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EFFECT OF STRAW INCORPORATION ON THE YIELD AND NITROGEN BALANCE IN THE SANDY SOIL-PEARL MILLET CROPPING SYSTEM OF SENEGAL

by F. GANRY*, G. GUIRAUD** and Y. DOMMERGUES***

SUMMARY

In a lysimetric experiment conducted in a sandy soil of Senegal, nitrogen fertilization (^{15}N) and straw incorporation, were combined factorially, the soil being left bare or cropped with millet. On the one hand, yields were estimated, and on the other hand nitrogen absorption, immobilization, and losses were estimated in the soil-plant system.

The depressive effect of straw incorporation on grain yield (32% on the average) was attributed mainly to the immobilization of fertilizer nitrogen in the rhizosphere. The depressive effect of such immobilization was alleviated by additional applications of nitrogen. Increasing the quantity of straw incorporated beyond the average amount resulted in a decrease of straw yield but had no effect on grain yield. Straw incorporation was thought to impede the plant growth during early stages but to promote it afterwards. Moreover, when the yield expressed in a fertilizer nitrogen unit basis was the highest, more than half of the plant nitrogen was nevertheless provided by the soil. The authors infer from this fact that soil organic matter was important in the efficiency of nitrogen fertilizer on pearl millet.

The reduction of fertilizer nitrogen absorption following straw incorporation and not compensated by additional nitrogen fertilizer storage in the soil appeared to be related (cause or effect) to the increase of total fertilizer losses.

Atmospheric losses significantly contributed to total losses (on the average 45%) of the fertilizer nitrogen applied to a planted soil. These losses can be mainly attributed to denitrification.

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PRELIMINARY REMARKS

For the sake of clarity we give hereafter the definition of the expressions used in this paper.

1. *N-storage in the soil* or *N- immobilization* is the sum of microbiological immobilization and chemical immobilization of N.
2. *N-fertilizer productivity* is the quantity of dry matter, expressed in g of millet (whole plant), produced per g of fertilizer-N added.
3. *Coefficient of actual utilization of fertilizer-N* is N-fertilizer absorbed by the plant expressed per 100 units of fertilizer-N applied.
4. *N-fertilizer efficiency* is N originating from fertilizer absorbed by the plant and immobilized in the cultivated soil layer, expressed per 100 units of fertilizer-N applied.

INTRODUCTION

The maintenance of the nitrogen fertility of tropical sandy soils containing low levels of total nitrogen (*ca.* 02%) relies, in the absence of long duration fallow, on maximum restitution of crop residues, and specially straw, this being a major prerequisite for efficient utilization of nitrogen fertilizer. However, drops in yield have often been observed as a direct result following incorporation of unmodified straw, which could not be suppressed by the use of mineral fertilizers[7 15]. Straw incorporation can be in some cases, therefore, the reason of a decreased efficiency of mineral nitrogen fertilizer.

We have likewise demonstrated in two field trials that the coefficients of actual utilization of fertilizer nitrogen in the grain remained less than 20%, which is a low level. On one of these trials, cropped with pearl millet, the total losses of fertilizer nitrogen (taking into account fertilizer nitrogen immobilized to a soil depth of 90 cm) were estimated to be 23% the first year and 17% the second, probably in the form of gaseous N.

The experiment which we present here is an attempt to elucidate the mechanisms involved in the N-fertilizer efficiency loss. The study deals with the effect of straw incorporation on nitrogen economy.

MATERIAL AND METHODS

Experimental design

The experiment was carried out in 35 × 35 × 40 cm microlysimeters containing 60 kg of a slightly eluviated tropical ferruginous soil, called 'Dior soil', collected at Bambey station after a groundnut crop and subjected to natural climatic conditions (no irrigation). The experimental design was a $3^2 \times 2$ factorial, or a total of 18 treatments with two replications.

Treatments

Crop (pearl millet)	Straw incorporation (tons/ha)	Addition of fertilizer-N (kg/ha)
Presence	M0 = 0	N0 = 0
Absence	M1 = 7.5	N1 = 90 N
	M4 = 30.0	N2 = 150 N

Hence we had 9 treatments for planted and non planted soil MoNo, MoN1, MoN2, M1No, M1N1, M1N2, M4No, M4N1 and M4N2.

Preparation of the lysimeters was carried out during the dry season, in February 1973. Finely chopped (but not pulverized straw) was incorporated into a soil remoistened to field capacity in order to reproduce conditions occuring at the end of the rainy season. Incorporation of 7.5 t/ha is an amount realizable in practice, while 30 t/ha is a theoretical figure, adopted here for understanding the mechanisms involved. The crop was sown on July 16, 1973.

Nitrogen fertilizer was added in the form of urea at 3 times during the growth cycle: 1/5 at planting, 2/5 at thinning, and 2/5 at the end of stem elongation. The nitrogen of urea was enriched with an excess of ^{15}N isotope of 9.49% for the 90 N treatments and 9.39% for the 150 N treatments.

Analytical methods. *Leachates during plant growth.* Four samplings of leachates were made during plant growth. Unfortunately a part of the leachates corresponding to the second sampling, could not be recuperated and was thus eliminated (Fig. 1). Total mineral nitrogen was determined on the remaining leachates.

Plant and soil at harvest. The whole plant was separated into three parts: grain, straw + rachis + glumes, and roots, on which dry matter production and total nitrogen were measured.

The soil of each lysimeter was sampled in its entirely and passed through a 2-mm sieve. Dry matter weights and total nitrogen were measured on the organic material remaining after a 2 mm sieving of this soil. Total nitrogen and hydrolyzable nitrogen were determined on the sieved soil.

Chemical and isotopic analyses of the different samples. In the leachates, ammoniacal nitrogen was recovered by alkaline distillation (direct measurement) in 0.01 *N* sulphuric acid; nitric nitrogen was reduced to ammoniacal nitrogen by Dewarda alloy, then distilling.

In the soil, total nitrogen was determined by the Kjeldahl method. Hydrolyzable nitrogen represents the organic nitrogen fraction liberated by hot acid hydrolysis[5]. Mineral nitrogen, found in negligible amounts in the soil at the end of the rainy season, was not determined.

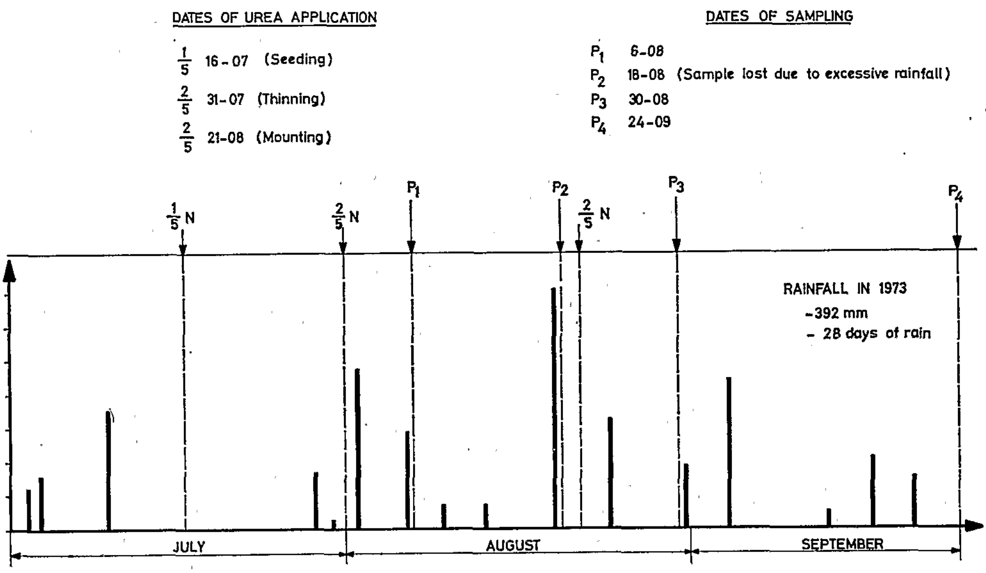


Fig. 1. Rainfall distribution, dates of N-fertilizer applications and of leachate sampling

In plant material, total nitrogen was measured by the Kjeldahl method modified by adding salicylic and sulphuric acids.

The percentages of ^{15}N were measured with a mass spectrometer, and isotopic excess determined by deducting the amount of naturally occurring ^{15}N of 0.362% from this percentage.

TABLE 1

Soil characteristics

pH (H_2O, 1:2.5)	6.2
pH(KCl, 1:2.5)	5.4
Clay + silt	4.0 %
Total carbon	2.4 ‰
Total nitrogen	0.17‰
Exch. bases (in meq/100 g of soil)	
Ca^{++}	0.7
Mg^{++}	0.3
Na^{+}	0.05
K^{+}	0.13
Sum of exchangeable bases (S)	1.2
Total exchange capacity (T)	4.0
Saturation rate (S × 100 : T)	35

Environmental conditions

Climate. The climate of Senegal is characterized by a marked contrast between the rainy season and the dry season. During the year of experiment, rainfall amounted to 392 mm distributed over 28 days of rain.

Soil. The main physical and chemical characteristics of the soil studied are given in Table 1.

Plant. The cereal used was a short stemmed, 75-day pearl millet (GAM), bred in Senegal to meet the requirements of intensified agriculture where rainfall is less than 500 mm.

RESULTS AND DISCUSSION

Effect of straw on yield and utilization of nitrogen by plants (planted and non planted soil)

Yield. The data are illustrated by Fig. 2 (A, B, C, D, E and F). Fig. 3 shows the principal effects of straw incorporation on plant yield.

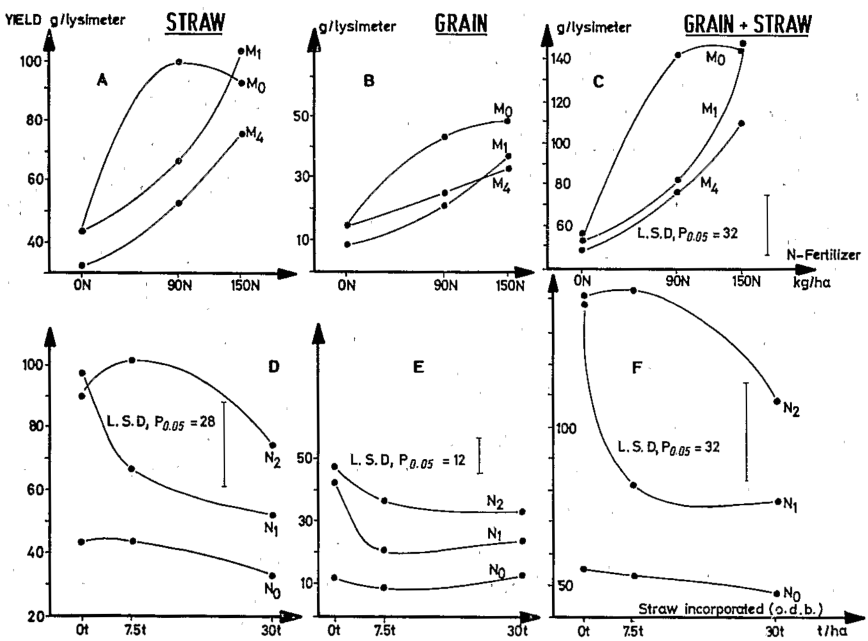


Fig. 2. Yield of pearl millet as affected by N-fertilizer and straw incorporation.

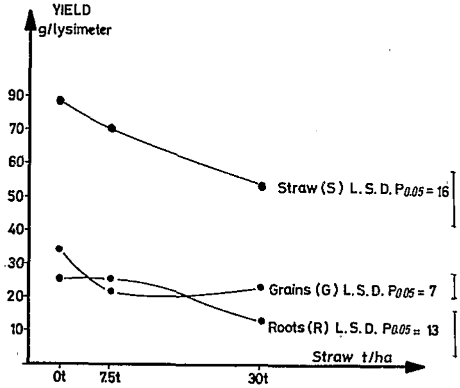


Fig. 3. Principal effect of straw incorporation on pearl millet yield

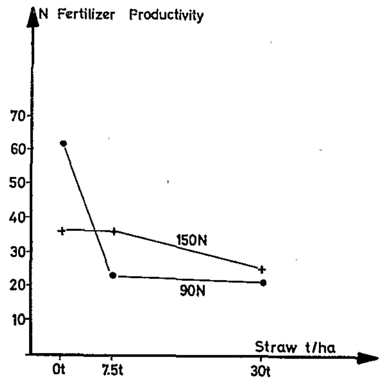


Fig. 4. Fertilizer-N productivity as affected by straw incorporation.

The principal effect of straw incorporation was a depression of both grain (32%) and straw yield (27%) (Fig. 3). However, the decrease in grain yields was very sharp between M_0 and M_1 and null between M_1 and M_4; in contrast, the decrease in straw and root yields was quite small between M_0 and M_1 but pronounced between M_1 and M_4. Although the 'N $\times$ incorporated straw' interaction was not significant, the shape of the curves suggests that the decrease in yield was particularly sharp in N_1M_1 treatment: amounting to 52% for grain, 32% for straw (Fig. 2E and 2D) and 39% for rachis + glumes. We may observe that, for the N_1M_1 treatment, an additional application of nitrogen increased total dry matter yield in a spectacular manner (Fig. 2F).

There are two possible interpretations of the phytodepressive effect observed: Phytotoxicity or/and nitrogen immobilization, which we shall try to explain in the Discussion.

Nitrogen uptake by the plant. The results are illustrated by Fig. 5(A, B, C).

The curves of total nitrogen uptake have not been presented because in general they parallel those of dry matter yield. It should be noticed, however, that total nitrogen content decreases in the grain, following straw incorporation whereas it increases in the straw (Table 3).

Fertilizer nitrogen uptake by the plant. The principal effect of straw incorporation on the coefficient of actual utilization of fertilizer

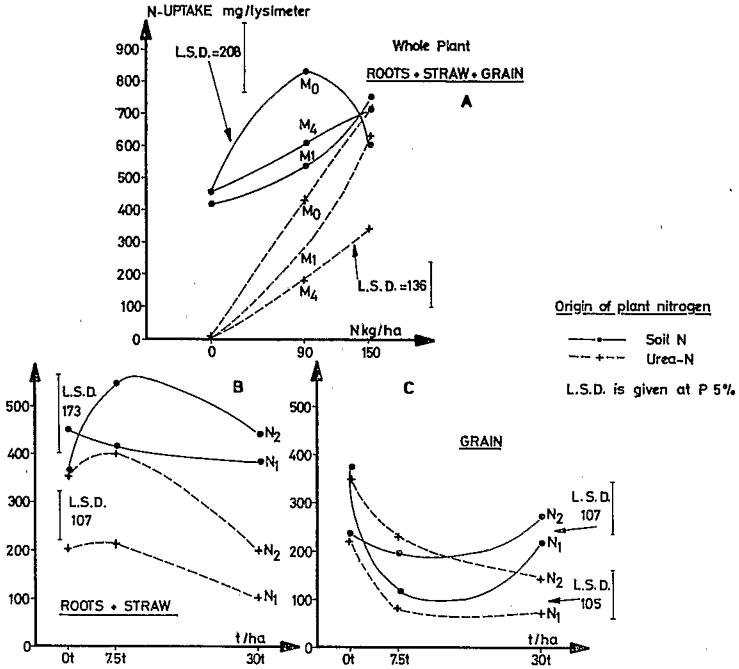


Fig. 5. Effect of N-fertilizer and straw incorporation on N uptake by the plant. (N_0, N_1 and N_2 respectively 0, 90 and 150 N) (M_0, M_1 and M_4 respectively 0, 7.5 and 30 t/ha)

nitrogen was depressive (Table 2) both in the case of grain, (it decreased from 15.6% to 6.5% between level M_0 and levels M_1 and M_4), and in the case of straw (it falls from 16.8% to 8.3% between M_0–M_1 and M_4). This coefficient of actual utilization of fertilizer nitrogen, relatively low, was approximately the same for both grain and straw and half as great as for roots: mean values of 9.6%, 8.7%, and 4.6% respectively for grain, straw, and roots. Its maximum values was 25.1% in the aerial parts (straw + grain) corresponding to the maximum yield obtained at M_0.

The quantity of fertilizer nitrogen absorbed by the entire plant (roots + straw + grain) varies linearly in function of the amount of fertilizer nitrogen applied (Fig. 5A); however, it was smaller in case of straw incorporation. The reduction in the quantity of fertilizer nitrogen absorbed, according to the amount of straw incorporated, was similar to the reduction of yield.

TABLE 2

Coefficient of actual utilization of N-fertilizer by plant. Percentage of total plant nitrogen derived from soil

	Grains			Straw			Roots			Grains + straw		
N fertilizer	N1	N2	Mean	N1	N2	Mean	N1	N2	Mean	N1	N2	Mean
Straw												
Coefficient of actual utilization of N-fertilizer												
M0	16.5	14.8	16.6a*	10.2	8.9	9.5a	4.8	6.5	5.7a	26.7	23.6	25.1a
M1	5.8	9.5	7.6b	9.7	9.7	9.7a	6.0	7.6	6.8a	15.5	19.2	17.3a
M4	4.9	5.9	5.4b	6.6	7.8	6.8a	1.4	1.6	1.5b	11.4	12.9	12.1b
Mean	9.1c	10.1c	9.6	8.8b	8.5b	8.7	4.1c	5.2c	4.6	17.9c	18.6c	18.2
Percentage of total plant N derived from soil												
M0	62.2	40.0	51.1a	68.7	49.8	59.3a	69.3	52.3	60.8a	65.0	44.0	54.5a
M1	59.6	46.8	53.2a	64.9	57.8	62.3a	68.2	56.3	62.3a	62.9	53.0	58.0a
M4	75.6	64.9	70.2b	77.5	68.8	73.2b	77.2	68.3	72.8	77.1	67.2	72.1b
Mean	65.8c	50.8b	58.2	70.4c	59.4b	64.9	71.6c	59.0d	65.3	68.3c	54.7b	61.5

* Data followed by the same letter are not significatively different at P 0.05

TABLE 3

Nitrogen content of grain, straw and root (expressed in p. 1000)

N fertilizer	Grains				Straw				Root			
	N0	N1	N2	Mean	N0	N1	N2	Mean	N0	N1	N2	Mean
M0	14.8	14.1	12.4	13.8a*	5.0	4.6	4.4	4.7a	9.0	9.0	7.5	8.5a
M1	11.0	9.6	11.5	10.7b	6.0	5.7	5.7	5.7b	8.2	9.8	8.9	9.0a
M4	10.6	11.2	12.2	11.3b	8.0	7.7	7.2	7.6c	9.5	9.0	9.0	9.2a
Mean	12.1c	11.6c	12.0c	11.9	6.3b	6.0d	5.7	6.0	9.0b	9.3b	8.5b	8.9

* Data followed by the same letter are not significatively different at P 0.05

Soil nitrogen uptake by the plant. The principal effect of nitrogen fertilization on the quantity of soil nitrogen was positive. However, the significant interaction 'Fertilizer-N × incorporated straw' by the plant into its straw and grain indicated that, at the level M_0, the quantity of soil nitrogen absorbed reached a maximum at N_1 rate; whereas at the levels M_1 and M_4 it increased as a function of the rate of fertilizer nitrogen applied (Fig. 5A). In general, nitrogen fertilizer increases the exploitation of soil nitrogen by the plant.

No significant modification of the quantity of soil nitrogen absorbed appeared as a result of the principal effect of straw incorporation; however, the 'N × straw' interaction was significant for straw + grain, indicating that the quantity of soil N absorbed reached a minimum at M_1 specially marked at the N_1 nitrogen level (Fig. 5B and 5C).

Percentage of nitrogen in plant derived from soil. Table 2 shows that the percentage of plant nitrogen derived from the soil nitrogen decreased with the rate of nitrogen fertilizer and increased with the amount of straw incorporated. The 'N × straw' interaction, significant on the soil N percentage, for grain and for straw, demonstrated that at N_1 rate, the percentage reached a minimum at M_1 while at level N_2 it increased uniformly though at a lower level from M_0 to M_4. The mean percentage is 58% for grain, 65% for straw, and 65% for roots; for aerial parts (grain + straw), the mean was 61%, varying from 44% at N_2 M_1 treatment to 77% at N_1 M_2 treatment. It is fitting to underline that at maximum dry matter yields, attained in N_1 M_0 and N_2 M_1 treatment, its value was 65% and 53% respectively. This means that, at nitrogen fertilizer levels resulting in maximum productivity per unit of nitrogen, the per cent of plant nitrogen derived from the soil was greater than 50%. The soil nitrogen plays a role in yield at least as important as that of fertilizer nitrogen. This result brings to light the importance of the level of mineralizable soil organic matter in the productivity per unit of nitrogen.

Discussion

These results provide evidence of a certain number of difficulties concerning yield and nitrogen uptake by the plant: straw incorporation decreased grain yield up to M_1 straw level; between M_1 and M_4 grain yield was not affected; by contrast, straw yield decreased as the amount of incorporated straw increased; the decrease of nitrogen content of grain linked to increased nitrogen content of straw under the action of straw incorporation and the decrease of soil nitrogen absorption between N_1 and N_2 at the level M_0.

These results could suggest that straw induces a phytodepressive effect probably caused by an early phytotoxicity and/or a modification of the rhythm of nitrogen supply to the plant during its growth cycle. Kimber[12] showed that the phytotoxicity due to the decomposition of wheat straw effects wheat seedlings after germination (particularly if the straw is placed on the soil surface), whereas nitrogen immobilization was responsible for the reduction in grain yield. Nevertheless, the yield, always less than the control (no incorporation) even when high rates of fertilizer are applied, leads Kimber to believe that the inhibitory effect of straw remains the limiting factor of production. Furthermore, the same author (1967), cited by Allison[1] points out that roots are more affected than aerial parts by inhibitory growth substances. Our results indicate that roots do not show any reduction in weight except between M_1 and M_4 (Fig. 3) whereas the aerial parts are affected starting with level M_1. For these reasons we think that the depressive effect at M_1 could be due to the immobilization of nitrogen (grain weight significantly reduced but not root weight) and that the depressive effect at M_4 would be principally due to phytotoxicity (decreased root and straw weight). The stability of grain yield between M_1 and M_4 linked to increased soil nitrogen uptake in the grain, could be explained by an improved supply of nitrogen during plant growth resulting from the incorporated straw.

However, in the presence of incorporated straw the plant most likely remains underfed in nitrogen as suggested by the substantial lowering of the nitrogen content of grain as compared to straw (Table 3). In general, as several authors have already demonstrated[2 4], nitrogen fertilizer increases the plant's exploitation of soil nitrogen.

Concerning the decreased use of fertilizer nitrogen with straw, we can not say whether this is the consequence of less development, or whether the unavailability of this fertilizer nitrogen to the plant (blockage, losses) caused it reduced development.

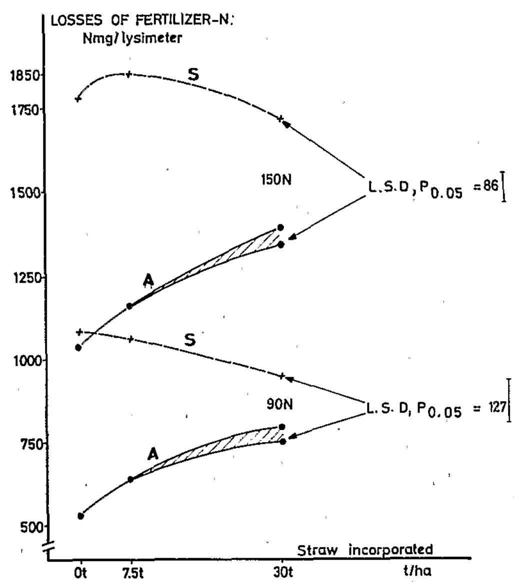
Role of straw in total losses of nitrogen fertilizer in the agrosystem

Determination of total losses. The portion of nitrogen fertilizer not stored in the plant nor in the soil represents the total losses. These losses include nitrogen lost by leaching and lost to the atmosphere. The results of these total losses are given in Table 4 for the case of a planted soil, and are illustrated in Fig. 6 for both a bare and a planted soil. For the planted soil, organic material greater in size than 2 mm was taken into account. Its importance as a storage compartment of fertilizer nitrogen is however negligible at level M_1, but represents 2 to 3% of nitrogen fertilizer at level M_4.

TABLE 4

Evaluation of total losses of fertilizer N from a planted soil. Per cent of fertilizer applied

Straw	N fertilizer	Total fertilizer N in plant	Total fertilizer N in soil	Total fertilizer N in plant + soil	Total losses of fertilizer N
M0	N1	31.5	29.2	60.7	39.2
	N2	30.1	25.4	55.5	44.5
M1	N1	21.5	32.3	53.8	46.2
	N2	26.8	25.0	51.8	48.1
M4	N1	12.8	32.5	45.3	54.7
	N2	14.5	28.7	43.2	56.8



[The hachured surface shows the quantity N-fertilizer stored in the coarse fraction of organic mater (> 2mm)]

Fig. 6. Losses of fertilizer-N in planted soil (A) and non planted soil (S) as affected by straw incorporation.

Importance of total losses in planted soil. These losses were a function of (1) the fertilizer nitrogen rate rising significantly from 47% to 50% for N_1 and N_2 respectively, and (2) the amount of straw incorporated, representing 42%, 47%, and 56% of fertilizer nitrogen for incorporation levels M_0, M_1, and M_4 respectively (significant differences).

It is quite probable that the lesser uptake of fertilizer nitrogen by the plant in the presence of straw (Fig. 5C) was linked – cause or effect – to an increase of nitrogen fertilizer losses. In a bare soil, these losses were relatively greater but decrease in function of the amount of straw incorporated.

Atmospheric losses. The method of budgeting enables the determination, via ^{15}N, of the exact portion of fertilizer nitrogen which has disappeared in the atmosphere by difference between the total losses and losses by leaching. Unfortunately in our experiment the latter can not be known precisely (see paragraph Analytical methods) but nevertheless an estimation in excess of their exact value enables us to deduce atmoshheric losses which are therefore evaluated conservatively.

If we take up again the estimated values of nitrogen fertilizer leaching, that was 19% for the bare soil and 9% for the cropped soil, we are led to mean values for this fertilizer nitrogen lost to the atmosphere of 55% for the bare soil and 45% for the cropped soil. These losses would be essentially due to the processes of denitrification.

Conclusion

In a planted soil, total losses of fertilizer nitrogen vary from 39% to 57% of the nitrogen fertilizer (urea) applied; they increase with straw incorporation and to a lesser extent with fertilizer rate. The portion of this nitrogen lost through leaching does not exceed 10%, which implies that at least 30% of the fertilizer nitrogen disappeared into the atmosphere, essentially by denitrification, straw incorporation increases these losses by denitrification (Fig. 7). This hypothesis is not new[10 11], but what is unexpected is the abnormally high intensity of this process of denitrification in tropical sandy soils. Results of a recent experiment, obtained by application of the method of N_2O reduction[9], showed that losses of nitrogen through denitrification can be considerable in the large organic fractions. Note that the sandy soils of Senegal, as a result of low porosity which in general is about 40%[13], with high temperature and high rainfall (therefore water saturation of soil) in August (Fig. 1) would probably be even more subject to substantial losses of nitrogen through denitrification. Leaching of fertilizer nitrogen is only detectable at the beginning of the growth cycle. It only affects therefore the first two fertilizer applications. Tourte *et al.*[14] and Blondel[3] studying nitrogen leaching under similar experimental conditions had already demonstrated that leaching of nitrogen in nitric form only occurred at the beginning of the drainage period.

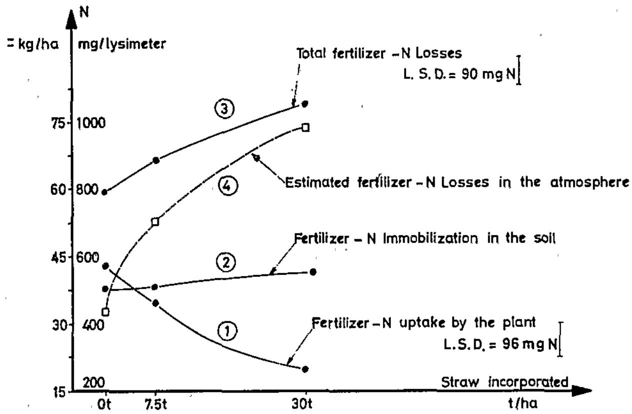
It is important to point out that if planting is carried out in a dry soil before the first rain, this leaching can still be greatly reduced; in fact, in an experiment[8] conducted the following year and similar to the present one, we showed that leaching did not exceed 1% of nitrogen fertilizer applied although the quantities of water leached were higher than in the present experiment.

Sowing in dry soil, split applications of nitrogen fertilizer or slow acting fertilizer are therefore sure ways to lessen leaching losses of fertilizer nitrogen. These results emphasize in particular the importance of root activity in the soil which limits the concentration of nitrates.

GENERAL CONCLUSION

Effect of incorporated straw

The results demonstrate that straw incorporation exerts a depressive effect on yield (about 30% reduction in grain yield on the average), which is related to a reduction of fertilizer nitrogen absorption both in total amount per plant (55%) as well as in percentage of total nitrogen absorbed in grain (30%). This reduction, which is not compensated by supplemental nitrogen fertilizer stored in the soil (Fig. 7), is the source (or the consequence) of substantial nitrogen fertilizer losses (+ 30% on average), the amount lost being proportional to the quantity of straw incorporated. In contrast, although total nitrogen losses are higher in the absence of a growing crop, they decrease gradually as the quantity of straw incorporated increases. The amount of nitrogen lost to the atmosphere always constitutes the greatest part of total fertilizer nitrogen losses, probably through denitrification, and increasingly so as the quantity of straw incorporated increases, with or without a vegetative cover. It should be noted that, with a medium amount of straw incorporation (a level feasible in practical agriculture), the processes of rhizo-



-The curve 3 was obtained by substracting the N losses (curves 1 and 2) from the initial doses of N-fertilizer applied

-L.S.D. is given at P 5%.

Fig. 7. Fate of fertilizer-N (applied at 90 and 150 kg N/ha) as affected by straw incorporation.

spheric immobilization of fertilizer nitrogen are pronounced, particularly in the hydrolyzable fraction. This rhizospheric effect is of prime importance because it makes up to a great extent for the lack of fertilizer nitrogen stored at this level of straw incorporation and in the absence of a growing crop. However, this effect competes most probably with the nitrogen nutrition of the plant; this last hypothesis is strenghened by the reduction of the nitrogen content in the grain and by the spectacularly positive effect on yield resulting from the application of additional nitrogen.

Effect of nitrogen fertilizer

In all cases the total amount of fertilizer nitrogen absorbed increases linearly as a function of the quantity of nitrogen applied. In a similar way, nitrogen fertilizer increases the output of soil N by the plant. This fact is actually verified concerning both rates of straw incorporated. However, it appears that the application of high amounts of N fertilizer, in the absence of straw incorporation – which by the way does not lead to a yield increase – will decrease the soil-N uptake by the plant.

The efficiency of nitrogen fertilizer – which can be evaluated by the sum of the immobilization of fertilizer N in the soil (cultivated layer) and the uptake by the plant – decreases with the rate of fertilizer use. But the decrease due to straw incorporation is more important. In this experimentation, efficiency values fall within the range: 41% to 61%. The better efficiency was obtained when 90 kg/ha N was applied, without any straw incorporated.

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