2000) did not find substantial amounts of N leached at 1.0 m depth in a Rodic Kandiudalf. In this case, a smaller

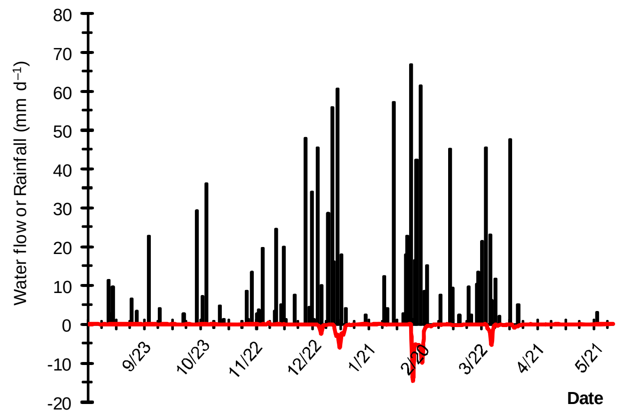

Figure 3 – Daily rainfall (bars) and water flow during the studied period (full line). Positive numbers indicate gain and negative numbers indicate loss of water in the system.

dose of fertilizer N was used (63 kg ha^{-1} de N–$(NH_4)_2SO_4$) and crop N use efficiency (60%) was higher than the 10 to 40% recovery usually registered in other experiments (Chapman et al., 1994; Trivelin et al., 1995; Vallis et al., 1996). Using containers of 220 L, with the root system confined to an unrepresentative volume, Trivelin et al. (2002) and Oliveira et al. (2002) showed that the total amount of leached N was 4.5 kg ha^{-1} (none of which was from the urea fertilizer), 53% of which occurred in the first three weeks due to poor development of the sugarcane root system and higher rainfall in that period.

Although the observed leaching losses were low, other studies using tensiometers and soil solution extractors with porous cups between 0.8 and 1.20 m soil depths, with doses higher than 100 kg ha^{-1} of N, have registered leaching losses between 15 and 21 kg ha^{-1} in a Typic Hapludox cultivated with corn (Fernandes et al., 2006), 15 kg ha^{-1} in an Oxic Paleudalf cultivated with bean (Meirelles et al., 1980) and a maximum of 76 kg ha^{-1} of N in a Typic Hapludox in the second ratoon of sugarcane (Oliveira et al., 2001). In all cases mentioned the water drained was greater than 200 mm, in contrast with this work (91 mm). All these studies were performed in the State of São Paulo (Brazil) with similar climatological water balances to that of the Pirassununga, showing that leaching losses could be higher if the conditions are favorable.

The N concentration at 0.9 m depth was lower than 10 mg L^{-1}, the maximum limit for human consumption, in contrast to the findings of Oliveira et al. (2001), who detected water quality alteration with an increase of the mean soil solution concentration at 0.9 m depth from 0.74 to 14.58 mg L^{-1} when 0 and 120 kg ha^{-1} of fertilizer N was applied to sugarcane. The concentration of N in the soil solution at 0.9 m depth was one of the causes of low loss by leaching.

Individual events of high precipitation (Figure 3), when the soil profile was close to field capacity (Figure 1), caused the higher values of drainage in the cycle (around 19 mm d^{-1}). In consequence, N could easily be lost since N was available in the soil, especially considering the predominance of negative charges in the soil with low capacity of nitrate adsorption (see ΔpH in Table 1). Ghiberto et al. (2009) applied 120 kg ha^{-1} as labeled ^{15}N urea to a sandy-clay-loam Arenic Kandiustults cultivated with sugarcane in a crop plant cycle, and measured leaching losses at 0.9 m using tensiometers and soil solution extractors with porous cups. Ghiberto et al. (2009) found that 18 kg ha^{-1} of N were leached, mainly as nitrate, and that only 25 g ha^{-1} was derived from the fertilizer. The soils of both experiments have similar textural class, hydraulic properties and millable stalk production; the main difference was the amount and distribution of rainfall during the period in which the surplus, calculated by the climatological water balance, normally takes place (December-March). In this study, compared to the experiment of Ghiberto et al. (2009), 115 mm less was drained and the month of January was drier than normal, as mentioned in the results.

The production of millable stalks was 141 t ha^{-1} (26% of dry matter). The amount of N uptake by the crop (167 kg ha^{-1}) was greater than the amount applied by fertilization (120 kg ha^{-1}). So, the high demand of N may restrict the leaching of N. The crop N uptake was distributed as follows: 46% in stalks, 15% in dry leaves, 22% in shoots, 7% in roots and 10% in rhizomes. The N recovered from the fertilizer by the crop was 25.4 kg ha^{-1} in the whole plant, representing 21% of the applied fertilizer (Franco et al., 2008). In this experiment, at the end of the crop cycle, sugarcane residue was not burnt before harvest and it is estimated that 90 kg ha^{-1} of N remained in the field; this could be used in the subsequent first ratoon.

Leaching increases markedly when the nitrogen application rate is higher than that recommended for the crop (Thorburn et al., 2003). However, the soil N balance was negative when ignoring N input to the system arising from rainfall and biological fixation. In Brazil, the recommended N doses in sugarcane crops are not as high as those used in other countries such as Australia (150-250 kg ha^{-1}) (Gourley and Ridley, 2005; Stewart et al., 2006). Thus, it appears that an increase in crop N use efficiency is beneficial, not only from the environmental point of view, but also due to the reduction of costs by reduced use of nitrogen fertilizer (Chapman et al., 1994).

In periods in which the water flow and leaching were greater, sugarcane was at the phenological stage of maximum growth with high demand for water and nutrients, thus contributing to avoid excessive loss of N. Based on data of Franco et al. (2008) estimated that for periods 3 and 5 (Table 4), the sugarcane accumulated 5,047 and 4,461 kg ha^{-1} of dry matter, respectively. According to Brito et al. (2009), the average actual evapotranspiration was 11 and 8 mm d^{-1}, respectively, showing that the demand for N and water was high. Similarly, Stewart et al. (2006) used the simulation model APSIM-SWIM to show that of the 29.5 kg ha^{-1} of N-NO_3 transported by drainage, the plants absorbed 26.6 kg ha^{-1} of N from the soil below the depth of 1.5 m at the end of the cycle. It was concluded that the net amount of N lost by leaching into the water table was 2.9 kg ha^{-1} N-NO_3.

The N uptake by the crop was mainly native; however, the low fertilizer-N recovery (21%) by the whole plant (Franco et al., 2008) was not caused by higher N leaching losses. Since volatilization was prevented at planting by incorporation of urea (Chapman et al., 1994; Franco et al., 2008; Trivelin et al., 2002), we hypothesize that the fertilizer N was immobilized in the soil organic pool at the same time that soil organic N was mineralized (Jansson and Persson, 1982). Furthermore, the high C/N ratio (80-120) of the residue results in an initial immobilization of soil mineral N and provision of little N available for crop uptake in the year after deposition (Thorburn et al., 2005), reinforcing the idea. This is especially important in sugarcane systems without straw burning where immobilization takes place (Basanta et al., 2003; Meier et al., 2006; Wood, 1991), and supports the conclusion of interference in biological N immobilization having an effect on the downward movement of fertilizer N (Ng Kee Kwong and Deville, 1987). There are few studies about leaching in this condition and in 2007 in the State of São Paulo, 40% of the harvest took place without burning (Goldemberg et al., 2008). In other studies, despite the low N leaching losses, significant amounts of K, Ca and Mg should have leached, which may result in soil acidification (Cahn et al., 1993; Ghiberto et al., 2009; Ng Kee Kwong and Deville, 1984; Oliveira et al., 2002). This is important if we consider that acidification is reversible by liming, but when it takes place in the subsoil, amelioration is much more difficult and expensive (Hartemink, 2008).

Conclusion

During the agricultural cycle of the crop plant, the leaching of N was not considerable, mainly because the surplus of water between the months of December and March was lower than expected; the high demand of N by the crop; and the analyzed cropping system did not include straw burning before planting.

Acknowledgements

To the financial support by FAPESP and CAPES, to the logistical support of the São Luiz Mill, and to the support of the laboratory analyses by the technicians at the Laboratory of Stable Isotopes at CENA.

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Received October 29, 2009
Accepted July 16, 2010