FERTILIZER ^{15}N BALANCE IN A COFFEE CROPPING SYSTEM: A CASE STUDY IN BRAZIL[1]

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SUMMARY

Knowledge about the fate of fertilizer nitrogen in agricultural systems is essential for the improvement of management practices in order to maximize nitrogen (N) recovery by the crop and reduce N losses from the system to a minimum. This study involves fertilizer management practices using the ^{15}N isotope label applied in a single rate to determine the fertilizer-N balance in a particular soil-coffee-atmosphere system and to deepen the understanding of N plant dynamics. Five replicates consisting of plots of about 120 plants each were randomly defined within a 0.2 ha coffee plantation planted in 2001, in Piracicaba, SP, Brazil. Nine plants of each plot were separated in sub-plots for the ^{15}N balance studies and treated with N rates of 280 and 350 kg ha^{-1} during 2003/2004 and 2004/2005, respectively, both of them as ammonium sulfate enriched to a ^{15}N abundance of 2.072 atom %. Plant shoots were considered as separate parts: the orthotropic central branch, productive branches, leaves of productive branches, vegetative branches, leaves of vegetative branches and fruit. Litter, consisting of dead leaves accumulated below the plant canopy, was measured by the difference between leaves at harvest and at the beginning of the following flowering. Roots and soil were sampled down to a depth of 1.0 at intervals of 0.2 m. Samples from the isotopic sub-plots were used to evaluate total N and ^{15}N, and plants outside sub-plots were used to evaluate dry matter. Volatilization losses of NH_3 were estimated using

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special collectors. Leaching of fertilizer-N was estimated from deep drainage water fluxes and ^{15}N concentrations of the soil solution at 1 m soil depth. At the end of the 2-year evaluation, the recovery of ^{15}N applied as ammonium sulfate was 19.1 % in aerial plant parts, 9.4 % in the roots, 23.8 % in the litter, 26.3 % in the fruit and 12.6 % remaining in the 0–1.0 m soil profile. Annual leaching and volatilization losses were very small (2.0 % and 0.9 %, respectively). After two years, only 6.2 % N were missing in the balance (100 %) which can be attributed to other non-estimated compartments and experimental errors. Results show that an enrichment of only 2 % atom ^{15}N allows the study of the partition of fertilizer-N in a perennial crop such as coffee during a period of two years.

Index terms: coffee crop, nitrogen uptake, N dynamics, ^{15}N tracer studies, stable isotope.

RESUMO: *BALANÇO DO ^{15}N DO FERTILIZANTE EM UMA CULTURA DE CA*FÉ: UM ESTUDO DE CASO NO BRASIL

A caracterização do destino do ^{15}N do fertilizante é uma ferramenta essencial para a melhoria de práticas de manejo de fertilizante que visam à maximização de sua recuperação pela cultura e para redução de perdas de nitrogênio (N) para fora do sistema a um mínimo. Este estudo envolveu práticas de manejo usando o ^{15}N como traçador, aplicado em uma só taxa, para determinação do balanço do N do fertilizante em um sistema particular de solo-café-atmosfera e melhor compreender a dinâmica desse elemento dentro da planta. Cinco repetições, constituídas de parcelas de cerca de 120 plantas, foram casualmente definidas dentro de um cafezal em Piracicaba, SP, Brasil. Em cada parcela, nove plantas constituíram subparcelas para os estudos de balanço de ^{15}N, onde receberam 280 kg ha^{-1} de N em 2003/2004 e 350 kg ha^{-1} em 2004/2005, ambas as adubações feitas com sulfato de amônio enriquecido com ^{15}N, em uma abundância de 2,072 átomos %. A parte aérea das plantas foi separada em caule central ortotrópico, ramos produtivos, folhas de ramos produtivos, ramos vegetativos, folhas de ramos vegetativos e frutos. A serrapilheira, constituída de folhas mortas acumuladas abaixo do dossel, foi medida por meio da diferença entre as folhas na colheita e as folhas no início da próxima floração. Raízes e solo foram amostrados em camadas de 0,20 m, até a profundidade de 1,0 m. As amostras das subparcelas isotópicas foram utilizadas para determinar a concentração de N total e a abundância em ^{15}N, e plantas fora delas foram usadas para estimar a matéria seca. Perdas de NH_3 por volatilização foram estimadas por meio de coletores especiais. A lixiviação de N do fertilizante foi estimada pela medida de fluxos de água na profundidade de 1,0 m e a coleta de solução do solo para avaliação da concentração de N mineral e ^{15}N. Depois de dois anos de medidas, verificou-se que a recuperação do N do sulfato de amônio foi de 19,1 % pela parte aérea; 9,4 % pelas raízes; 23,8 % pela serrapilheira; e 26,3 % pelos frutos (exportação), restando 12,6 % no solo da camada de 0–1,0 m. As perdas por volatilização e lixiviação foram muito pequenas, representando 2,0 e 0,9 %, respectivamente. Para fechar o balanço em 100 % após dois anos, faltaram apenas 6,2 %, o que pode ser atribuído a N em outros compartimentos não medidos e erros experimentais. Os resultados mostram que um enriquecimento em ^{15}N de apenas 2 % permitiu o estudo do destino do N do fertilizante em uma cultura perene, como a do café, por um período de dois anos.

Termos de indexação: cultura de café, absorção de nitrogênio, dinâmica de N, estudos com traçador ^{15}N, isótopo estável.

INTRODUCTION

Coffee, cultivated in more than 50 countries and on several continents, is worldwide an important agribusiness. Brazil, Colombia and Vietnam are responsible for more than half of the total global coffee production. In Brazil, coffee is the most important cash crop, grown on an area of about 3 million hectares with an annual production of 2 million tons of coffee beans worth 700 million US dollars (FNP, 2004).

After potassium (K), nitrogen (N) is the nutrient most required by coffee plants, since it is a constituent of protein molecules, enzymes, co-enzymes, nucleic acids and cytochromes, as well as part of the chlorophyll molecule. It is responsible for substantial yield increases in coffee. Because of the abundant N

translocation to the fruit, large amounts of the element are exported from cultivated fields with each coffee bean harvest (Catani & Moraes, 1958; Malavolta, 1993). Although the lack of any nutrient affects the normal crop development, the lack of N is most restrictive for coffee growth and yield (Rena & Maestri, 1987). Miss-management of N fertilization is characterized by the inadequately timed application of either too low or too high fertilizer rates, contributing to high N losses from the system due to low plant uptake at the time of application (Prado & Nascimento, 2003).

Meirelles et al. (1980) points to the fact that N dynamics in soils of humid tropical regions is characterized by great mobility and high organic matter mineralization rates due to the predominantly high temperatures. These and other aspects, including the cost of N-fertilizers, make an efficient N management fundamental for successful agriculture. It is therefore essential to understand the processes and interactions underlying the soil-plant-atmosphere system to be able to maximize plant uptake of fertilizer N.

When N-fertilizer is applied to crops in the most distinct agricultural systems, plants rarely recover more than 50 % of the fertilizer-N. Some of it remains in the soil or is immobilized in the litter. The rest is lost from the soil-plant system by mechanisms such as volatilization, denitrification, leaching from the root zone and in runoff of soil or water erosion (Trivelin et al., 1995; Bustamante et al., 1997; Gava et al., 2001).

The use of a stable isotope in the form of a ^{15}N-labeled fertilizer is indicated for studies of this nature. It allows the identification of the fate of N within the soil-plant-atmosphere system and elucidates processes which can be controlled so as to improve crop efficiency of fertilizer use (Hardarson, 1990). The purpose of this study was to improve the understanding of N dynamics in a soil-coffee-atmosphere system, in order to help in the establishment of efficient fertilizer management practices that maximize the use of fertilizer N by the coffee crop.

MATERIAL AND METHODS

Field studies were conducted from 2003 to 2005, on the campus of the Universidade de São Paulo, Research Station in Piracicaba, SP, Brazil (22 ° 42 ' S, 47 ° 38 ' W, 580 m asl) on a Typic Rhodudalfs (US Soil Taxonomy) or Nitossolo Vermelho Eutroférrico (Brazilian classification system) (Embrapa, 2006). The area has an average slope of 9.2 ± 0.3 % and average initial soil test levels (August 2003) in the 0–0.2 m surface layer were: 5.3 pH; 21.2 g kg^{-1} organic matter; 5.5 mg kg^{-1} available P; 2.9, 19.9, 13.7 and 20.5 mmol$_c$ kg^{-1} exchangeable K, Ca, Mg and (H + Al), respectively (Raij et al., 2001); 64 % base saturation; 25.5 % sand; 30.9 % silt; 43.6 % clay; and 1,460 kg m^{-3} soil bulk density.

The climate (Köppen, 1931) is tropical highland (Cwa) and is completely satisfactory for coffee cultivation. Annual averages of air temperature, rainfall and relative humidity are: 21.1 °C, 1,257 mm and 74 %, respectively (Villa Nova, 1989). The rainy and warm season extends from October to April, and the dry and cold season from May to September.

Coffee seedlings (*Coffea arabica* L.) of the variety Catuaí vermelho IAC-44 were planted in May 2001 on a 0.2 ha area, in 200 m long rows, along contour lines with a row spacing of 1.75 m and 0.75 m between plants, corresponding to 7,620 plants ha^{-1}. Coffee is a perennial crop which starts fruit production in the third year. In the Southeast of Brazil the crop is grown mainly under full sunshine and the cycle begins with flowering at the end of the cold and dry season, after the first significant rain, which occurs in August or September, in the region of Piracicaba. Fruit setting, grain filling and maturation last 9–10 months, and harvest occurs between May and June. Standard crop management practices were adopted for this study. A dead leaf mulch (8 to 12 cm thickness) below plant canopy was maintained, and the inter-row was weeded manually and by application of herbicide twice a year using 2 kg ha^{-1} active ingredient of glyphosate (Roundup 480). This last practice minimizes the destruction of the voluminous superficial root system which is kept moist under the mulch layer. For this reason fertilizers were broadcast over the mulch below canopy in two broad strips on either side of the plant row.

The experiment began on September 1, 2003 (plant height 1.2 m), and lasted two years, until August 31, 2005 (plant height 2.0 m). Dates were determined as Days after Beginning (DAB). The 0.2 ha area of the coffee plantation was divided into 15 plots of about 120 plants each (Figure 1), located side by side so that all were exposed to the same direction of slope. Three treatments with five replicates were randomly attributed to plots: T_0 – control without N ; T_1 – 50 % of full N rate and T_2 – full N rate , corresponding to 280 kg ha^{-1} N during 2003/2004 and 350 kg ha^{-1} during 2004/2005. The nitrogen was applied as ammonium sulfate, split into four applications a year: 0, 60, 105 and 150 DAB in the first year and 366, 426, 471, and 516 DAB in the second year. All plots received the same P rates (75 kg ha^{-1} y^{-1}of P_2O_5) and K (280 kg ha^{-1} yr^{-1} of K_2O), applied once at 0 DAB and 366 DAB. Owing to the high cost of ^{15}N-labeled experimentation, this fertilizer-N balance case study was carried out only for treatment T_2. This rate was calculated according to well-established agronomic practices (Raij et al., 1996; Ribeiro et al., 1999).

In the center of each of the five T_2 plots (Figure 1), sub-plots of 11.8 m^2 with nine plants (three plants of three adjacent rows) were separated for the N-labeled fertilizer study. The lower limit of the soil volume evaluated for the balances was a depth of 1 m, below which it was assumed that coffee roots do not extend.

These isotopic sub-plots were framed with a 0.3 m thin metallic sheet (inserted 0.1 m into the ground and 0.2 m above soil surface) to prevent surface lateral water and fertilizer flow, and to monitor run-off from the 9.2 % slope field. The ammonium sulfate was enriched to 2.072 ± 0.001 atom %, in both years of application. The fertilizer was broadcast by hand below the plant canopy on the dead leaf mulch so that fertilizer N recovery data would reflect the efficiency of this standard application method.

Sub-plots (Figure 1) were instrumented with: (1) three neutron probe access tubes to measure soil water contents θ ($m^3\ m^{-3}$) in the soil profile at a depth of 1 m (Bacchi et al., 2002); (2) tensiometers to measure the soil-water matric potential underlying the total soil-water potential H (m) and gradients ∇H (m m^{-1}) at 1 m depth by finite difference; (3) three porous cup soil-solution extractors installed at a depth of 1 m to evaluate total soil solution N ($NO_3 + NH_4$) content C_N (g L^{-1}) and the isotopic abundance AN (%) (Kutílek & Nielsen, 1994); (4) one Ville de Paris rain gauge with a capture area of 709 cm^2 (Pereira et al., 2002); (5) one 60 L run-off collector, installed down slope and outside main plots (Reichardt & Timm, 2008).

Total shoot dry matter was evaluated for fertilizer-N balances at the end of each cropping season [366 DAB (August 31, 2004) and 731 DAB (August 31, 2005)] using five whole trees, of similar shape and size as the isotope-labeled plant, selected within each T_2 plot (Figure 1) 3 to 5 m outside each isotope sub-plot. The five whole plants were divided into the following compartments (C) (Figure 2): C_1 represents the central stem or orthotropic branch; C_2 the productive plagiotropic branches; C_3 leaves of productive branches; C_4 vegetative plagiotropic branches; C_5 leaves of vegetative branches; C_6 fruits (beans) harvested before balance dates, i.e., 243 DAB in the first year and 636 DAB in the second year, since coffee is harvested about 3 months before the following flowering season, which is the time chosen to establish balances. The N contained in the fruit represents the exported N which has to be taken into account at the balance date. To minimize experimental costs, only three plants of the central row were treated with labeled fertilizer (Figure 1). The central plant of this row was used for total-N and N abundance evaluations and since the experiment was planned for two years, sampling of this plant should ideally not affect its growth and development. Therefore, only one complete lateral branch (out of more than 50 branches at 366 DAB and more than 100 branches at 731 DAB) was collected at each sampling time. These branches (Figure 2) have compartments C_2 to C_6. The first centimeter of each branch is hardwood and was considered as a sample of the orthotropic central branch C_1. All samples were oven-dried at 65 °C to constant weight and finely ground in a Wiley type mill. Sub-samples were used for total-N and N abundance evaluations by mass spectrometry in an

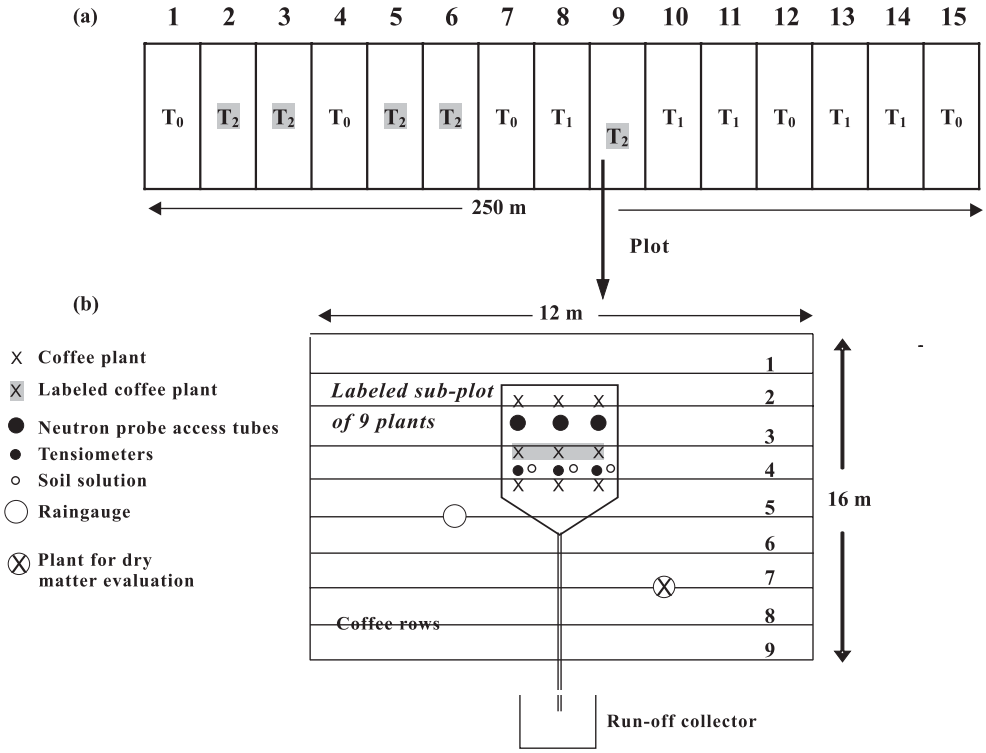

Figure 1. Schematic field layout: (a) Distribution of treatments T_0, T_1 and T_2 on plots across the 0.2 ha coffee plantation; (b) Details of a T_2 plot indicating the nine coffee rows of 12 m, and the fertilizer-N balance sub-plot of nine plants, with the central row of three ^{15}N labeled plants, and the location of instruments.

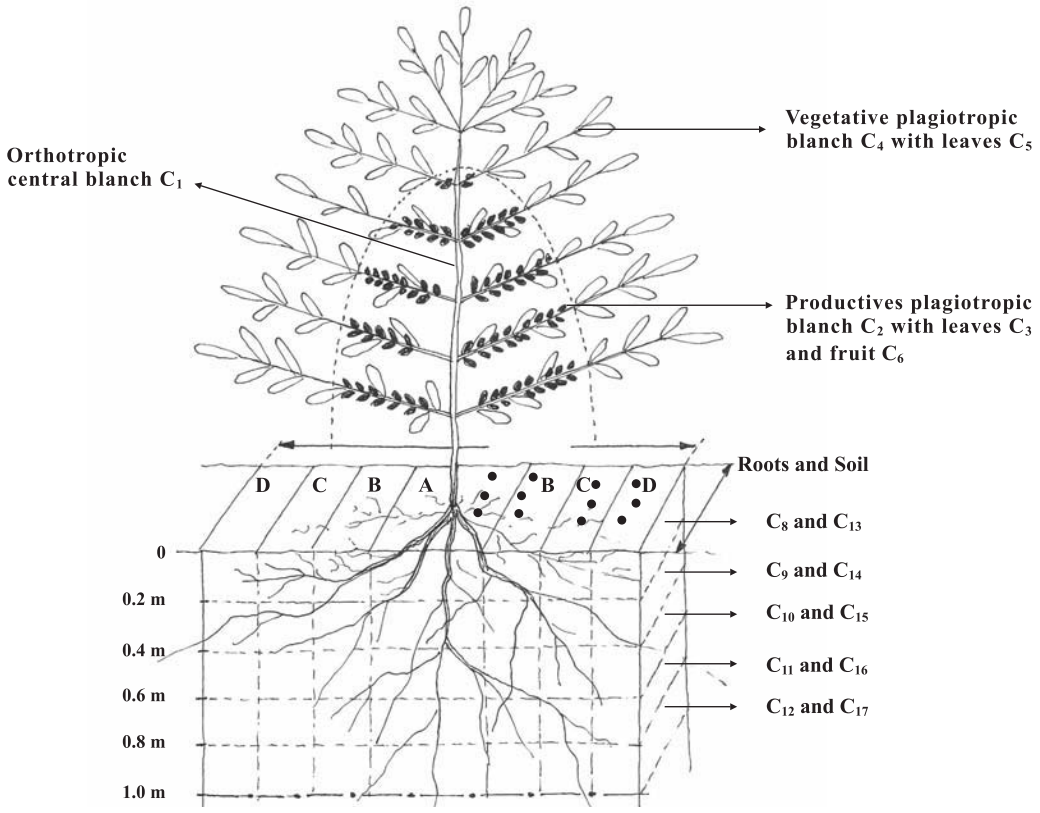

Figure 2. Schematic view of shoot, root and soil compartments (C). Points (●) in areas A, B, C and D indicate positions of auger samplings.

automated continuous flow Mass Spectrometer, Model ANCA-SL (Europa Scientific) as described by Mulvaney (1993) and Barrie & Prosser (1996). In relation to the litter layer, corresponding to compartment C_7, initially no sampling was planned. Therefore, to avoid an inclusion in compartment C_{20} (used to close the balance, includes other minor not evaluated compartments), the best solution found was to estimate the difference between maximum and minimum leaf dry matter, data presented elsewhere (Fenilli et al., 2007b).

Low N contents and ^{15}N abundance were measured only at the dates of balance estimation, which is a shortcoming because N contents in senescenced and dropped leaves are different from attached green leaves. Furthermore, mineralization of dead leaves implies a further N content reduction including volatilization losses of the decomposing litter.

For root-N and soil-N, and isotope analysis, also at 366 and 731 DAB, one auger sampling (0.05 m diameter) was performed in each sub-plot under the canopy of the labeled central plant, to minimize influence on the crop. Soil and total roots were collected from the layers 0–0.2; 0.2–0.4; 0.4–0.6; 0.6–0.8 and 0.8–1.0 m assuming that these variables (total N and ^{15}N abundance) do not change considerably from point to point within the soil-root system. The resulting auger hole was thereafter carefully filled with soil to avoid direct water entrance to deep soil layers during the following cropping season. For total root and total soil dry mass evaluations the area (0.75 x 1.75 m^2) of the same plant used for shoot evaluation located outside the isotopic plot (Figure 1) was divided into four equal parts (A, B, C, D, shown in Figure 2) in the direction row-interrow. Each part was carefully auger-sampled (0.1 m diameter) at three positions, at the same depths as the isotopic sampling: 0–0.2; 0.2–0.4; 0.4–0.6; 0.6–0.8; 0.8–1.0 m, saving all soil and roots.

Total roots (dead and living) were water-separated from soil using a Root Washer Delta-T device, in which samples are agitated in flowing water separating soil from roots that float and are retained on a screen. After drying at 65 °C soil and roots were weighed. Root and soil dry matter from each of the 12 cylinders per 0.2 m soil layer were extrapolated to total volumes. These samples correspond to compartments (C_8 roots 0–0.2 m; C_9 roots 0.2–0.4 m; C_{10} roots 0.4–0.6 m; C_{11} roots 0.6–0.8 m; C_{12} roots 0.8–1.0 m; C_{13} soil 0–0.2 m; C_{14} soil 0.2–0.4 m; C_{15} soil 0.4–0.6 m; C_{16} soil 0.6–0.8 m; C_{17} soil 0.8–1.0 m). Roots below 1 m were assumed to be negligible but, if present, were included in C_{20}, which also includes other not evaluated compartments. It is important to mention that when evaluating roots of compartments 8 to 12 there may have been contributions of roots from neighboring

plants. This introduction is however compensated by the amount of roots of neighboring plants, which is on average equal to that lost to a neighboring plant.

N leaching from fertilizer to below the root zone (more than 1 m) was measured during the rainy season from soil water samples extracted at a depth of 1 m using porous cups submitted to vacuum (Reichardt & Timm, 2008). To observe the N dynamics in the soil profile, complete water balances were established every 14 days (Silva et al., 2006) aiming at an evaluation of periods of water excess during which drainage might occur and, as a consequence, N would be leached from the soil profile. The instantaneous leaching N flux densities q_N (kg m^{-2} day^{-1}) were estimated from the product of the water drainage flux densities q_w (L m^{-2} day^{-1}) and the total-N (NO_3 + NH_4) concentration C_N (kg L^{-1}) (Kutílek & Nielsen, 1994):

$$q_N = q_W C_N \quad (1)$$

which were integrated over time to obtain total N leaching amounts Q_L (kg ha^{-1} $year^{-1}$), at 366 and 731 DAB, corresponding to C_{19}. Deep drainage fluxes q_W were estimated through the Darcian flux-gradient approach (Hillel, 1980) using a soil hydraulic conductivity function determined for the experimental field site (Silva et al., 2007). During and immediately after heavy rain periods, hydraulic gradients ∇H and the N concentration of soil solution extracts were measured daily in order not to miss leaching events. At a depth of 1 m, rainfall infiltration and nitrate fluxes are sufficiently attenuated (Kutílek & Nielsen, 1994) to allow daily measurements to provide quantitative estimates of N leaching losses from the soil profile. The soil solution extracts were concentrated by evaporation before ammonia and nitrate + nitrite analysis using a Flow Injection Analysis (FIA) system (Giné et al., 1980; Bergamin Filho et al., 1980), and mass spectrometry, as already described.

The volatilization losses (C_{18}) in the form of NH_3 from the fertilizer (ammonium sulfate), although expected to be minimal in a low pH soil, were evaluated by integrating information from static semi-open ammonia collectors over time (Lara-Cabezas et al., 1999). To evaluate the re-absorption of volatilized fertilizer ammonia by plants (Fenilli et al., 2007a) soil trays (0.05 x 0.4 x 0.7 m) filled with soil of the 0–0.15 m layer were placed under the plant canopy containing ^{15}N-labeled fertilizer. Losses referring to C_{18} at 366 and 731 DAB corresponded to the difference between the integrated volatilization losses and the integrated re-absorption of the volatilized ammonia.

In the C compartments defined above the following parameters were evaluated: (1) dry matter DM (kg ha^{-1}); (2) total nitrogen concentration C_N (%); and (3) ^{15}N isotopic abundance A_N (%), to calculate (Hardarson, 1990):

a) The total N accumulated in each compartment C, NA (kg ha^{-1}) at any DAB:

$$NA = DM \times \frac{C_N}{100} \quad (2)$$

b) The quantity of N derived from fertilizer in each C, QNdff (kg ha^{-1}) at any DAB:

$$QNdff = \left(\frac{A_N - A_{N_c}}{A_{Nf} - A_{Ncf}} \right) \times NA \quad (3)$$

where $A_{Nc,}$ and A_{Ncf} are the natural ^{15}N isotopic abundances of compartment C and of the fertilizer, respectively, in general taken as 0.365 %; and A_{Nf} the isotopic ^{15}N abundance of the fertilizer (here 2.072 %).

c) The fertilizer recovery by the plant R at any DAB:

$$R = \left(\frac{QNdff}{Q_{N_f}} \right) \times 100 \quad (4)$$

where Q_{Nf} is the amount of applied fertilizer. Because the fertilizer application was split, Q_{Nf} represents the amount of fertilizer applied on dates before the measurement of the isotopic abundance (AN) of the respective compartment. It is also important to remember that in the isotopic evaluations of the second year the residual label of the first year plays a role and, therefore, values of Q_{Nf} of the second year included the fertilizer applied in the first year.

To close balances a compartment C_{20} was defined, which includes other non-evaluated compartments such as fertilizer-N below 1 m, fertilizer-N absorbed by neighboring plants, N lost in run-off water, N lost to the atmosphere (Trivelin et al., 2002) as well as errors committed in the evaluation of all other compartments. Data are presented as averages of five replicates and their respective standard errors.

RESULTS AND DISCUSSION

The climatic conditions that prevailed during the experimental period (Figure 3), expressed in terms of air temperature (T_{air}), rainfall (P), potential crop evapotranspiration (Et_c) evaluated according to the method of Penman-Monteith (Allen et al., 1998) and actual evapotranspiration (ER) estimated from water balances (Silva et al., 2006), did not deviate very much from the long-term behavior for Piracicaba (Villa Nova, 1989). Total rainfall during the first and second years, 1,342.9 and 1,118.9 mm, respectively, were somewhat above and below the long-term average of 1,247 mm and did not induce water stress to plants during vegetative growth, fruit development and maturation. In the first year the water balances presented (P-ER) = 241.7 mm; deep drainage Q_L = 241.1 mm and runoff RO = 5.5 mm and in the second

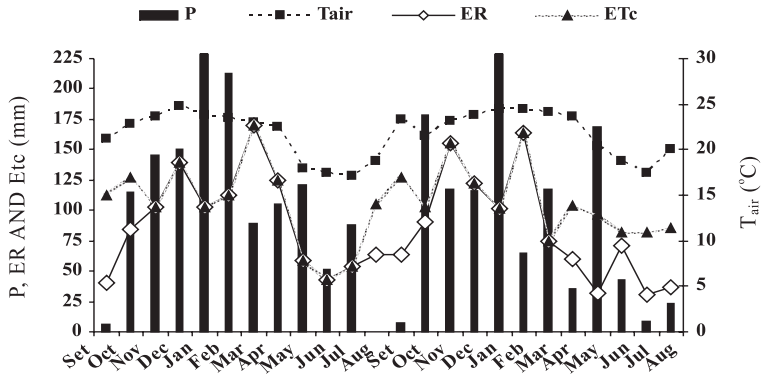

Figure 3. Rainfall (P), average air temperature (T_{air}), actual evapotranspiration (ER), and potential crop evapotranspiration (ETc) in the experimental period.

Table 1. Plant height (PH) and coffee bean dry matter yield (Y) for treatments T_0, T_1 and T_2, at both harvest times. DAB = Days after (Sept 01,03)

	DAB	Treatment		
		T_0	T_1	T_2
PH (cm)	243	147	155	160
	548	178	194	204
Y (kg ha^{-1})	243	234	294	288
	548	294	858	4,764

year these data decreased to - 121.2; 150.5 and 0.8 mm, respectively. Although this study focuses on the fate of N from the fertilizer only in the labeled treatment T_2, the treatments T_0, T_1 and T_2 were compared (Table 1) in terms of plant height (PH) and coffee bean dry matter yield (Y), at both harvest times. This data showed the importance of N fertilization as compared to the non-fertilized control T_0, and indicated that the fertilizer rate used in T_2 resulted in coffee bean dry matter yields considered high for Brazil (Malavolta, 1993).

Shoot and root average DM distribution (Figure 4) in the different shoot-root compartments illustrated in (Figure 2) shows that the DM values were highest in compartments C_1, C_7 and C_8 over the two years, with a significant increase in C_1 for the second year due to plant growth, a significant reduction in C_7 for the second year caused by sugar translocation from leaves to fruit to produce a high yield in the second year, and almost no change in C_8. DM values for C_6 were very low in both years because the fruits were harvested before balance dates; nevertheless, they represent an export. Calculated according to equation (2), the total-N (NA) distribution in shoot and root followed a similar pattern (Figure 5) in relation to DM; differences were due to variations in the total-N concentration C_N within the different compartments.

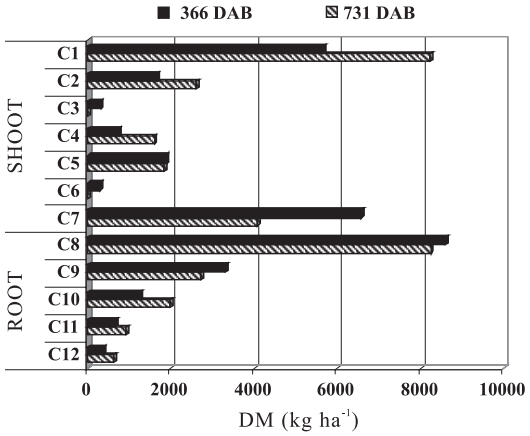

Figure 4. Shoot and root average dry matter (DM) distributions at the end of each agricultural year. C_1 to C_{12} are compartments of shoot and root, and DAB = days after beginning.

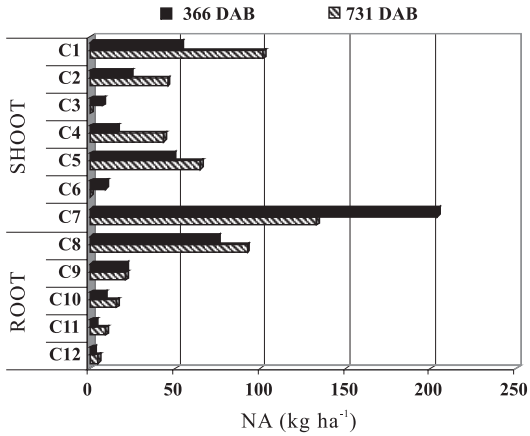

Figure 5. Shoot and root average accumulated total N (NA) distributions at the end of each agricultural year. C_1 to C_{12} are compartments of shoot and root, and DAB = days after beginning.

Total soil-N (NA) decreased with soil depth (Figure 6). The surface layers C_{13} and C_{14} contain more than twice as much soil-N as the deeper layers C_{15} to C_{17}.

The annual balance of fertilizer-derived N for all compartments of the soil-coffee-atmosphere system (100 %) was completed by C_{20} (Table 2). It is important to understand that the estimated values of the second year (731 DAB) are accumulated because they include the labeled nitrogen of fertilizer applications of both years.

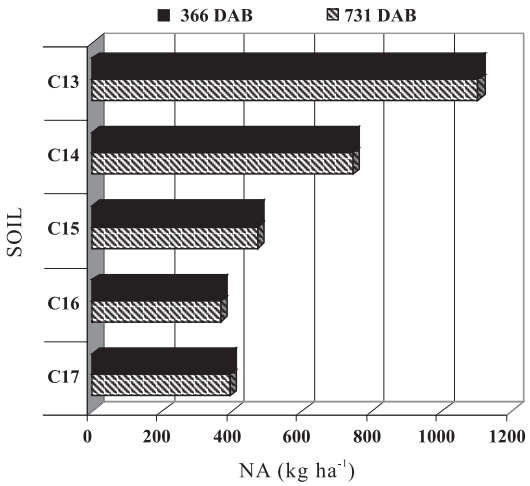

Figure 6. Average soil total-N (NA) distribution at the end of each agricultural year. C_{13} to C_{17} are compartments within soil profile, and DAB = days after beginning.

366 DAB, a recovery of fertilizer N of 54.7 kg ha^{-1} was observed in the compartments C_1 to C_5 (aerial part of the crop), which corresponds to 19.5 % N applied in the first year. 731 DAB the N recovery value increased to 120.3 kg ha^{-1}. As the N recovery of the second year includes N from the fertilizer applied in the first year, the N recovery from the fertilizer applied in this year was slightly reduced to 19.1 %. Of these compartments, the orthotropic central branch and leaves of vegetative branches contained the greatest amounts of fertilizer N. Fruits in C_6 exported 19.1 kg ha^{-1} fertilizer N in the first year. During the second year, fruits in C_6 exported 146.4 kg ha^{-1} N (the difference between 165.5 and 19.1 in Table 2) since values of the second year are accumulated. This high N export, corresponding to 26.3 % of the fertilizer applied in both years, emphasizes the need to deepen the understanding for an enhanced management of N fertilizer levels. The difference between yields in the first and second year (Cannel, 1985) is due to the ongoing formation of the crop during the first year,

Table 2. Fate of fertilizer N regarding the quantity of N derived from fertilizer (QNdff) and fertilizer N recovery (R) for the different compartments of the soil-coffee-atmosphere system after one (366 DAB) and two (731 DAB) years of cultivation. DAB = Days After Beginning

Compartment		QNdff (kg ha^{-1})		R(%)	
		366 DAB	731 DAB	366 DAB	731 DAB
C1	Orthotropic central branch	17.9 (± 2.6) [(1)]	48.4 (± 4.0)	6.4	7.7
C2	Productive branches	9.1 (± 2.0)	22.3 (± 2.8)	3.2	3.5
C3	Leaves of productive branches	3.4 (± 1.1)	0	1.2	0
C4	Vegetative branches	5.6 (± 0.8)	19.9 (± 2.9)	2.0	3.2
C5	Leaves of vegetative branches	18.7 (± 3.2)	29.7 (± 6.3)	6.7	4.7
C6	Fruits (export)	19.1 (± 0.8)	165.5 (± 26.9)	6.8	26.3
C7	Litter	79.4	149.8	28.4	23.8
	Shoot sub-total	**153.2**	**435.6**	**54.7**	**69.2**
C8	Roots (layer 0–0.2 m)	26.1 (± 6.1)	36.3 (± 1.3)	9.4	5.7
C9	Roots (layer 0.2–0.4 m)	7.2 (± 2.0)	8.6 (± 0.4)	2.6	1.3
C10	Roots (layer 0.4–0.6 m)	4.0 (± 0.9)	7.4 (± 0.4)	1.4	1.2
C11	Roots (layer 0.6–0.8 m)	1.2 (± 0.3)	4.8 (± 0.5)	0.4	0.8
C12	Roots (layer 0.8–1.0 m)	1.2 (± 0.3)	2.3 (± 0.3)	0.4	0.4
	Root sub-total	**39.7**	**59.4**	**14.2**	**9.4**
C13	Soil (layer 0–0.2 m)	30.4 (± 11.7)	47.8 (± 5.2)	10.9	7.6
C14	Soil (layer 0.2–0.4 m)	8.8 (± 2.2)	14.6 (± 2.9)	3.1	2.3
C15	Soil (layer 0.4–0.6 m)	4.1 (± 1.3)	8.7 (± 1.2)	1.5	1.4
C16	Soil (layer 0.6–0.8 m)	2.9 (± 1.1)	2.5 (± 0.9)	1.0	0.4
C17	Soil (layer 0.8–1.0 m)	3.8 (± 1.6)	5.7 (± 0.6)	1.4	0.9
	Soil sub-total	**50.0**	**79.3**	**17.9**	**12.6**
C18	Volatilization + re-absorption	2.6 (± 1.4)	5.9 (± 2.2)	0.9	0.9
C19	Leaching	6.5 (± 0.1)	10.5 (± 0.3)	2.3	1.7
C20	Other[(2)]	28.0	39.3	10.0	6.2
	Total	280.00	630.00	100	100

[(1)] Numbers in brackets are standard errors of the mean. [(2)] Other: non-evaluated compartments were determined by the difference between the sum of all compartments and the total.

whereas the second year was actually the first year of full production of the crop.

The litter (C_7) contained 79.4 kg ha^{-1} of the N applied during the first year, and 149.8 kg ha^{-1} at the end of both years. These values do not include litter N mineralization or losses to the atmosphere because litter was estimated through the difference of leaves present in the shoot just before harvests, and the leaves present at the end of each cropping season. The high amounts of fertilizer-N in the litter indicate it as a large source of organic N derived from the applied mineral fertilizer, and further stresses the importance of reasonable management decisions during coffee cultivation.

During the first year, roots (C_8 to C_{12}) containing 39.7 kg ha^{-1} or 14.2 % fertilizer N, of which 9.4 % were in the 0–0.2 m soil layer, clearly evidence the need to manage and protect the soil surface root system which is so essential for water and nutrient uptake. 731 DAB values of fertilizer-derived N in the roots (C_8 to C_{12}) increased to 59.4 kg ha^{-1} with a reduction of the recovery percentage to 9.4 %. Total-N and fertilizer-N contents were still highest in the 0–0.2 m layer.

In the soil (C_{13} to C_{17}), 50.0 kg ha^{-1} fertilizer-derived N was found, corresponding to 17.9 % of N applied in the first year. N concentration from the fertilizer was highest in the 0–0.2 m layer (60.9 %). In the second year, these values shifted to 79.3 kg ha^{-1} and 12.6 %, 60.3 % of which in the 0–0.2 m layer. These quantities of fertilizer-derived N remain available for plants for the following cropping cycle.

Volatilization losses (C_{18}) estimated in an additional plot (Fenilli et al., 2007a) amounted to 1.6 % of the applied N, i.e., 4.6 kg ha^{-1} N in the first year and 10.3 kg ha^{-1} N at the end of both years. These results showed that volatilization losses are very low when using N sources of low volatilization potential such as ammonium sulfate. Freney et al. (1991) also verified that the application of ammonium sulfate resulted in low N losses. For example, they found that only 1.8 % of the N fertilizer applied to a sugarcane crop grown on a slightly acid soil was lost by volatilization. The re-absorption of the volatilized ammonia, described in more detail elsewhere (Fenilli et al. 2007a), reached 43 %, therefore reducing volatilization losses from 4.6 and 10.3 kg ha^{-1} to 2.6 and 5.9 kg ha^{-1}, in the first and second year, respectively (Table 2). Studies for other crops report much lower re-absorption of volatilized ammonia. Sommer et al. (1993) found that wheat leaves reabsorbed about 2.2 % of the ammonia lost to the atmosphere. In turn, Ping et al. (2000) reported an average ammonia re-absorption of 11 % by wheat leaves. The particular conditions of coffee crop with a dense canopy favor a longer contact time between the diffusing ammonia gas and the leaves, potentially explaining the high re-absorption indicated before. However, since the total quantity of volatilized N was small, the re-absorption process had very little impact in this study.

The total amount of N leached from the fertilizer to a depth below 1 m depth, between 0 and 366 DAB was 6.5 kg ha^{-1}, corresponding to only 2.3 % of the applied N during the first year. This amount increased to 10.5 kg ha^{-1} or 1.7 % by 731 DAB. Several ^{15}N tracer studies reported by Reichardt et al. (1982) indicate that in the climate and soil conditions of Piracicaba, State of São Paulo, N leaching losses from fertilizer are very small. More recently, Fernandes et al. (2006) reported insignificant leaching of fertilizer N applied to a corn-oat-corn sequence grown on a similar soil in Piracicaba in the same period as this experiment.

In general terms, it was verified that 366 DAB, 19.5 % of the nitrogen derived from the fertilizer was found in the aerial plant parts, 14.2 % in roots, 28.4 % in the litter, and 6.8 % exported through coffee bean harvest. Hence, during the first year, 68.9 % of the fertilizer N was absorbed by the plant (C_1 to C_{12}) which represents a very high fertilizer use efficiency, due mainly to: (1) appropriate timing of fertilizer, applied before the coffee plant growth rate started to decrease (Fenilli et al., 2007b); (2) the mode of N fertilization, applied split in four, below the plant canopy, available to roots of the surface soil layer kept moist by the mulch; (3) the choice of ammonium sulfate as N source, with a low volatilization potential; and (4) the favorable soil-water regime throughout the year and at times of fertilizer application (Silva et al., 2006). In other situations, reports show lower recoveries, e.g. Bustamante et al. (1997) found that coffee absorbed 35 to 46 % of the fertilizer-N depending on the fertilizer type used as N source. It is important to mention that these authors considered only the aerial plant part, which here would be 42.9 % in the first year.

At the end of the 2-year experiment (731 DAB), the recovery of applied fertilizer N (280 kg ha^{-1} in the first year and 350 kg ha^{-1} in the second year) was 120.3 kg ha^{-1} (19.1 %) for the aerial plant parts (C_1 to C_5). Export by fruit was 165.5 kg ha^{-1} or 26.3 %, and the litter contained 149.8 kg ha^{-1} or 23.8 %. Roots contained 59.4 kg ha^{-1} (9.4 %). Therefore, the total recovery by the plant (shoot, root, litter and export) during both years was 78.6 %. The soil presented 79.3 kg ha^{-1} (12.6 %), mostly concentrated in the 0–0.2 m layer. Both soil and litter N continue to be available for plant use in the following cycles.

CONCLUSIONS

The fertilizer-N balance at the end of each agricultural year showed that approximately 20 % N from the fertilizer is found in the aerial plant parts, 12 % in the roots, and 15 % in the soil. Dead leaf litter corresponds to about 25 %, and at the end of two years, fruit export corresponded to 26 % of the applied fertilizer N. Volatilization and leaching losses are very low, of the order of 1 % and 2 %, respectively,

per year. The relatively low standard errors of the quantities of fertilizer-N present in the different compartments (C_1 to C_{19}) and the small quantities in C_{20} manifest high accuracy and precision of the tracer methodology in finding almost all fertilizer N after two years in such a complex system such as a coffee crop grown under field conditions. The apparently low crop efficiency in recovering fertilizer N when considering only the aerial part (20 %) is miss-leading because the partitioning within the whole plant (78.6 %) is very high. Partitioning also shows the importance of: i) the litter as an organic-N source, indicating that management practices that involve its removal export a significant part (25 %) of fertilizer-N; ii) the harvest exported N (26 %) which has to be replaced by future fertilizer applications; and iii) the soil surface and root layer that holds most of the underground fertilizer N.

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