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Management effects on nitrogen recovery in a sugarcane crop grown in Brazil

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Abstract

The present study's objectives were to quantify the fertilizer-N and residue-N balances of a sugar cane crop under two trash management systems. The fate of nitrogen (N) derived from fertilizer (NdfF) and N derived from residue (NdfR) was studied comparing: (i) the traditional harvest system with trash burning before harvest ("trash burning") and (ii) an alternative system without trash burning, in which crop residues are left on the soil surface ("trash mulching"). The experiment consisted of three treatments: (i) T1: at planting, the sugarcane crop was fertilized with 63 kg N ha^{-1} as ^{15}N-labeled ammonium sulfate, and after the 1st harvest received unlabeled trash from T2; (ii) T2: at planting, the crop was fertilized with 63 kg N ha^{-1} as unlabeled ammonium sulfate. At the 1st harvest time, this treatment received the labeled trash from T1; (iii) T3: at planting, the crop was fertilized with 63 kg N ha^{-1} as ^{15}N-labeled ammonium sulfate, and every year, immediately before cutting, the crop residues were burnt. After the first harvest fertilizer-N was applied over the total soil area at a rate of 80 kg N ha^{-1} as unlabeled ammonium sulfate. The results indicated that the trash remaining as a surface blanket resulted in an average N recycling of 105.0 kg ha^{-1} $year^{-1}$, while the practice of burning the trash produced an average N loss from the system of 83.5 kg ha^{-1} $year^{-1}$. At the first harvest, about 75% of the labeled N was recovered in the soil–plant system. The majority was found in the plant, indicating a high availability of the fertilizer-N for the crop. At the end of the third crop cycle (2nd ratoon crop harvest), the total output of fertilizer-N (export + burning) was 60% for the burnt-trash treatment, and only 42% (export) for the trash-blanket treatment. The N liberated from the residue is mainly immobilized in the soil, reflecting that sugarcane trash is an N source of slow availability to the crop. This study indicated that green cane harvesting followed by mulching

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leads to a more efficient recycling of the N applied to the system and therefore reducing fertilizer-N needs.

Keywords: Sugarcane; ^{15}N; Fertilizer-N; Nitrogen balance; Trash management

1. Introduction

Brazil is the world's greatest sugarcane producer with a cultivated area of about 5 million ha. The sugarcane crop is traditionally harvested after burning the trash, mainly to facilitate manual cutting. This management practice is recently being replaced by machine harvesting, without previous burning, therefore leaving on the field a considerable amount of crop residues for the next ratoon crop (Trivelin et al., 1995; Oliveira et al., 2000). Pressures for this management change have come from environmentalists who address the issue of more sustainable land use.

Some of the main benefits of green cane harvesting include soil water conservation (Tominaga et al., 2002), reduced soil temperature (Oliveira et al., 2000; Dourado-Neto et al., 1999), reduced erosion, increased soil fertility, increased soil organic matter levels (Vallis et al., 1996), improved soil structure (Blair, 2000), and increased yield (Wood, 1991).

It is well documented that trash-mulched management contributes in the long term to an increase of the soil organic matter (SOM) level (Vallis et al., 1996). Although soil organic matter content is very important in both temperate and tropical agroecosystems in the tropics, there is a greater proportion of poor nutrient and highly weathered soils that are more susceptible to losses of organic matter (Feller and Beare, 1997). The rapid breakdown of organic inputs as a result of high temperature and high rainfall in many tropical areas makes the rehabilitation of SOM a slow process in these environments (Blair, 2000).

On the other hand, residue burning results in losses of nitrogen (Biederbeck et al., 1980; Raison et al., 1985; Lefroy et al., 1994) and may also have long-term negative effects on SOM (Biederbeck et al., 1980). The latter may cause deterioration of physical (Blair, 2000) and microbiological (Collins et al., 1992) conditions of the soil. In addition, residue combustion is a source of particulates and gaseous (CO_2, NO, NO_2, and N_2O) emissions to the atmosphere that may contribute to the "greenhouse effect", and the associated global warming.

A large quantity of nitrogen (N) is lost during burning in the traditional sugarcane harvest. Biederbeck et al. (1980) found that burning of grassland and wheat residues resulted in losses of 50–70% of the N contained in the residue, while Lefroy et al. (1994) recorded losses between 65% and 70% when rice trash was burnt.

The harvest of green sugarcane reduces N loss, so that nutrients contained in vegetal trash remain on the field and can be recycled in the system. Our hypotheses are: (1) that without trash, burning the N contained in the residues can be recycled in the system; (2) over time, an equilibrium could be achieved in which the N incorporation rate from trash into soil organic matter would be similar to the mineralization rate of the organic N, keeping the N content in the system more stable; and (3) nitrogen fertilization would only be needed to replace the N exported by the stalks. Therefore, fertilizer-N applied at planting would be readily available to the initial crop phase and would be complemented by the N mineralized from SOM. Thus, we would have a system with lower fertilizer-N inputs and with a stable soil N content as consequence of efficient trash nutrient recycling.

The objective of this work was to study the N cycling in a soil–plant system and compare the fertilizer-N and residue-N use efficiency by a sugarcane crop grown under the two above-mentioned trash managements.

Effects of these management systems on soil physical properties were published elsewhere (Dourado-Neto et al., 1999; Oliveira et al., 2000).

2. Material and methods

The sugarcane experiment was started last October 1997, on a Dark Red Latosol soil (Rhodic Kandiudox), locally called "Terra Roxa Estruturada" (Table 1), in Piracicaba, State of São Paulo, Brazil (22°4′S; 47°38′W), 580 m above sea level, 250 km inside the continent. The sugarcane variety SP 80-3280 was planted on an area of 0.21 ha, in 15 rows 100-m long, 1.4 m apart. The experimental scheme during the 3 years of evaluation was:

1. October 1997 to October 1998: plant-cane crop
2. October 1998 to October 1999: first ratoon crop
3. October 1999 to October 2000: second ratoon crop

At planting time (October 1997), three N treatments with four replicates each were imposed on the central part of the field (rows 7, 8 and 9), in such a way that each plot had three cane rows 4 m long (16.8 m^2). The N-fertilizer was broadcasted over the cane rows in a section of 0.5 m (0.25 m at each side of the row), covering therefore 0.5/1.4 = 0.36 of the total area, to assure maximum label uptake.

Treatment T1 consisted of green cane harvesting with surface trash mulching. At planting, the crop was fertilized with 63 kg N ha^{-1} as ^{15}N-labeled ammonium sulfate (11.6 at.% ^{15}N excess), and after the 1st harvest (October 1998), the first ratoon crop received unlabeled trash from T2. At the following harvests, no interchange of trash was made. Treatment T2 also consisted of green cane harvesting with trash mulching. At

Table 1
Physical and chemical soil characteristics of the 0–0.15 m layer at the beginning of the trial

Characteristic	Mean value
Sand (g kg^{-1})	290.0
Silt (g kg^{-1})	160.0
Clay (g kg^{-1})	550.0
Bulk density (Mg m^{-3})	1.349
pH (in $CaCl_2$)	5.0
Organic matter (kg m^{-3})	25.0
Calcium (molc m^{-3})	64.0
Magnesium (molc m^{-3})	18.0
Potassium (molc m^{-3})	4.3

planting, the same N rate as T1 was applied but with unlabeled fertilizer. After the first harvest, the first ratoon crop of T2 received the labeled trash from T1. Treatment T3 consisted of trash burning before each harvest. This treatment also received ^{15}N-labeled ammonium sulfate in October 1997 at the same rate as T1.

Phosphorus (P) and potassium (K) fertilization and other management practices adopted during the cane development were the same for all treatments. For the ratoon crops, N fertilization was uniform over years with the fertilizer broadcasted over the total soil surface at a rate of 80 kg N ha^{-1} as unlabeled ammonium sulfate.

During the first cycle (1997–1998), corresponding to the sugarcane plant–cane crop, the trash management treatments were not imposed yet. According to the procedure described above, at the first harvest, the ^{15}N-labeled trash from T1 was applied on T2 and the unlabeled trash of T2 on T1. So, after this first harvest, treatments T1 and T2 were considered complementary to each other, representing the trash-mulched treatment for the study of N derived from fertilizer (NdfF). This allowed us to differentiate between both N sources, soil and crop residues.

The soil system was considered as being the 0–0.5 m layer, which contains more than 90% of the active roots of the sugarcane. The plant system was considered as being the sugarcane shoot, i.e., stalks (export), straw and tips (trash). Roots and rhizome were not sampled separately due to the difficulties of their quantification and was therefore considered as part of N in other compartments (NOC). The NOC also includes N found below the 0.5-m soil depth and other possible losses, like volatilization, leaching, and run-off.

At the end of every cropping cycle, soil and plant compartments were sampled. For each replicate, three soil samples were taken (composed of three sub-samples, one from each rows 7, 8 and 9) at the depths of 0–0.15, 0.15–0.30, and 0.30–0.50 m. Auger holes were carefully closed after each sampling in order to avoid residue contamination at greater depths and also water infiltration. Plant samples (also composed of three sub-samples of 1 m, one from each rows 7, 8 and 9) were taken at harvest to determine the number of stalks per meter, weight of stalks, and weight of trash (straw + tips). After drying at 65 °C, the dry matter (DM, kg ha^{-1}) for each plant compartment was determined.

Plant and soil samples were analyzed for total N (Nt) and for ^{15}N/^{14}N isotope ratio using a mass spectrometer ANCA-SL, Europe Scientific, Crewe, UK (Barrie and Prosser, 1996).

The percentage of N derived from fertilizer (NdfF, %), the quantity of N derived from fertilizer (QNdfF, kg N ha^{-1}), and the fertilizer-N recovery (NdfFRec, %) for each compartment of the soil–plant system were calculated based on IAEA, 1983.

NdfF (%) in each compartment was calculated through the relation between the percentage of ^{15}N atoms in excess in a compartment x (atom %^{15}N.excComp.$_x$) and the percentage of ^{15}N atoms in excess in the fertilizer (atom %^{15}N.excFert.):

$$\%\text{NdfF}_x = \frac{(\%^{15}\text{N.excComp.}_x)}{(\%^{15}\text{N.excFert.})} \times 100$$

QNdfF (kg N ha^{-1}) for each compartment of the system was calculated by the product of NdfF (%) and the quantity of total N (QTN, kg N ha^{-1}) in the compartment:

$$QNdfF_x = \left(\frac{\%NdfF_x}{100}\right) \times QTN_x$$

For each plant compartment, QTN is the product of the dry matter (DM, kg ha^{-1}) and the percentage of total N (%, Nt), and for soil compartments, QTN is the product between the oven dry soil mass (SM, kg ha^{-1}) of the layer under consideration and %Nt of the layer, the soil mass being calculated from the soil bulk density (ρ_s) and the total soil volume (V_s), i.e., $QTN = \rho_s \cdot V_s \cdot \%Nt$.

Finally, NdfFRec (%) in a compartment (or system) is the relation between QNdfF and the total N supplied as fertilizer (TNF, kg N ha^{-1}), corresponding to the fertilizer-N use efficiency:

$$\%NdfFRec = \frac{QNdfF}{TNF} \times 100$$

The same procedure was followed for calculating the percentage of N derived from residues (NdfR, %), the quantity of N derived from residues (QNdfR, kg N ha^{-1}), and the residue-N recovery (NdfRRec, %) for each compartment of the soil–plant system.

For each variable, three samples were taken per replicate, their means calculated and compared by the *t*-test at the 5% probability level in order to determine whether or not the variable under consideration was influenced by the trash management system.

3. Results and discussion

3.1. Stalk yield and nitrogen accumulated in shoots

Stalk yield for the trash-mulched treatment was 120 and 103 Mg ha^{-1} for the 1999 and 2000 ratoon crops, respectively. For the burnt trash treatment, the cane production was 138 Mg ha^{-1} for the 1999 harvest and 119 Mg ha^{-1} for the 2000 harvest (Table 2). These differences were statistically significant ($P \leq 0.05$) for both 1999 and 2000 harvests. On the average, the yield of the burnt treatment was 17.0 Mg ha^{-1} higher than the mulched, which is important from the agricultural viewpoint. These results contrast with those observed by Ball-Coelho et al. (1993) in Brazil, Wood (1986) and Ridge and Dick (1989) in Australia, and McIntyre et al. (1996) in Mauritius, who found increases in sugarcane production when trash was left as a surface blanket.

Wood (1991) observed that trash cover on well-drained soils resulted in a large stalk yield increase in relation to the burnt trash practice, a difference that can average up to 10 Mg ha^{-1} $year^{-1}$; however, on heavier textured soils with restricted drainage, a slight yield reduction occurred with trash blanketing. In the case of our silty soil (Table 1), the harvest of the experimental plots was made manually (not using machines) and the trash cover was not chopped and remained bulky with a thickness of 0.15–0.20 m. This resulted in the

Table 2
Measured sugarcane crop variables: (1) fresh cane (Mg ha^{-1}); (2) quantity total of nitrogen (QTN, kg N ha^{-1}) of cane, tip and straw; (3) quantity of nitrogen derived from fertilizer (QNdfF, kg N ha^{-1}) in cane, tip and straw; and (4) unlabeled nitrogen uptake (kg N ha^{-1}) in cane, tip and straw for the three harvests of the trial

Variable	1998	1999 (1st ratoon crop)		2000 (2nd ratoon crop)	
	Plant-cane crop	Trash-mulched	Burnt-trash	Trash-mulched	Burnt-trash
Stalk Yield	112 (± 9.51)[a]	120 b (± 10.53)	138 a (± 3.45)	98 b (± 10.14)	119 a (± 9.71)
QTN					
Cane[b]	137.1 (± 14.26)	88.2 b (± 8.24)	127.5 a (± 14.28)	30.4 b (± 8.55)	47.0 a (± 5.43)
Tip[c]	77.1 (± 2.13)	48.4 a (± 3.55)	50.0 a (± 5.00)	50.8 a (± 12.77)	60.5 a (± 3.32)
Straw[d]	50.1 (± 2.66)	53.5 a (± 9.04)	59.0 a (± 3.55)	35.2 b (± 3.81)	47.5 a (± 4.96)
Total	264.3 (± 12.43)	190.0 b (± 20.38)	236.5 a (± 18.87)	116.6 b (± 22.07)	155.0 a (± 10.94)
QNdfF					
Cane[b]	22.2 (± 5.03)	3.1 a (± 0.33)	3.2 a (± 0.60)	0.9 a (± 0.18)	0.9 a (± 0.16)
Tip[c]	8.6 (± 0.58)	1.6 a (± 0.16)	1.3 b (± 0.16)	1.0 a (± 0.31)	1.0 a (± 0.22)
Straw[d]	9.0 (± 0.69)	2.3 a (± 0.42)	1.7 b (± 0.08)	0.6 a (± 0.12)	0.6 a (± 0.18)
Total	39.9 (± 5.76)	6.9 a (± 0.84)	6.1 a (± 0.54)	2.5 a (± 0.60)	2.5 a (± 0.38)
Unlabeled N[e]					
Cane[b]	114.9	85.1	124.3	29.5	46.1
Tip[c]	68.5	46.9	48.7	49.9	59.1
Straw[d]	41.1	51.2	57.4	34.4	46.8
Total	224.5	183.1	230.4	113.8	152.0

Treatments in the same year followed by different letters are statistically different at the 5% probability level. Each value is the mean of four replicates.

[a] Standard deviation appears in parenthesis.

[b] Export in the two treatments.

[c] Remaining in the system: 100% for Trash-mulched Treatment; 50% for Burnt-trash treatment.

[d] Remaining in the system: 100% for Trash-mulched Treatment; 0% for Burnt-trash treatment.

[e] Unlabeled N = QTN − QNdfF.

trash cover affecting sprouting and promoting fungal development, which can possibly be an explanation for the lower yields.

Carvalho et al. (1996), in an experiment set-up in Brazil, observed that the sugarcane trash produced an inhibitory effect considered as allelopathic. Allelopathy is a negative biochemical interaction between plants resulting from compounds produced by living plants and present in their residues, that may contribute to yield decline, as shown by Lovett and Hurney (1992) for sugarcane. In the present experiment, trash left on the soil surface might have exercised an inhibitory effect on ratoon sprouts whether by simple physical effects or by some allelopathic compounds liberated from trash, which can explain the lower yield in the trash-mulched treatment. A possible solution for this problem would be to spread the crop residues in the interrow.

Total amounts of N taken up by the above ground parts of the crop, N derived from fertilizer, and unlabeled N which is derived from other sources (mainly from the soil and subsequent fertilizations) are presented in Table 2. Values of QTN decreased consistently with time. Although there was an increase in stalk yield in 1999, QTN decreased because the N content of the stalks decreased. For 2000, there was a double effect, stalk yield and N content decreased, resulting in low values of QTN. Tips and straw had a consistent behavior.

During sugarcane preharvest trash burn, most residue biomass is burnt. In our experiment, for the burnt-trash treatment, it was observed that the straw (dead leaves) was completely burnt and that tips, which are green leaves and the apical gem of the stalk, were only partially burnt. A field evaluation of the remaining residues after burning indicated that about 50% of the dry matter of the tips was not burnt and remained as plant residue for the next crop. In the burnt-trash treatment, on the average, for the 3 years, the crop produced 6937 kg DM ha^{-1} $year^{-1}$ of tips and 13 998 kg DM ha^{-1} $year^{-1}$ of straw. So, the DM trash (tips + straw) produced was 20 935 kg DM ha^{-1}, and the burn of trash resulted in losses of 17 466 kg DM ha^{-1} (83.4% of DM trash). The trash N content averaged 114.7 kg N ha^{-1} of which 83.5 were lost by burning, corresponding to 72.8% of the total N in trash.

Similar results in a Brazilian sugarcane crop were reported by Ball-Coelho et al. (1993), who observed that 80% of dead leaf material and 64% of trash N were lost during preharvest burn.

In terms of total N available for recycling in the system, the residue mulch treatment counted with 105.0 kg N ha^{-1} $year^{-1}$, while the burnt-trash treatment only with 31.3 kg N ha^{-1} $year^{-1}$ (averages of the three harvests shown in Table 2), since it lost to the atmosphere 83.5 kg N ha^{-1} $year^{-1}$.

3.2. Recovered fertilizer nitrogen

Most of the NdfF in plant was taken up during the first year (plant-cane crop), decreasing thereafter in an approximately exponential way. It can also be seen that the contribution of sources other than labeled N-fertilizer to the crop is very large.

For the fertilizer-N balance shown in Table 3, the QNdfF in tips (8.6 kg N ha^{-1} in 1998 and 0.2 kg N ha^{-1} in 1999) and straw (9.0 kg N ha^{-1} in 1998 and 0.2 kg N ha^{-1} in 1999) represent the N input for the next ratoon cycle for the trash-mulched treatment. For the burnt-trash treatment, these values are much lower due to the above-mentioned losses to the atmosphere, resulting only 4.3 0 kg N ha^{-1} in 1998 and 0.7 0 kg N ha^{-1} in 1999.

As expected, at the 1st harvest (cycle 1, October 1998), no differences were observed between the trash-mulched treatment (T1) and the burnt-trash treatment (T3) in relation to NdfF recovered in the soil–plant system because during the first year, trash management treatments were not yet imposed (Table 3). The crop took up 63% of the fertilizer-N, of which 35% was allocated to stalks (exportation), and 28% to trash (tips + straw) (Tables 2–4). About 10% of the fertilizer-N was incorporated into the soil (Tables 3 and 4). These results are higher than the 20 to 30% of recovered NdfF reported by Vallis and Keating (1994). Although environmental factors have a great influence on fertilizer-N use efficiency (Trivelin et al., 1995), past research indicates that the recovery of fertilizer-N by sugarcane generally ranges between 21% and 40% (Takahashi, 1969, 1970; Chang and Weng, 1983; Sampaio et al., 1984). Wood (1991) using ^{15}N-labeled urea, observed that the sugarcane crop recovered 50% of the fertilizer-N when trash was left on the soil surface and less than 40% when trash was burned.

Table 3
Balance of nitrogen derived from fertilizer (QNdfF, kg N ha^{-1}) recovered in the soil–plant system

Cycle 1 = October 1997–October 1998 (Plant crop)				
	T1	T2	Trash-mulched T1 + T2	Burnt-trash T3
Input: ^{15}N-fertilizer October 1997	63.0	0	63.0	63.0
NdfF recovered at harvest October 1998				
Soil (0–50 cm)	8.1	0	8.1 a (± 1.00)	6.3 b (± 0.81)
Plant	39.9	0	39.9 a (± 5.76)	39.5 a (± 6.87)
Total: soil + plant	48.0	0	48.0 a (± 6.29)	45.8 a (± 6.78)
NOC 98[a]	15.0	0	15.0	17.2
Cycle 2 = October 1998–October 1999 (1st ratoon crop)				
Residual NdfF at the beginning of cycle				
Soil	8.1	0.0	8.1	6.3
Tips	0.0	8.6	8.6	4.3
Straw	0.0	9.0	9.0	0.0
Total	8.1	17.6	25.7	10.6
Part of NOC 98[b]	[15.0]		[15.0]	[17.2]
NdfF recovered at harvest October 1999				
Soil (0–50 cm)	11.1	10.0	21.1 a (± 0.74)	16.0 b (± 2.53)
Plant	6.3	0.6	6.9 a (± 0.84)	6.1 a (± 0.54)
Total: soil + plant	17.4	10.6	28.0 a (± 1.39)	22.1 b (± 2.59)
NOC 99[a]	5.7	7.1	12.8	5.8
Cycle 3 = October 1999–October 2000 (2nd ratoon crop)				
Residual NdfF at the beginning of cycle				
Soil	11.1	10.0	21.1	16.0
Tips	1.4	0.2	1.6	0.7
Straw	2.1	0.2	2.3	–
Total	14.6	10.3	25.0	16.7
Part of NOC 99[b]	[5.7]	[7.1]	[12.8]	[5.8]
NdfF recovered at harvest October 2000				
Soil (0–50 cm)	9.6	7.0	16.6 a (± 4.83)	14.4 a (± 1.21)
Plant	2.0	0.5	2.5 a (± 0.60)	2.5 a (± 0.38)
Total: soil + plant	11.6	7.5	19.1 a (± 4.90)	16.9 a (± 1.45)
NOC 00[a]	6.5	9.7	18.6	5.5

Treatments in the same year followed by different letters are statistically different at the 5% probability level. Each value is the mean of four replicates.
T1: Crop receiving labeled N-fertilizer in cycle 1 and mulched with unlabeled trash (tips + straw) in cycle 2.
T2: Crop receiving unlabeled N-fertilizer in cycle 1 and mulched with labeled trash (tips + straw) in cycle 2.
T3: Crop receiving labeled N-fertilizer in cycle 1 and being burnt before each harvest.

[a] NOC = Nitrogen in other compartments.

[b] Brackets indicate that the amount of NOC that would be recovered in the system at the beginning of each new cycle is unknown.

Table 4
Nitrogen derived from fertilizer recovered in the soil–plant system as percentage of the nitrogen applied as fertilizer (%NdfFRec) at each harvest

	Harvest 98 (Cycle 1)	
	Trash-mulched (T1)	Burnt-trash (T3)
Soil (0–50 cm)	12.8	10.0
Plant	63.3	62.7
Total: soil + plant	76.1	72.7
	Harvest 99 (Cycle 2)	
	Trash-mulched (T1 + T2)	Burnt-trash (T3)
Soil (0–50 cm)	33.5	25.4
Plant	10.9	9.7
Total: soil + plant	44.4	35.1
	Harvest 00 (Cycle 3)	
	Trash-mulched (T1 + T2)	Burnt-trash (T3)
Soil (0–50 cm)	26.3	22.9
Plant	4.0	4.1
Total: soil + plant	30.3	27.0

In most of the cases, the low recovery of fertilizer-N is caused by high losses, mainly by volatilization (Denmead et al., 1990). Urea is the mostly used N-fertilizer for sugarcane in Brazil (Cantarella, 1998) and in Australia (Wood, 1991). When urea is broadcasted over crop residues, the losses of N by ammonia volatilization increase considerably due to the activity of the urease present in the trash (Trivelin et al., 1998) and can reach values of 20–40% according to Cantarella (1998), and still higher (Wood, 1991).

The cause of the relatively high fertilizer-N recovery by the crop in our experiment can be attributed to the following factors: (i) localized application of the fertilizer (0.5-m band on the plant row) followed by an adequate rainfall (13.4 mm) which distributed the fertilizer within the root zone, (ii) the used fertilizer, ammonium sulfate, is a less susceptible N source to volatilization as compared to urea, (iii) the N rate used can be considered low when compared to those used in most experiments that reported low values of recovered fertilizer-N.

The fact that the main sink for fertilizer-N was the crop shows that this N was rapidly available for the sugarcane plants during the first cycle (plant-cane crop). Nevertheless, only 15% of the Nt taken up by the plant crop comes from the fertilizer (Table 2). In general, 80% of N taken up by sugarcane comes from other sources, mainly the soil, and only 20% from fertilizer (Chang and Weng, 1983; Weng and Li, 1992).

In the following years, a lower availability of the N from the ^{15}N-fertilizer was observed for the crop, due to N immobilization in soil organic matter and microbial biomass.

At the 2nd harvest (cycle 2, October 1999), trash mulching (T1 + T2) had a more efficient use of the labeled fertilizer-N in comparison to burnt trash (T3), 28.0 and 22.1 kg N ha^{-1} (Table 3) or 44.4% and 35.1%, respectively (Table 4). The difference between treatments in recovered fertilizer-N could be a consequence of the N lost by burning. Although the same trend was observed at the 3rd harvest (cycle 3, October 2000), the difference between the two residue managements in recovering the labeled fertilizer-N in the soil–plant system was not significant (Table 3).

For the two ratoon crops, a high percentage of NdfF remaining in the system for the trash-mulched treatment was mainly immobilized in soil organic pools. After the first cycle, on average, 74% of NdfF was recovered by the system and 26% was unaccounted for. The fertilizer-N not recovered is here referred as N in other compartments (NOC) and is shown in Table 3. NOC is calculated by difference at each harvest. These amounts are only partially available for the next ratoon crop, so their contribution to the residual NdfF at the beginning of each cycle is unknown and presented between brackets in Table 3. The NOC of 1998 explains the increase of soil NdfF in October 1999 and its relatively small decrease in October 2000.

Since the N-fertilizer was applied just before a rain event of 13.4 mm, the immediate incorporation into the soil probably avoided possible losses by volatilization. Losses by leaching were also considered insignificant because the incorporation of the N-fertilizer was slow and did not reach a great depth due to the low rate of N application and the light rain. Soil solution extraction cups, installed at the depth of 0.5 m showed, during the first cycle, very little $N-NO_3^-$ content, of which less than 1% was derived from fertilizer.

On the other hand, the N of the below ground plant parts represents a stock of N that is available over time. During decomposition of these plant parts, N is released and becomes available for the new ratoon crop or immobilized by soil microorganisms.

In our study, an important fraction of the NOC 98 could be in the below ground parts of the plant, i.e. rhizomes and roots. The turnover of this plant material is the source of some NdfF that was found in the system at the first ratoon crop harvest, complementing the NdfF that remained in the soil (including that below 0.5 m) after the 1998 harvest (Table 3).

Fig. 1 shows that over the 3-year experimental period, about 42% of the fertilizer-N applied to the system was exported by canes for both trash managements. The remaining NdfF in the soil–plant system was 29.4% for the trash-mulched treatment and 23.7% for the burnt-trash treatment. The burning process was responsible for a fertilizer-N loss of 27%. Therefore, at the end of the crop cycle 3, the total output of fertilizer-N (export + burning)

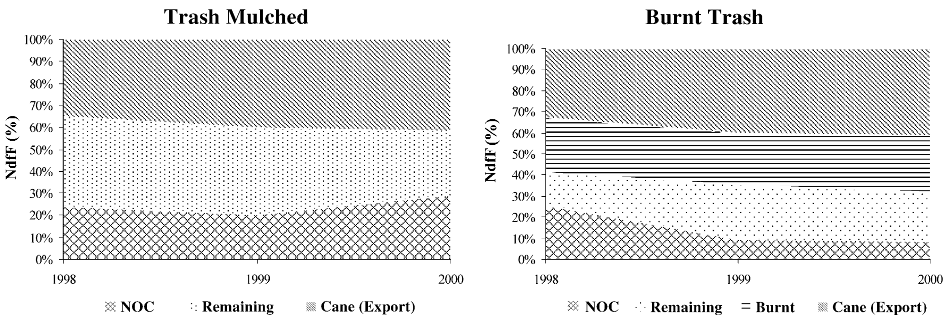

Fig. 1. Fate of nitrogen derived from fertilizer in the two trash management systems. Cane (stalk) is the N export of the system; burnt is the nitrogen lost by burning straw and tips; remaining is the nitrogen that is left in the system; NOC is the nitrogen in other compartments unaccounted for.

was 60% in the burnt-trash treatment and only 42% (export) in the trash-blanket treatment, assuming no other N losses occurred.

It can also be noted that while in the NOC compartment, only 8.6% of the fertilizer-N remain for burnt-trash management, for the trash blanket remain 29.0%. This difference is explained by the N recycling that occurs when the trash remains in the system. Probably, a great part of the NOC that represents N in below ground plant biomass could become available in the future for subsequent ratoon crops. It is important to say that soil samples were sieved and that the below ground plant biomass greater than 2 mm was removed from them.

3.3. Recovered trash nitrogen

The use in T2 of labeled trash from T1 permits us to study separately the fate of ^{15}N from both soil and crop residues. Thus, the treatment T2 besides being complementary to T1 for the study of N derived from the fertilizer (NdfF) allows following the redistribution in the system of the N derived from residues (NdfR). The labeled trash produced in T1, which was added to T2 in October 1998, had 127 kg N ha^{-1} of which only 17.7 kg ha^{-1} came from the fertilizer (NdfF).

Of the total trash biomass produced by the plant crop at the 1998 harvest, 7532.7 kg ha^{-1} (40.6%) corresponds to tips (with 1.3 at.% ^{15}N excess) and 11,015 kg ha^{-1} (59.4%) to straw (with 2.1 at.% ^{15}N excess). Therefore, the atom percent ^{15}N excess of the trash was taken as the weighed average of tips and straw [at.% ^{15}N excess in trash=$(1.3\% \times 0.406)+(2.1\% \times 0.594)=1.8\%$]. Thus, the labeled trash added to T2 was considered as having an excess of 1.8 at.% ^{15}N.

At the October 1999 harvest, 12 months after covering the soil of T2 plots with the labeled trash of T1, NdfR recovery in the soil–plant system was 55.1% (69.9/127 kg N ha^{-1}). At the October 2000 harvest, the NdfR recovery fell to 39.3% (49.9/127 kg N ha^{-1}) (Table 5). This N release rate from trash is large in comparison to the rate of 18% of trash-N mineralization found by Oliveira et al. (1999) during a period of 11 months and to the N liberation from, residues of 27% reported by Ng Kee Kwong et al. (1987) after 18 months of residue stay on the field.

Table 5
Nitrogen derived from residues (QNdfR and %NdfR)[a] recovered in different compartments of the soil–plant system for the two ratoon crops (T2: trash-mulched treatment)

Compartment	October 1999 harvest		October 2000 harvest	
	QNdfR (kg N ha^{-1})	NdfR (%)	QNdfR (kg ha^{-1})	NdfR (%)
Stalk	1.8 (± 0.26)[b]	1.4	1.8 (± 0.30)	1.4
Tip	1.0 (± 0.24)	0.8	1.1 (± 0.38)	0.9
Straw	1.1 (± 0.28)	0.9	0.6 (± 0.20)	0.5
Soil	66.0 (± 3.48)	52.0	46.4 (± 7.45)	36.5
Total: plant + soil	69.9	55.1	49.9	39.3

[a] NdfR is the nitrogen that comes from the plant crop residue remaining in the system after the first harvest in 1998.

[b] All values are means of four replicates ± SD.

Most of the N liberated from the trash and incorporated into the soil–plant system was immobilized in the soil (94%), i.e. the N residue absorption by the crop was very low. This fact reflects the lack of synchronization between the availability of N from trash and the crop N demand.

Although sugarcane trash is not an important N source to the crop in the short term, the organic crop material that is left on the field when using the trash-mulched management system contributes, in the long term, to an increase of the soil organic matter level (Vallis et al., 1996) and improves soil structure (Blair, 2000).

4. Conclusions

In this study, the trash retained as a surface blanket allowed N recycling of 105 kg N ha^{-1} $year^{-1}$, while the practice of burning the trash before harvest presented only 31.3 kg N ha^{-1} $year^{-1}$ for recycling, since it lead to a N loss from the system of 83.5 kg N ha^{-1} $year^{-1}$.

At the plant-cane harvest, about 75% (46–48 kg N ha^{-1}) of NdfF was recovered in the soil–plant system, and most part was found in the plant, indicating a high availability of the fertilizer-N for the crop. For the subsequent ratoon crops, the availability to the crop of the NdfF that still remained in the system, decreased sharply.

At the end of crop cycle 3 (October 2000 harvest), 23.7% of NdfF remained in the system and 8.6% was unaccounted for (NOC) in the burnt-trash management system. For the trash-blanket management, NdfF remaining in the soil–plant system was 29.4% and a similar amount of NdfF (29%) corresponded to NOC. Although the NdfF that remained in the system was not significantly different between trash-mulched and burnt-trash management systems, for the trash-mulched treatment, the amount of NOC after 3 years of evaluations was still high. An important amount of this NOC is contained in rhizomes and roots. The turnover of the below ground plant parts could liberate this N and make it available to the subsequent ratoon crops.

The sugarcane trash is an important source of N; nevertheless, the N liberated from these residues is mainly immobilized in the soil, reflecting that sugarcane trash is a N source of slow availability to the crop.

The quantification of the flow of organic matter presented above, evaluated in terms of N balance, indicates that when the sugarcane trash is not burnt before harvesting, a more conservative and sustainable agroecosystem is obtained. Besides avoiding air pollution due to burning, this study indicated advantages of the green cane harvesting followed by mulching include more efficient N cycling, thus reducing fertilizer-N input requirements.

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