Nitrogen fertilizer (^{15}N) leaching in a central pivot fertigated coffee crop[1]

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ABSTRACT

Nitrogen has a complex dynamics in the soil-plant-atmosphere system. N fertilizers are subject to chemical and microbial transformations in soils that can result in significant losses. Considering the cost of fertilizers, the adoption of good management practices like fertigation could improve the N use efficiency by crops. Water balances (WB) were applied to evaluate fertilizer N leaching using ^{15}N labeled urea in west Bahia, Brazil. Three scenarios (2008/2009) were established: i) rainfall + irrigation the full year, ii) rainfall only; and iii) rainfall + irrigation only in the dry season. The water excess was considered equal to the deep drainage for the very flat area (runoff = 0) with a water table located several meters below soil surface (capillary rise = 0). The control volume for water balance calculations was the 0 – 1 m soil layer, considering that it involves the active root system. The water drained below 1 m was used to estimate fertilizer N leaching losses. WB calculations used the mathematic model of Penman-Monteith for evapotranspiration, considering the crop coefficient equal to unity. The high N application rate associated to the high rainfall plus irrigation was found to be the main cause for leaching, which values were 14.7 and 104.5 kg ha^{-1} for the rates 400 and 800 kg ha^{-1} of N, corresponding to 3.7 and 13.1 % of the applied fertilizer, respectively.

Key words: Penman-Monteith, evapotranspiration, deep drainage, urea.

RESUMO

Lixiviação de nitrogênio (^{15}N) do fertilizante em uma cultura de café fertirrigada

O nitrogênio possui uma dinâmica complexa no sistema solo-planta-atmosfera. Considerando o elevado custo dos adubos, é fundamental o desenvolvimento de manejos da adubação nitrogenada que visem ao melhor aproveitamento do N pelas culturas, como é o caso da fertirrigação e o mínimo impacto ambiental. Balanços hídricos e a lixiviação de N derivado do fertilizante são apresentados para um cafezal sob fertirrigação com uréia marcada com ^{15}N no oeste baiano, em três cenários para um ciclo da cultura 2008/2009: i) precipitação + irrigação no ano inteiro, ii) apenas precipitação; e iii) precipitação + irrigação apenas na estação seca. Nos balanços hídricos os componentes ascensão capilar e escoamento superficial foram considerados nulos por se tratar de solo arenoso em declive praticamente nulo, com lençol freático profundo. A irrigação foi realizada por pivô-central e no balanço hídrico o volume de controle conside-

Received for publication on March 5th, 2012 and approved on August 10th, 2012.

[1] Part of the first author's Doctor Science Thesis. Work funded by CNPq and FAPESP.

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rou a camada 0 – 1 m responsável pela disponibilidade de água pela cultura. A água drenada abaixo de 1 m foi considerada para os cálculos da lixiviação do nitrogênio do fertilizante. O balanço hídrico utilizado calculou a evapotranspiração baseado no modelo matemático de Penman-Monteith, considerando um coeficiente de cultura unitário. Foi possível verificar que a alta quantidade de N, associada à precipitação concentrada são os grandes responsáveis pela lixiviação, cujos valores foram 14,7 e 104,5 kg ha^{-1} de N do fertilizante para as doses de 400 e 800 kg ha^{-1} de N aplicadas na forma de uréia, correspondendo a 3,7 e 13,1 % da quantidade total do fertilizante aplicado.

Palavras-chave: Penman-Monteith, evapotranspiração, drenagem profunda, uréia.

INTRODUCTION

The dynamics of nitrogen in the soil-plant-atmosphere system is complex. The N fertilizer is subject to a series of chemical and biological transformations that can lead to significant N losses to the environment. Therefore, it is important to search for agricultural practices that enable a more efficient use of the applied N fertilizer, such as fertigation. Advanced farming practices have been adopted for coffee production to increase crop yields, such as denser planting, harvest mechanization and fertigation (Coelho & Silva, 2005). This has been the case of the western Bahia, in Brazil, in which the coffee production is only viable with irrigation (Silva *et al*., 2005).

Fertigation has several advantages in relation to conventional cropping practices, allowing for the control, monitoring and split of fertilization according to the plant requirements along the productive cycle (Coelho & Silva, 2005), although increasing the risk of losses to the environment (Oliveira *et al*., 2002); the remaining N stays in the soil, mainly in the organic form (Scivittaro *et al*., 2003; Silva *et al*., 2006). The N fertilization efficiency is also influenced by the irrigation management, N rates and intervals of applications (Quiñones *et al*., 2007). Results of the most different crop scenarios show that the absorption of the total N applied rarely exceeds 60% (Reichardt *et al*., 2009).

Several studies of N uptake have used ^{15}N as a tracer to quantify this plant nutrient in the different compartments of a soil-plant- system (Lara Cabezas *et al*., 2000; Boaretto *et al*., 1999; Boaretto *et al*., 2007; Fenilli *et al*., 2004; Oliveira *et al*., 2002; Lima Filho & Malavolta, 2003). However, the widespread adoption of advanced farming practices such as N fertigation requires further studies on the interactions climate-soil-coffee. This study uses the ^{15}N tracer to quantify N fertilizer leaching, and the consequent environmental risk of fertigation associated with high N fertilizer rates in a "cerrado" or savanna area, where the supplemental irrigation is used over the whole year.

MATERIAL AND METHODS

An area of fertigated coffee crop was chosen for this study due to the high fertilizer rate routinely used (600 kg ha^{-1} year^{-1} of N) over the last seven years, showing a high risk of N leaching below the crop root zone. This central pivot irrigated coffee crop belongs to a commercial farm (Fazenda Morena) located in Barreiras, BA, Brazil (11° 46' S and 45° 43' W, 740 m asl). The soil, previously covered by "cerrado" or savanna vegetation, was classified as a "LATOSSOLO VERMELHO-AMARELO Alumínico típico" (Embrapa, 2006) and as a Typic Hapludox (Soil Survey Staff, 2010), of low natural fertility, with 75% sand, 3% silt and 22 % clay, of sandy texture. The climate, according to Köppen's (1931) classification, is tropical sub-humid (Aw) with yearly rainfall ranging from 800 to 1800 mm concentrated between October and April, with a well defined dry season that for perennial crops, which requires supplemental irrigation, andannual average air temperature of 25 ^{o}C. Table 1 shows the climate data obtained from the meteorological station of the "Instituto Nacional de Meteorologia" (INMET) of Barreiras. Rainfall and irrigation were measured *in situ* at the farm.

Soil water retention properties were evaluated for each 0.2 m layers (Table 2), leading to an available water capacity (AWC) of 86.4 mm for the 0 – 1.0 m soil layer. This soil depth was considered for water balance (WB) calculations, assuming that it contains 100% of the active coffee root system, so that all water fluxes below the 1.0 m depth are considered as deep drainage (Q_l), used to estimate fertilizer N leaching. The chemical characterization of the soil (Table 3) indicates that this Oxisol has a very low natural fertility level that requires heavily fertilizer input for crop production.

Coffee plants (*Coffea arabica* L.), variety Catuaí Vermelho, were planted on January 2001, with a spacing of 3.8 m between circles (central pivot arrangement) and 0.5 m between plants in order to form a tier. During the experimental period, August 2008 to July 2009, plants were adult, 7 to be 8 years old, with about 3 m height and 1.9 m width, leaving a free inter-row of 1.9 m for machinery traffic. This cropland has been fertilized since 2002, with 600 kg ha^{-1} $year^{-1}$ of N. The crop yield was an average of 56 bags for ha^{-1} $year^{-1}$green bean (60 kg), almost three times higher than the Brazilian average (20 bags $ha^{-1}year^{-1}$).

Fertigation was performed with low energy precision application (LEPA) sprinklers, which distribute the solution in a localized form directly over the circular coffee rows, with minimum wetting of the inter-row. Irrigation depth is of the order of 3 to 4 mm day^{-1} applied in alternated days. During regular operation of fertigation N, the experimental row (row 4) did not receive the usual urea N fertilization in order to allow the application of labeled ^{15}N urea, used to estimate N fertilizer leaching.

In order to evaluate WB components the sequential water balance (SWB) program suggested by Rolim *et al*., (1998) was used for five-day intervals and then monthly values were obtained. Considering the elemental volume of 1 m soil depth (assumed to contain 100% of the active root zone) the changes in soil water storage (△SWS) were calculated by equation (1):

$$\pm\triangle SWS = P + I - ET_r + CR - Q_i - RO \qquad (1)$$

Where:

P = rainfall (mm);

I = irrigation (mm);

ET_r = actual evapotranspiration (mm);

CR = capillary rise (mm);

Q_i = internal drainage (mm);

RO = runoff (mm).

The SWB program was set to estimate the potential evapotranspiration through the methodology of Penman-Monteith, adapted by Allen *et al*. (1989), and to consider the sum CR + Q_i + RO = excess (EXC). Because the experimental area was flat (slope approximately zero) and has a very deep water table, we consider CR = 0 and RO = 0, so that the EXC given by the balance is equal to Q_i.

In order to evaluate the effect of, I on Q_i, WBs were carried out in the real scenario i) considering P + I, and, additionally, in two alternative scenarios: ii) no irrigation, only P; and iii) P + irrigation only in the dry season (I_{dry}).

The application of ^{15}N urea was made every 15 days (counting was made in days after beginning (DAB), starting September 1, 2008) on plots consisting of 3 plants of the cycle N° 4 of the central pivot, using a ladder and a watering can in order to simulate the LEPA sprinkler. The fertilizer was diluted in a volume of water corresponding to an irrigation of 4 mm. Plants bordering experimental plots received fertilization of solid urea on the soil surface. Two treatments with four replicate were tested, one below the normal N fertilization rate of the farm (600 kg ha^{-1} of N) and the other above, as following: 1) T_{400} (400 kg ha^{-1} of N), corresponding to 76 g $plant^{-1}$ of N or 169 g $plant^{-1}$ of urea; 2) T_{800} (800 kg ha^{-1} of N), corresponding to 152 g $plant^{-1}$ of N or 338 g $plant^{-1}$ of urea. All other fertilization and management practices were maintained as usually performed on the farm, and are shown elsewhere (Bruno *et al*., 2011).

Under the central plant of each plot, 0.2 m from the trunk were installed porous soil solution extraction probes at the depth of 1m, the lower boundary of the WB control volume (Figure 1A), to measure nitrate concentration by flow injection analysis (Giné *et al*., 1980) and abundance of ^{15}N by mass spectrometry (ANCA SL Mass Spectrometer). Soil solution extractions were made at least once a week before of the application of N fertilizer.

Table 1. Rainfall (P), irrigation (I), average air temperature (T), air relative humidity (RH), net solar radiation (Rn) and average wind speed (V) for the study period (DAB = days after beginning)

Month/Year	DAB	P	I	P + I	T	RH	Rn	V
			mm		°C	%	$MJ\ m^{-2}\ d^{-1}$	$m\ s^{-1}$
AUG/08	15	0.0	118.1	118.1	24.0	42.4	10.2	1.6
SEP/08	46	31.5	128.8	160.3	26.4	49.5	10.4	1.9
OCT/08	76	0.0	139.9	139.9	28.5	36.1	11.8	2.2
NOV/08	107	314.5	69.6	384.1	26.8	70.8	7.8	1.5
DEC/08	137	195.0	22.4	217.4	25.3	76.3	9.7	1.4
JAN/09	168	230.0	26.5	256.5	25.4	76.6	10.7	1.3
FEB/09	199	185.5	11.2	196.7	25.5	77.5	10.2	1.1
MAR/09	227	350.5	7.5	358.0	25.7	76.3	9.7	1.0
APR/09	258	108.5	26.1	134.6	24.7	83.5	7.9	0.9
MAY/09	288	67.0	48.5	115.5	23.7	78.1	8.0	1.0
JUN/09	319	52.5	46.6	99.1	22.6	76.2	8.4	0.9
JUL/09	349	0.0	52.2	52.2	22.2	69.9	9.3	1.1
Total (average)	-	1535.0	697.3	2232.3	(25.1)	(67.8)	(9.5)	(1.3)

Average nitrate ion concentrations (C_i) and average abundances ($^{15}N_i$), for month i, were estimated taking averages of solutions collected at each month.

Because of the low C_i values and the need of having a minimum N quantity for the isotope analysis, solutions collected from the replicates were joined in a single sample for each date. This fact did not allow a statistical analysis of the variability due to replicates. The quantity of leached N for month i, derived from fertilizer ($QNdff_i$, kg ha^{-1}) was calculated using the equation (2):

$$QNdff_i = Q_i.C_i.Ndff_i \quad (2)$$

Where: Q_i (kg ha^{-1}) is the value calculated by the SWB program, first given in mm and then transformed in kg of drained water per ha;

C_i initially expressed in mg L^{-1} of the nitrate ion, was transformed in kg of N per kg of water, i.e., kg kg^{-1} of N;

$Ndff_i$ is the fraction of nitrogen derived from the fertilizer, given by the equation (3):

$$Ndff_i = \frac{^{15}N_{sample\,i} - 0.365}{^{15}N_{fertilizer} - 0.365} \quad (3)$$

Because our leaching calculations were based on the hectare, and the fertilizer N leaching occurred only in the area of fertilizer application, which is the area effectively used by the plants (0.5 x 1.90 = 0.95 m^2 , which is less than the area occupied by one plant 0.5 x 3.8 = 1.90 m^2, Figure 1A), it was assumed the effective area per plant for leaching calculations was 1.425 m^2, based on the assumption that the N displacement from the soil surface to the depth of 1 m is dispersed, having 100% as probe concentration at the edge of the plant canopy and 0% in the middle of the inter-row (Figure 1B) that does not receive N fertilizer.

The annual leaching loss PL (kg ha^{-1} year^{-1} of N) is simply the sum of the monthly values, given by equation (4):

$$PL = \sum_{i=1}^{n} QNdff_i \quad (4)$$

The significance level of R^2 was determined by the JMP IN software version 3.2.1 (Sall *et al*., 2005).

RESULTS AND DISCUSSION

Losses of nitrogen by leaching are important and need to be estimated in order to improve fertilizer recommendation in coffee, especially in sandy soils of the “cerrado” region of western Bahia with low soil fertility, where large amounts of N fertilizers are usually applied every year (400; 800 kg ha^{-1} year^{-1} of N). The inward flow Q_i and drain of N soil to a depth of 1 m are shown in Table 4 for scenario i, providing evidence of the potential pollution of the ground water by nitrate.

During the complete coffee crop cycle, for scenario i, Q_i amounted to 1010.5 mm (Table 4), with P + I = 2232.3 mm, corresponding to 45.3% of the total water inflow, and as expected, showing that the management of irrigation can partially control Q_i. Irrigation amounted to 697.3 mm and the actual evapotranspiration to 1270.4 mm. It is clear that irrigation (31.2% of P+I) is a strong contributor to Q_i, mainly during the wet season (Figure 2A) when I is not necessary for demand of water in the plant, but that is still performed as fertilizer application (fertigation). For the alternative scenario ii, with only P, Q_i was reduced to 811.5 mm, and scenario iii with irrigation only in the dry season, Q_i was reduced to 873.1 mm.

Table 2. Soil water storage (SWS) and available water capacity (AWC) of 0.2 m soil layers estimated by the van Genuchten (1980) model, where $_{330}$ is the volumetric soil water content at field capacity and q_{15000} at the permanent wilting point

Depth	θ_{330}	SWS	θ_{15000}	SWS
m	cm^3 cm^{-3}	mm	cm^3 cm^{-3}	mm
0–0.2	0.172	34.4	0.107	21.4
0.2-0.4	0.169	33.8	0.102	20.4
0.4-0.6	0.183	36.6	0.108	21.6
0.6-0.8	0.214	42.8	0.114	22.8
0.8-1.0	0.242	48.4	0.117	23.4
Total SWS		196.0		109.6
AWC				86.4

Table 3. Main chemical characteristics of the soil

Depth	pH[1]	OM[2]	P[3]	S[4]	K[3]	Ca[3]	Mg[3]	Al[5]	H+Al[6]	SB[7]	T[8]	V[9]	M[10]	Total N[11]
m	$CaCl_2$	g dm^{-3}	mg dm^{-3}		mmol$_c$ dm^{-3}							%		mg L^{-1}
0-0.2	4.7	25	114	10	2	23	9	3	31	34	65	52	8	1080
0.2-0.4	3.6	20	40	21	1	5	3	9	34	9	43	21	50	620
0.4-0.6	3.8	16	5	60	0.8	4	2	9	31	6.8	37.8	18	57	532
0.6-0.8	3.6	14	1	72	0.8	3	1	9	31	4.8	35.8	13	65	520
0.8-1.0	3.8	14	1	96	0.8	2	1	10	31	3.8	34.8	11	72	505
0-1.0	3.9	17.8	32.2	51.8	1.1	7.4	3.2	8.0	31.6	11.7	43.3	23.0	50.4	631.4

[1]Active acidity by $CaCl_2$ (0,01 mol L^{-1}) method; [2]Organic matter by colorimetric method; [3]Phosphorus, potassium, calcium and magnesium by ion exchange resin method; [4]Sulfur by turbidimetry method; [5]Exchangeable aluminum by titrimetric method (1 mol L^{-1}); [6]Potential acidity by pH SMP method; [7]Sum of bases; [8]Cation exchange capacity; [9]Base saturation (100 * SB/T); [10]Aluminum saturation (100 * Al^{3+}/ Effective T); [11]Kjeldahl method (Raij *et al*. 2001).

Monthly averages of C_i in soil solution (Figure 2B) do not follow either the P + I distribution, or the continuous and cumulative applications of fertilizer. Data were very scattered and show only a tendency of an increase in time through the linear regressions (Figure 2B), with low R^2 coefficients.

The abundant average monthly of % ^{15}N abundances (Figure 3) also do not present the expected distribution

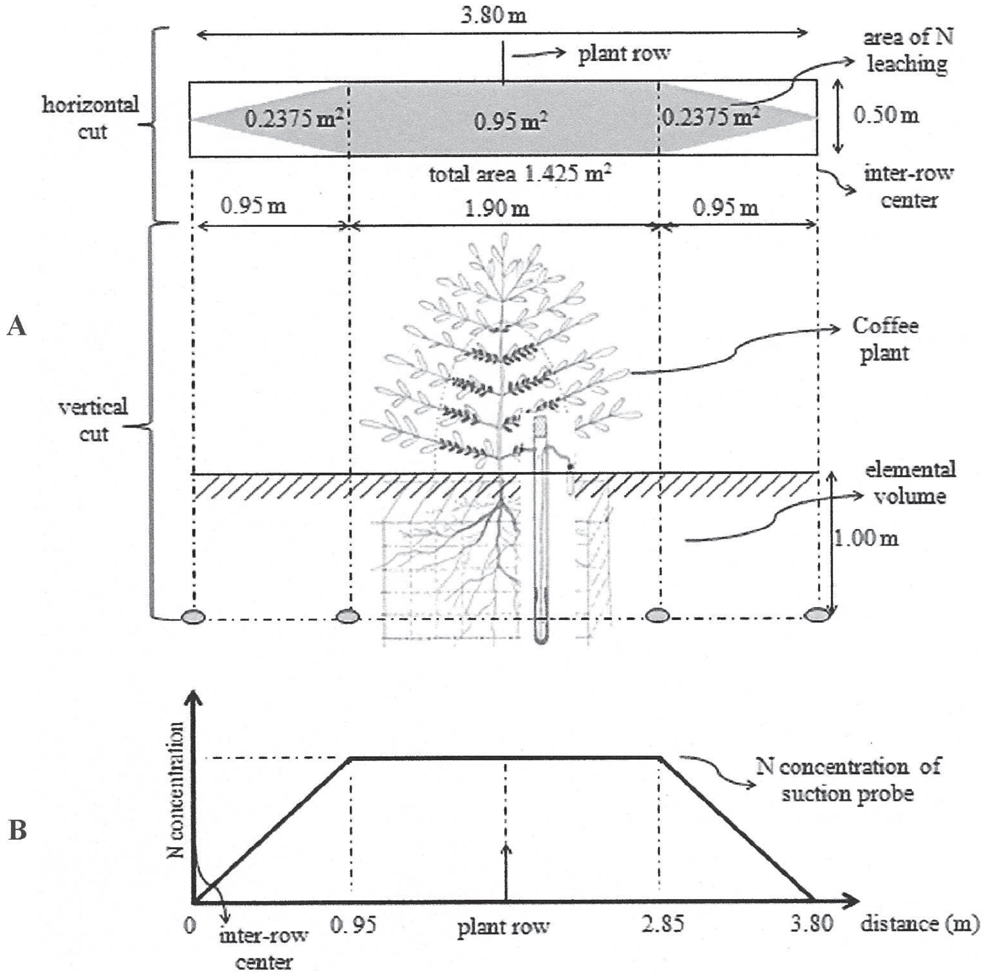

Figure 1. A: Spacing, area considered for leaching, soil solution extraction probe, and elemental volume for water balances; B: Assumed concentration distribution from inter-row center to inter-row center.

Table 4. Soil solution data for treatments T_{400} and T_{800}, for scenario i. DAB, days after beginning; Q_i, internal drainage flux below 1m; C_i, monthly average nitrate ion concentration; $^{15}N_i$, monthly average abundance

DAB	Q_i		T_{400}	T_{800}	T_{400}	T_{800}
	mm	Kg ha^{-1}	C_i - mg L^{-1}		$^{15}N_i$ - at% ^{15}N	
15	8.3	0.08x10^6	-*	-*	-*	-*
107	245.0	2.45x10^6	9.73	38.88	0.689	0.901
137	131.6	1.32x10^6	12.73	70.18	0.843	0.948
168	140.2	1.40x10^6	13.82	90.08	0.914	1.029
199	89.5	0.89x10^6	33.19	176.07	1.075	1.026
227	258.4	2.58x10^6	14.73	132.06	0.997	1.025
258	56.6	0.57x10^6	42.82	173.55	0.997	1.058
288	59.0	0.59x10^6	7.50	105.66	0.868	1.058
319	21.8	0.22x10^6	8.04	62.62	0.981	1.052
349	0	0	73.59**	147.57**	1.073**	1.137**
-	1010.5	10.0x10^6	-	-	-	-

*solution could not be extracted.

**even with Qi = 0, it was possible to extract solution.

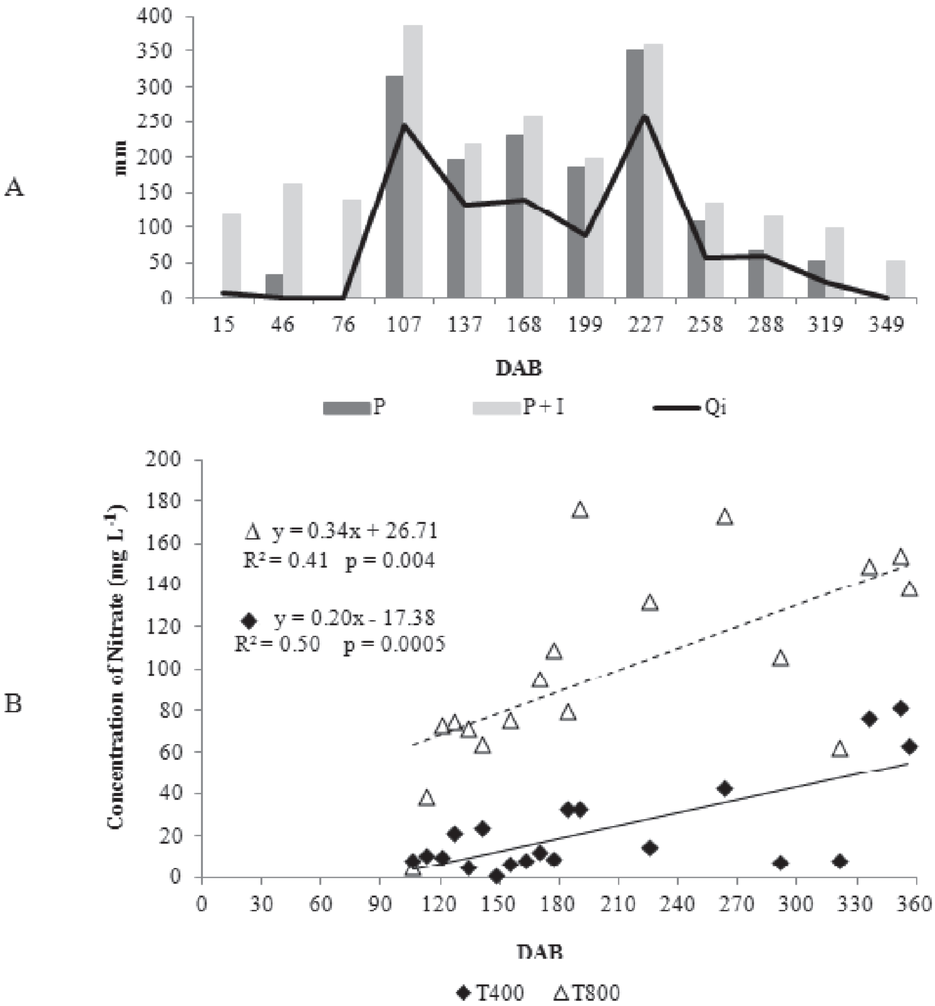

Figure 2. A: Deep drainage (Q_i), rainfall (P) and irrigation (I) data; B: Distributions of monthly average nitrate ion concentrations in soil solution samples C_i and linear regressions as a function of days after beginning DAB, for the treatments T_{400} and T_{800}.

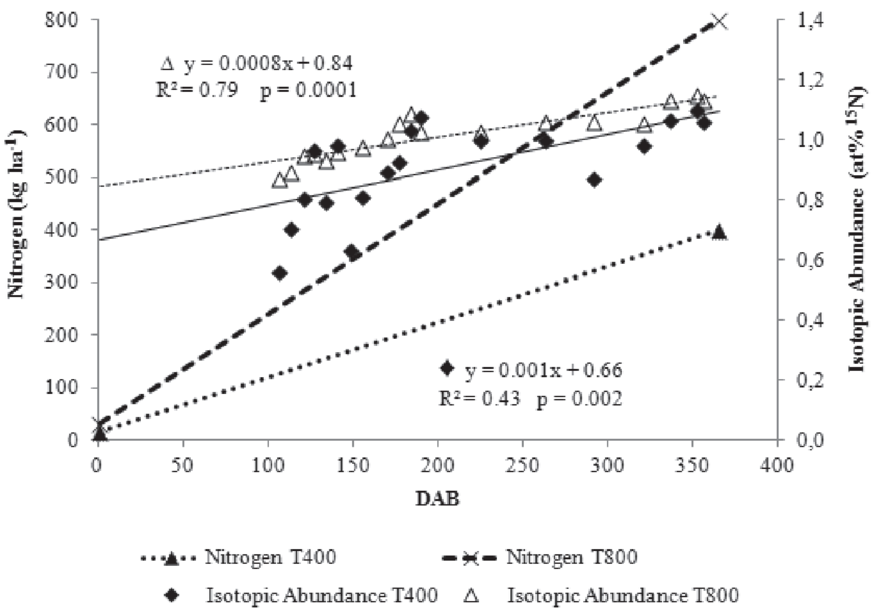

Figure 3. Distributions of monthly averages of ^{15}N abundance and their linear regressions as a function of days after beginning DAB, for the treatments T_{400} and T_{800}. Dashed and point lines starting from 0.0 indicate the progressive applications of ^{15}N urea, for T_{800} and T_{400}, respectively.

that would be an asymptotic behavior with decreasing increments and a tendency of stabilization due to the progressive ^{15}N applications. Data are less scattered as C_i and also show a tendency to increase with time, and linear regressions with significant R^2 coefficients. Figure 3 also shows the continuous lines of the urea applications, starting at 1 DAB with 15.4 for T_{400} and 30.8 kg ha^{-1} of N for T_{800}, and ending at 350 DAB with 400 and 800 kg ha^{-1} of N, respectively.

The distributions of C_i and %^{15}N in the deep drainage water are actually a function of several processes occurring in the atmosphere (rainfall and irrigation), in the plant (absorption and redistribution of N), and in the soil (physico-chemical and biological N transformations), which explain the scattering of the data. Details of plant N uptake evaluated at the same site and time, can be found in Bruno *et al*. (2011).

With the monthly data of C_i, $^{15}N_i$ and Q_i , the leached $QNddf_i$ was calculated by equation (2). Figure 4A shows that the peak of leached N happens in March (227 DAB), when 66.7% of the fertilizer had already been applied by fertigation. The difference between treatments T_{800} and T_{400} at this leaching peak was of 33 kg ha^{-1} month^{-1}of N, or 9.3 times higher for T_{800} in relation to T_{400}. The great difference between treatments is also a strong argument to justify the no use of statistical differences between them, because replicates were lost when making composite samples. The results showed that doubling the rate from 400 to 800 kg ha^{-1} year^{-1} of urea N led to about seven-time more leached N fertilizer. Bruno *et al*., (2011) demonstrated that the rate of 800 kg ha^{-1} is too high in terms of plant uptake efficiency and recommended the rate of 200 kg ha^{-1}, which would also reduce leaching losses significantly.

The accumulated leached N data (Figure 4B) also showed great differences between the treatments T_{400} and T_{800}, which at the end of the cropping cycle amounted to 14.7 and 104.5 kg ha^{-1}, respectively, or about 10 times more in favor to T_{800}. The accumulated data of $QNddf_i$ presented a good relationship with accumulated Q_i, for both treatments (Figure 5A), which was expected because

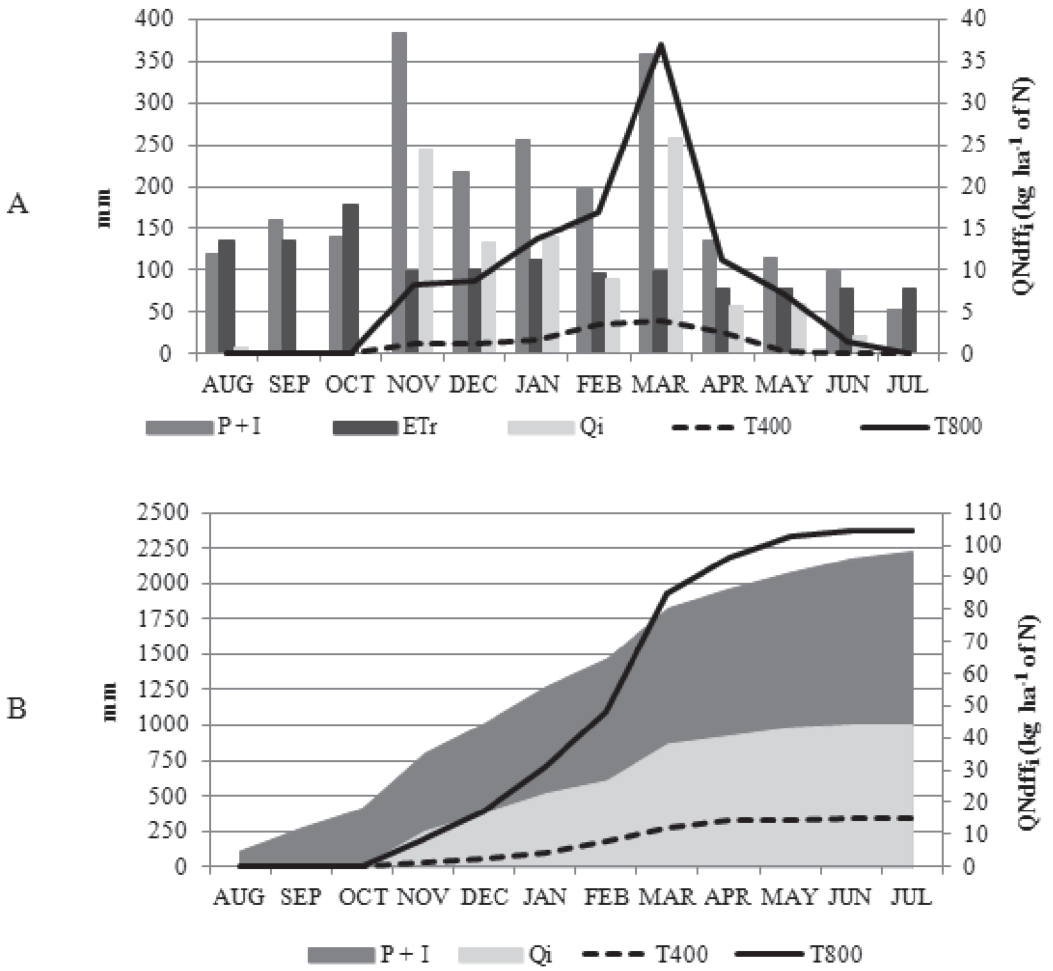

Figure 4. A: Rainfall + irrigation (P + I), actual evapotranspiration (ET_r), deep drainage (Q_i), and quantity of leached fertilizer N ($QNddf_i$) for the treatments T_{400} e T_{800} as a function of time; B: Accumulated data of rainfall + irrigation (P + I), deep drainage (Q_i), and quantity of leached fertilizer N ($QNddf_i$) for the treatments T_{400} e T_{800}.

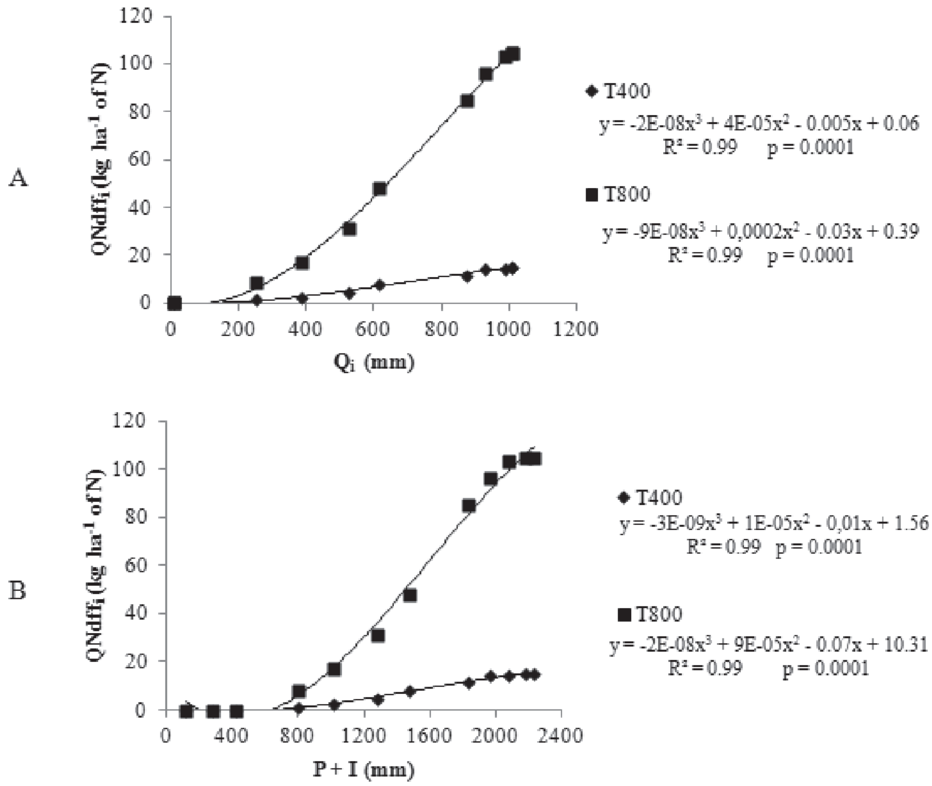

Figure 5. A: Relation between accumulated data of deep drainage (Q_i) and accumulative quantity of leached fertilizer N ($QNddf_i$) for the treatments T_{400} e T_{800}; B: Relation between accumulated rainfall and irrigation (P + I) and accumulated leached fertilizer N ($QNddf_i$) for the treatments T_{400} e T_{800}.

Table 5. Quantity of leached fertilizer N ($QNddf_i$) for the different scenarios using the two treatments T_{400} and T_{800}

Scenario	**T_{400}**		**T_{800}**	
	kg ha^{-1}	**% dose**	**kg ha^{-1}**	**% dose**
i (P + I)	14.7	3.7	104.5	13.1
ii (P)	12.0	3.0	88.4	11.0
iii (P + I_{dry})	12.3	3.1	91.0	11.4

P = rainfall, I = irrigation, I_{dry} = irrigation only in dry season.

calculations of the first included the second. Anyway, it was an interesting result, mainly in view of the scatter of C_i and $^{15}N_i$ data. Although the best regressions are third-order polynomials, the very low coefficients of x^3 and x^2 (Figure 5A) indicate that the relationship is essentially linear.

Similarly good relations were found for accumulated data of $QNdff_i$ and P + I (Figure 5B) showing the importance of the water input in the amount of leached N. Again, the coefficients of x^3 and x^2 (Figure 5B) indicate almost linear relations.

Nario *et al*. (2003), stress the fact that the leaching process depends on irrigation management. Quiñones *et al*. (2005) reported that the response to N fertilizer is influenced by irrigation methods, frequency and application timing, as well as by the processes of nitrification, imobilization, denitrification, volatilization and leaching. Boaretto *et al*. (2007) report that for citrus trees, the absorption of N is hindered in rainy periods due to leaching losses. According to Oliveira *et al*. (2002) and Franco *et al*. (2008) N losses by leaching may be negligible because most of the ^{15}N studies in sugarcane indicate very little leaching losses, as also recently reported by Ghiberto *et al*. (2011), however, for Silva *et al*. (2006) and Duete *et al*. (2008) these low losses cannot be disregarded.

In our study, to understand better the impact of irrigation on $QNdff_i$, three scenarios were analyzed: i, the first that really occurred under field conditions and the simulations ii and iii (Table 5).

For scenario i, in $T_{400,}$ the leaching amounted to 14.7 kg ha^{-1} of N fertilizer, which corresponds only to 3.7% of the total N applied. For scenario ii, this amount was only reduced to 12.1 per ha or 3.0%, showing that the major contributor to QNdff is P not I. Irrigation only during the dry season does not change very much this trend (scenario iii, Table 5). Because irrigation is widely spread for coffee plantations in this region, fertigation can be also applied during the wet season, however, following the recommendations of Bruno *et al*. (2011). Fenilli *et al*. (2008) reported a leaching of 6.5 kg ha^{-1} of N, corresponding to 2.3% of the total rate, in an area where 280 kg ha^{-1} of N rate was applied. In the second year, with a dose of 350 kg ha^{-1} of N, the leaching remained at the same 2.3% of the total N applied. Oliveira *et al*. (2007) also reported very low leaching losses in a pasture, however under very low N rates.

Results of treatment T_{800} were more than five times higher, showing that doubling the N fertilizer rate the effect on leaching is highly significant, leading to a loss of about 12% of the total applied urea. Again, for scenarios ii and iii the N leaching losses were not significantly reduced showing that the main responsible for this result is the rainfall, and that a reduction in N leaching can only be achieved by reducing the amount of N applications. As already mentioned, in other regions and other experiments the N leaching component was always of minor importance. Reichardt *et al*. (2009) also working with coffee found N leaching of 2.3% of the total N applied, Gava *et al*. (2006) for corn and Boaretto *et al*. (2004) for wheat reported losses of 1%, and Quiñones *et al*. (2005 and 2007) for citrus under controlled environment found only 0.1% of N losses.

CONCLUSIONS

Sequential water balance calculations using the model of Penman-Monteith for potential evapotranspiration and measured values of rainfall and irrigation, indicate that high amount of N fertilizer applied in fertigated coffee plantations in association with the high volume of precipitation (rainfall plus irrigation) are the main causes of N leaching in western Bahia, in Brazil. N fertilizer leaching of 14.7 and 104.5 kg ha^{-1} year^{-1} were recorded for the rates 400 and 800 kg ha^{-1} year^{-1}of N fertigated during the whole year, corresponding to 3.7 and 13.1% of the total amount of fertilizer input, respectively. Restricting irrigation only to the dry season, reduced N losses only to 12.3 and 91.0 ha^{-1}year^{-1}, showing that rainfall is the major determinant of N leaching.

ACKNOWLEDGEMENTS

The authors express their gratitude to CNPq and FAPESP for financial support and fellowships.

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