The fate of fertilizer N in field studies in the volcanic Lesser Antilles with ^{15}N-urea

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In the Lesser Antilles, recent replacement of old rural systems by intensive market gardening (MG) has led to a decrease of the soil organic matter (OM) content. A field experiment was designed on different types of soils (vertisol, ferrallitic soils, and andisol), to determine the effect on soil OM content of previous land use, either fallow (F) and pasture (P) or MG and banana plantations (B). The fate of ^{15}N-urea applied to a maize crop was studied under the different combinations of soil type and previous land use history. Plant productivity of maize crops reflected N uptake, but not the N levels in soil OM. In the Lesser Antilles, soil OM does not limit plant productivity. However, immobilization of fertilizer N in soil (and thus a reduction of N losses) was positively linked to soil OM status. Losses, except for the andisol, were less than 30% of applied urea N, an observation which favours the use of urea in this humid tropical area.

Keywords: Andisol; Ferrallitic soils; Humid-tropical Caribbean volcanic islands; Maize; ^{15}N-urea plant efficiency; ^{15}N-urea immobilization; ^{15}N-urea losses; Vertisol

Most Caribbean volcanic islands are characterized by a wide variety of climates and parent materials, resulting in a large diversity of soils (Colmet Daage and Lagache, 1965; Starck *et al.*, 1966; Lang, 1967). Historical and socioeconomic circumstances have led to a variety of imposed agrosystems, such as co-existence of low-intensified rural systems [fallow (F) systems] and plantation systems and market gardening (MG) crops and livestock (CEE, 1988). These systems can lead to variations of organic content in the top layer of the soil (Feller, 1988; Feller *et al.*, 1990). However, the effects of land management on soil organic status depend upon climatic conditions, soil types, and texture. In Puerto Rico, Lugo *et al.* (1986) indicated that variations of soil organic content under dry climatic conditions were lower than those recorded under moist conditions.

The effect of soil organic matter (OM) on soil fertility is well known. It promotes plant productivity (Siband, 1974; Diatta, 1975), controls the distribution of soil microorganisms, and influences soil structure (Feller *et al.*, 1996). However, very little of the extensive literature on the role of soil OM in soil properties is aimed at describing the main processes of N balance (e.g., plant nutrition, immobilization, and losses) in the soil–plant system.

As part of a research programme dealing with the dynamics of soil OM in different farming systems, the effects of different cropping histories on the fate of ^{15}N-urea in the soil–plant system have been investigated for a maize cropped in some of the most representative soils of the Caribbean.

Materials and Methods

Soils and site

The soils represented some typical volcanic soils of the Caribbean zone; an andisol (A3) located in Dominica (La plaine), a vertisol (V1) situated in the south-east part of Martinique (Sainte-

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Anne), and two ferrallitic soils (F2 and F4), one located in St Lucia (Roblot) and the other in Guadeloupe (Petit Bourg). With the exception of the A3 whose mineral fraction is dominated by allophane, these soils are heavy clay soils, mainly consisting of kaolinite or halloysite in the two ferrallitic soils (F2 and F4) and smectite in the V1.

Climatic conditions

The annual air temperature in the Caribbean region averaged 26°C. The main climatic difference between the four sites was annual rainfall and its seasonal distribution. Annual rainfall varied from 5400 mm in Dominica (A3) to 1300 mm in Martinique (V1), where the dry season is the more pronounced.

Maize grown on V1 was irrigated. For the rainfed crops, the rainfall during the entire cycle was 829 mm, 739 mm, 752 mm, and 966 mm for A3, F2, F4 after F, and F4 after MG, respectively (Table 1). With the exception of A3, where a heavy rain of 150 mm was recorded the day after the fertilization, rainfall was equally distributed within the growing cycle, with average daily rainfall ranging from 6.3 mm to 7.2 mm.

Previous cropping history

For each type of soil, two experimental sites were investigated according to previous cropping histories, which was either F or pasture (P) or banana (B) or MG. The selected sites had similar soil depth, pedological feature in the profile, position in the slope, top layer clay content, and clay mineralogy. The organic C and N contents of the top layer (0–10 cm) varied according to the previous history of land use. With the exception of A3, soils previously under F or P have higher C and N contents than those used for MG (Table 1).

Experimental procedure

The experimental procedure was the same for each experimental site. Maize (Eto Amarillo of CYMMIT population) was sown at a rate of 50 000 plants ha^{-1}. Each experimental site consisted of six plots (six replicates) of five rows (3.25 m length, 4.50 m width, and 100 maize plants in each row). Mineral fertilizers (80 kg P ha^{-1} and 80 kg ha^{-1}), were provided to the seedlings, in the form of triple superphosphate and potassium chloride, respectively. Nitrogen (100 kg N ha^{-1}, as ^{15}N-urea or non-enriched urea), was spread one month later (maize with 5–7 leaves) in solution on a 30-cm wide strip on one side of the row of plants. A 3-m^2 subplot was delineated on three of the six plots, and was supplied with ^{15}N-urea (isotopic excess = 1.20%). The other three plots were fertilized with non-enriched N-urea. Six plots were left unfertilized (control) but they were not analysed in this paper (Chotte *et al.*, 1990).

Sampling and analyses

Maize was harvested 100–110 days after sowing. Yields were assessed from six plots (total number of 600 maize plants) and expressed on an oven-dried weight basis (80°C).

Soil samples (0.2 kg) were taken from 0–10 cm, 10–20 cm, and 20–40 cm depth ranges in the central row of each of the six plots, on the fertilized strip, and between maize plants after harvesting. This operation was repeated

Table 1 Site characteristics

Geographical location				Rainfall (mm)		Pedological characteristics (0–10 cm layer)						
Soil types[†]	Location	Symbol	Past cropping[††]	Annual	Growing cycle	Mineralogy[†††]	C (mg g^{-1})	N (mg g^{-1})	CEC (mmol kg^{-1})	0–2 µm (g 100 g^{-1})	pH (water)	Bulk density (g cm^{-3})
A	Dominica	A3	F	5400	829	AL	107.70	10.70	46	nd	4.6	0.42
A	Dominica	A3	B	5400	829	AL	93.40	9.10	25	nd	4.3	0.42
F	Guadeloupe	F2	P	3000	739	Kao/Hal	41.00	3.23	38	60	5.8	0.85
F	Guadeloupe	F2	MG	3000	739	Kao/Hal	19.90	1.64	31	63	5.8	1.18
V	Martinique	V1	P	1300	Irrigated	Sme	31.20	3.06	417	84	5.5	0.98
V	Martinique	V1	MG	1300	Irrigated	Sme	11.80	1.68	617	75	6.2	0.99
F	St Lucia	F4	F	2000	752	Kao	29.40	2.52	52	61	5.9	1.09
F	St Lucia	F4	MG	2400	966	Kao	19.00	2.21	16	70	5.8	0.90

[†]A = andisol, F = ferrallitic soil, V = vertisol
[††]F = fallow, P = pasture, B = banana, MG = market gardening or food-producing crops
[†††]AL = allophane, Kao = kaolinite, Hal = halloysite, Sme = smectite
nd = not determined
CEC = cation exchange capacity

three times per plot and replicates were pooled to obtain an average sample (0.6 kg) per plot. For this sample, roots [alive and (or) dead] were separated from the soil by successive sievings (Feller, 1988). Total root mass of the maize was calculated in relation to above-ground mass using the ratio tops:roots of 15% (Hétier *et al.*, 1986).

Soil samples were air-dried, sieved (2 mm), and ground (200 µm) before analysis. Roots were dried at 80°C and ground (200 µm). Total N in soil and plant were measured by the Kjeldahl-Olsen method, modified by Guiraud and Fardeau (1977a) so that nitrate was included. The ^{15}N isotopic excess of plant parts was measured by an optical spectrometer (SOPRA GS1), after oxidation to N_2 by lithium hypobromite within a vacuum device, after Ross and Martin (1970). Soil samples were analysed by mass spectrometry, with a device desiged for measuring natural abundances (Mariotti and Letolle, 1978). Inorganic N was extracted from the soil by a solution of 1M KCl, and ^{15}N-inorganic was measured by an optical spectrometer as mentioned above. The ^{15}N isotropic technique was used:

- (i) to differentiate between N derived from urea (dfu) and N derived from soil OM (dfs) (i.e., Np = Np dfu + Np dfs) in the total amount of N used by the plant (Np) [i.e., tops (Nt) or roots (Nr)];
- (ii) to calculate the Coefficient of Real Utilization (CRU) of urea N which is expressed as the percentage of applied N used by the plant;
- (iii) to calculate the amount of N derived from urea (dfu) present in the soil (Ns) as inorganic N or immobilized as organic microbial metabolites; and
- (iv) to calculate the amount of N lost as the difference between the amounts of fertilizer applied and those recovered in tops, roots, and soil.

Statistical analyses

The data were analysed with one-way analysis of variance and the mean values were compared with the Student's test ($P < 0.05$). Comparisons between sites were not performed because of climatic and pedological differences.

Results and Discussion

Maize productivity

Maize growth was not impeded by erratic rainfalls at any of the sites. The lowest productivities were obtained on F4 amounting to 4 and to 6 t dry matter (DM) ha^{-1} for maize following F and MG, respectively, and on A3 for those plots following F (7.5 t DM ha^{-1}) (Figure 1). The yields obtained on V1 and F2 soils were similar to those obtained by others working in tropical environments and with equivalent applications of fertilizer (Taylor and Bailey, 1979; Hétier *et al.*, 1989). On these soils, maize cropping after MG and P did not lead to any differences in maize yield. However, on A3 and F4, maize crops planted in plots which had been left F, produced less yields than after B planting, or after a food-producing and MG rotation, respectively.

Nitrogen plant nutrition

Tops

Total N (kg ha^{-1}) in tops (Nt) varied from 24–142 kg N ha^{-1} (Table 2). The N contents of specific parts of plant tops were constant for all sites and cropping histories (grain = 1.70 ± 0.15%, cob axis = 0.46 ± 0.04%, stalks + leaves = 0.80 ± 0.08%) (Chotte *et al.*, 1990). Therefore, the total N in tops was positively correlated with plant DM productivity. The CRU of urea N expressed as a percentage of the initial amount applied, varied from 12 to 51%. The lowest CRUs were calculated for F4 (from 12 to 22%); they were slightly higher for A3 (from 20 to 35%) and ranged between 38 and 51% for V1 and F2. For each soil, CRU values assessed on plots corresponding to F or P precedents were lower than those obtained on plots corresponding to either B or MG rotation precedents. The quantities of N derived from applied ^{15}N-urea and exported in tops, expressed as a percentage of total N in tops (Nt), was about 50%. The highest proportion was found for F4 (from 49 to 50%), and the lowest (20 to 50%) for A3. For V1 and F2, percentages varied from 31 to 45%. Consequently, most of the N in tops originated from soil OM (Nt dfs); this quantity, expressed as a percent-

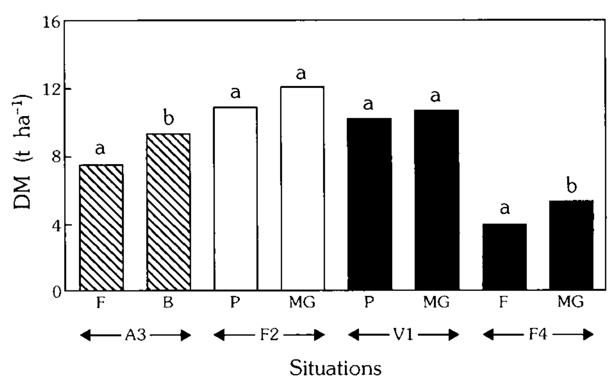

Figure 1 Total maize yield. For each soil type, two different letters indicated a significant difference at $P < 0.05$ (Student's test)
Past cropping: F = fallow; P = pasture; B = banana; MG = market gardening or food-producing crops
Soil type: A = andisol; F = ferrallitic soil; V = vertisol

Table 2 Total yield (DM) and nitrogen (N) derived from urea (dfu) or from the soil (dfs) in the tops (t), the roots (r), and the whole plant (p = t + r)

Soil	Past cropping	DM (t ha^{-1})			N dfu (kg ha^{-1}) or CRU[1] (%)			N dfs (kg ha^{-1})			N dfu + N dfs (kg ha^{-1})		
		Nt	Nr	Np	Nt	Nr	Np	Nt	Nr	Np	Nt	Nr	Np
A3	F	7.9	1.2	9.1	20	3	23	79	12	91	99	15	114
A3	B	10.1	1.5	11.6	35	5	40	107	16	123	142	21	163
F2	P	11.1	1.7	12.8	40	5	45	67	11	78	107	16	123
F2	MG	12.4	1.9	14.3	51	7	58	63	10	73	114	17	131
V1	P	10.3	1.5	11.8	38	7	45	95	11	96	123	18	141
V1	MG	10.7	1.6	12.3	42	7	49	89	13	102	131	20	151
F4	F	4.1	0.6	4.7	12	2	14	12	2	14	24	4	28
F4	MG	5.5	0.8	6.3	22	3	25	21	3	24	43	6	49

Past cropping: F = fallow; P = pasture; B = banana; MG = market gardening or food-producing crops
Soil type: A = andisol; F = ferrallitic soil; V = vertisol
[1]CRU is Coefficient of Real Utlization

age of Nt, was always greater than 50%. For all situations, the soil supplied from 12 to 107 kg N ha^{-1}. The lowest values were observed for F4 (from 12 to 21 kg N ha^{-1}) and the highest for A3 (from 79 to 107 kg N ha^{-1}). For V1 and F2, the Nt dfs values varied from 63 to 89 kg N ha^{-1}. For A3 and F4, Nt dfs values were lower on plots which had been left F, compared to those obtained on plots previously used for B for A3 and MG for F4. For V1 and F2, Nt dfs did not vary with the nature of the previous crop (P or MG). The key role played by soil OM in N plant nutrition has been well documented (Campbell *et al.*, 1984; Moraghan *et al.*, 1984a, b; Shinde *et al.*, 1985; Hétier *et al.*, 1989; Ganry, 1990). In the present study, the contribution of soil OM to plant nutrition was not related to organic status. This result was unexpected, since a positive relation between N mineralization potential and soil organic status had been established in a previous laboratory experiment (Chotte *et al.*, 1994). This may have arisen from the presence of active maize roots modifying the mineralization of soil OM (Jenkinson, 1977; Billes and Bottner, 1981; Ried and Goss, 1982).

Roots

Total N present in roots ranged from 4 to 21 kg N ha^{-1}, with 2 to 7 kg N ha^{-1} derived from urea N (Nr dfu). Consequently, roots utilized from 2 to 7% of the initial fertilizer supplied. The Nr dfu, expressed as the percentage of total N of roots, varied from 49 to 51% for F4, from 31 to 41% for V1 and F2, and from 19 to 25% for A3.

With the exception of F4, more than 50% of the total root N came from the soil. Soil OM was thus the main source of root N, supplying from 2 to 16 kg N ha^{-1} to plant roots.

The whole plant

Total plant N varied from 28 to 163 kg N ha^{-1} (Table 2), and was positively correlated to yield (Figure 2). The CRU values for the entire plant ranged from 14 to 58%. For A3 and F4, the highest values were obtained on plots previously occupied by B and MG, respectively. For V1 and F2, the nature of previous land use did not modify the CRU values. There were no clear relationships between efficiency of N fertilizer use and previous cropping history and thus soil OM status.

The contribution of soil N to the whole plant, Np dfs, ranged from 14 to 123 kg N ha^{-1}. For A3 and F4, amounts were greater in plots following B or MG. For V1 and F2, there was no difference with respect to the nature of past cropping. These results alone, over one year of cropping, did not demonstrate a link between the level of soil OM, and the quantities of N taken up by the plant.

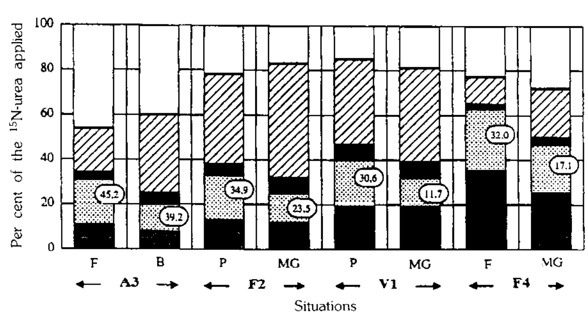

Figure 2 Relationship between total dry yield (DM kg ha^{-1}) and total plant N (Np kg ha^{-1}); 0–10 cm layer carbon content (t ha^{-1})
Past cropping: F = fallow; P = pasture; B = banana; MG = market gardening or food-producing crops
Soil type: A = andisol; F = ferrallitic soil; V = vertisol

Soil immobilization of fertilizer N

At the harvest, no ^{15}N-urea-derived inorganic N was present in the soils (Table 3). Since the quantities of ^{15}N fixed to the absorbing complex of A3 (Ahmad *et al.*, 1982), F2 and F4 (François *et al.*, 1991), and V1 (Chotte *et al.*, unpubl.) were very low, ^{15}N-urea present in the soil was completely immobilized as microbial metabolites. They were expressed as a percentage of the initial supply of ^{15}N-urea, and varied from 20% to slightly more than 60% (Figure 3). The lowest quantities were found for A3, possibly as a result of significant N losses by leaching due to the heavy rain (150 mm) on the day after fertilizer was applied. For the V1 and F2, 25 to 40% of ^{15}N-urea was immobilized in the soil. The highest quantities were found in F4 located in St Lucia, where they represented 61 and 47%, respectively, for plots previously F and planted with MG crops. On this soil, plant yields were the lowest and, in the absence of mineral fertilization (control treatment), maize did not proceed beyond the flowering stage (Chotte *et al.*, 1990).

Table 3 Soil organic matter (SOM) content, and urea-derived organic N and inorganic N present in the soil at the harvest (Ns dfu)

Soil	Past cropping	Layer (cm)	SOM content t ha^{-1} C	SOM content t ha^{-1} N	Ns dfu (kg ha^{-1}) Organic N	Ns dfu (kg ha^{-1}) Inorganic N
A3	F	0–10	45.2	4.5	20	0
		10–20	37.0	3.5	5	0
		20–40	44.2	4.2	6	nd[1]
A3	B	0–10	39.2	3.8	12	0
		10–20	36.3	3.6	4	0
		20–40	35.0	3.6	4	nd
F2	P	0–10	34.9	2.7	20	0
		10–20	38.9	2.9	4	0
		20–40	66.0	5.0	9	nd
F2	MG	0–10	23.5	1.9	13	0
		10–20	22.2	1.8	3	0
		20–40	53.6	5.6	9	nd
V1	P	0–10	30.6	3.0	21	0
		10–20	18.6	2.1	10	0
		20–40	31.5	4.1	9	nd
V1	MG	0–10	11.7	1.7	13	0
		10–20	11.1	1.7	9	0
		20–40	16.4	3.1	10	nd
F4	F	0–10	32.0	2.7	28	0
		10–20	25.3	2.3	19	0
		20–40	45.8	4.8	16	nd
F4	MG	0–10	17.1	2.0	22	0
		10–20	17.8	1.9	11	0
		20–40	39.4	4.5	14	nd

Past cropping: F = fallow; P = pasture; B = banana; MG = market gardening or food-producing crops
Soil type: A = andisol; F = ferrallitic soil; V = vertisol
[1]nd = not determined

Comparison between the amount of ^{15}N-urea immobilized in a soil as microbial metabolites, suggested that these quantities were higher for the site that had been previously under F or P than those recorded on the other site planted with MG crops. These observations can be related to the significantly lower OM content of the latter site in comparison to those of the F or P situations (Table 3). The highest differences in immobilized ^{15}N-urea were observed in the 0–10 cm layer, where the variations of OM content were also the most significant. For example, for V1, ^{15}N-urea-derived microbial metabolites (Ns dfu) in the 0–10 cm layer was about 13 kg ha^{-1} on plots following MG crops. In post-P soils, where the organic content of the 0–10 cm layer was three times higher than that of the cropped plot, microbial immobilization of applied ^{15}N urea was about 21 kg ha^{-1}. Approximately 10% more of the N-urea applied was immobilized in the richest OM soils. This may have resulted from the stimulating effect of the plant residues on immobilization processes (Huntjens, 1971; Guiraud and Fardeau, 1977b; Pichot and Egoumenides, 1981), this residue being more abundant in soils under F than under crops (Feller, 1988). Differences in ^{15}N-urea immobilized were not significant in deeper layers (10–40 cm) whose organic content was slightly modified by previous cropping histories.

Losses of fertilizer N

The losses were calculated as the difference between the amount of fertilizer applied and that recovered in tops, roots, and soil. The quantities of ^{15}N-urea taken up by the roots were calculated using the ratio tops:roots of 15%. The use of this ratio is supported by the fact that in the present experiment, (i) N is not a limiting factor for maize (tops and roots) growth; and (ii) an error of 50% on the estimation of this ratio leads to a low variation in the calculated losses (i.e., 20 and 4% for low and high losses, respectively).

The A3 differed from the other soil types because of the high losses (40 to 45%) of fertilizer N incurred during maize growth. The heavy rain (150 mm) following fertilizer application produced leaching which was probably

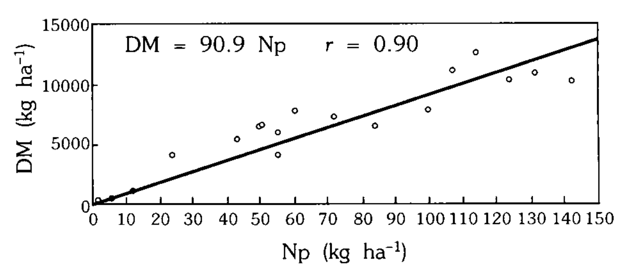

Figure 3 Recovery of ^{15}N-urea (per cent of the ^{15}N applied)

the main cause of the loss. In tropical conditions, urea hydrolysis to NH_4^+ can be very rapid, from a few hours to a few days (Wickremasinghe *et al.*, 1981; Victoria *et al.*, 1982; Vyas and Mistry, 1985). This process leads, soon after fertilization, to an accumulation of ammonium in the solution, which can then be leached if no transformation has occurred (i.e., immobilization through microbial synthesis or fixation by the absorbing complex). This is also supported by the fact that A3s are characterized by a low capacity to fix ammonia-N (Ahmad *et al.*, 1982) and by large quantities of mineral N present in the soil after fertilization (Godefroy and Dormoy, 1983a). Losses could be reduced by using several low-level fertilizer applications rather than a single high-level application (Godefroy and Dormoy, 1983b; Powlson *et al.*, 1992).

For V1 and the F2 and F4, losses of fertilizer N averaged 20% of that applied. Similar losses were assessed for other tropical clay soils (Campbell *et al.*, 1984; Moraghan *et al.*, 1984a, b; Shinde *et al.*, 1985; Hétier *et al.*, 1989). For an alfisol from Venezuela (Oxic Tropustalf, yearly rainfall = 1700 mm), Hétier *et al.* (1989) showed that only 2% of fertilizer N was lost by leaching, whereas total losses amounted to 30%. Losses were mainly due to denitrification. Losses through volatilization as NH_3 were low because of the rapid urea hydrolysis, an acid to neutral pH, and high cation exchange capacity (CEC) values of the soils (Faurie and Bardin, 1970; Fergusson *et al.*, 1974).

For these soils, representing most of the typical soils of the Caribbean zone, the results obtained within the first maize cropping cycle allowed the following conclusions to be drawn:

1. With the exception of the F4 in St Lucia, total maize yields exceeded 8 t DM ha^{-1}. For this soil, applied N-urea was not lost but immobilized as microbial metabolites, indicative of the good microbial health of the soil. Although the nature of the constraint responsible for the weak growth of maize has not been worked out, the depressive effect of pathogens such as phytoparasitic nematodes can be advocated.
2. With the exception of A3s, field losses of urea-N (20 to 30% of the N applied) are not high enough to dissuade growers from using urea in these environments.
3. The amounts of N taken up by the plants derived either from urea or from soil were highly dependent on plant productivity, but non-dependent on soil OM content.
4. Urea-N immobilization in a given soil appeared to be influenced by soil OM content, and, thus, by the nature of previous cropping history.

In the Lesser Antilles, land use histories of either F and P or MG and B have a significant effect not only on soil OM but also upon fertilizer N lost and immobilized in the soil. Although the soils of this zone have higher OM content than most African soils, the development of sustainable intensive food cropping should preserve their organic status. This would enhance the economic viability of smallholders by avoiding unnecessary losses of fertilizers.

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