

[Laboratoire d'Ecologie Végétale, Office de la Recherche Scientifique et Technique Outre Mer, Centre de Dakar, Senegal]

Participation of Light and Organo-mineral Fractions of Soil Organic Matter in Nitrogen Mineralization in a Sahelian Savanna Soil

F. BERNHARD-REVERSAT

With 2 Figures

Summary

A tropical semi-arid soil was fractionated by successive wet sieving at 200 μm and 50 μm in order to separate two light fractions, two mineral fractions, and one organo-mineral fraction. Each fraction was incubated separately for N mineralization.

It was observed that 60 to 80 per cent of mineral N, produced in the whole soil was due to the organo-mineral fraction. Expressed as per cent of total N in the fraction, mineralized N was higher in organo-mineral fraction than in light fractions, and was weakly correlated with C/N ratio. Mineralized N decreased with soil depth in all fractions.

Zusammenfassung

Durch aufeinanderfolgende Naßsiebung bei 200 und 50 μm wurde ein semi-arider tropischer Boden in zwei „leichte“ (gewonnen durch Flotation), zwei mineralische und eine organo-mineralische Fraktion getrennt. An jeder Fraktion wurde die N-Mineralisation während einer 20tägigen Bebrütung bestimmt.

Etwas 60-80 % des insgesamt mineralisierten Stickstoffs entstammte der organisch-mineralischen Fraktion. In Prozent des Gesamt-N einer Fraktion ausgedrückt, war der Anteil des mineralisierten N in der organisch-mineralischen Fraktion höher als in der „leichten“ und korrelierte schwach mit dem C:N-Verhältnis. In allen Fraktionen sank die Menge an mineralisiertem N mit der Bodentiefe.

A study of the nitrogen cycle in a savanna of northern Senegal was undertaken with special reference to the presence of trees (BERNHARD-REVERSAT 1977, 1978).

The nitrogen mineralization processes, occurring *in situ* only during the short wet season, received particular attention. It had been shown previously that they were limited by factors other than soil water, since mineralization decreased sharply before the end of the rainy season. The amount of mineral nitrogen produced ranged from 5 to 10 per cent of the total soil nitrogen each year (BERNHARD-REVERSAT 1977).

The problems of the resistance to degradation of organic nitrogen was studied by several authors like BREMNER (1967), and the variability of nitrogen stability in various fractions of organic matter, chemically or physically separated, was pointed out (GREENLAND and FORD 1964, CHICHESTER 1969, OADES and LADD 1977, CAMERON and POSNER 1979).

The present work is an attempt to clarify the involvement of naturally occurring organic fractions in the global production of mineral nitrogen.

O.R.S.T.O.M.

Fonds Documentaire
N° : 82/81/01143
Cote : B- ex1
Date : 23 MARS 1982

Materials and Methods

The study was carried out in northern Senegal on a "weakly leached ferruginous tropical soil" (French classification ¹), with a clay content of 3.9 to 4.5 per cent, developed on eolian sands. In the top layer of soil (0–5 cm) the organic matter content ranges from 0.25 per cent in the open to 2 per cent under the trees.

The site was previously described (BILLE and al. 1972). The vegetation is an open steppe with trees scattered on the dunes, and more abundant in the lower parts between the dunes. The mean annual rainfall is 320 mm.

The soil samples were taken either in the open or under two species of trees, *Acacia senegal* and *Balanites aegyptiaca*.

Organic matter fractionation

The soil was prealably sieved at 4 mm to take off larger plant fragments. The following procedure was an adaptation described by FELLER (1980) of a widely used method. It consisted in granulometric fractionation by sieving the soil under distilled water with different mesh sized sieves. The light fractions were taken off by floatation and washed away with water. Five fractions were obtained:

> 200 μm light fraction.	L1
> 200 μm mineral fraction (sand)	M1
200–50 μm light fraction	L2
200–50 μm mineral fraction (sand).	M2
< 50 μm organo-mineral fraction (silt + clay)	SC

No acid was added to flocculate the clay. The organo-mineral fraction was separated from water by centrifugation. The fractions were air-dried.

Nitrogen mineralization measurements

The initial mineral N of each fraction was extracted on the wet material before drying. Only $\text{NH}_4\text{-N}$ was determined, $\text{NO}_3\text{-N}$ was lost during the fractionation in water.

Each fraction was incubated separately. The mineral fractions were humidified and incubated directly. The light fractions and the organo-mineral one were mixed with washed and calcinated sand, in the proportion of 0.5 to 1.5% and 10 to 20%, respectively. The mixtures (70 g) were humidified and incubated in Erlenmeyer flasks (250 ml) at 32 °C during 20 days, after which $\text{NH}_4\text{-N}$ and $\text{NO}_3\text{-N}$ were determined. Simultaneously, a sample of reconstituted soil with various fractions mixed in their initial proportions was incubated, together with a sample of the initial soil (control) without fractionation.

Chemical analysis

The carbon content of soils and fractions was determined by combustion (Carmograph®). The total N content was determined after digestion, by the indophenol blue methode (Technicon® autoanalyser). $\text{NO}_3\text{-N}$ was extracted by a mixed solution of CuSO_4 (2.5%) and Ag_2SO_4 (0.6%), and analysed by the phenol disulfonic acid method. $\text{NH}_4\text{-N}$ was extracted whit a solution of NaCl (10%) and analysed by the same method as total N.

Results

1. Detailed results from one experiment

Table 1 shows the mineral N produced during incubation of a soil taken under an *Acacia* in the 0–5 cm layer. For the light fraction and the organo-mineral fraction the mean of two replications is given.

There is a good agreement between the sum of fractions, reconstituted soil and control soil. Although the mineral N production of the two mineral fractions is low, it points out to the fact that separation is not complete, a part of organic matter

1) "Psammentic ustropept" (American classification, USDA, 7th Approximation).

being gathered with the sand. It is probably not the same material as the separated matter, but as an approximation they have been considered to be equivalent in the following results, and have been joined in a single fraction for each mesh size, referred to as the "light fractions" in the subsequent discussions.

This approximation may lower the precision of the results in the "open" soils where the amount of light fractions is very small.

Table 1. Mineralization after a 20 days incubation of a soil and its fractions (0–5 cm)

Fraction	Increase in $\text{NH}_4\text{-N}$		Increase in $\text{NO}_3\text{-N}$		Total mineral N $\mu\text{g/g}$ soil	Percent of total mineralised
	$\mu\text{g/g}$ fraction	$\mu\text{g/g}$ soil	$\mu\text{g/g}$ fraction	$\mu\text{g/g}$ soil		
L1	11	0.1	1,240	16.9	17.0	21
L 2	-12	-0.4	356	11.5	11.1	14
SC	-18	-3.6	270	53.3	49.7	61
M1	-0.5	-0.1	3.0	0.9	0.8	1
M2	-0.8	-0.3	6.5	3.0	2.7	3
Sum		-4.3		85.6	81.3	
Reconstituted soil		-5.3		77.8	72.5	
Control soil		-4.9		81.2	76.7	

2. Mineralization in the 0–5 cm layer of soil

The 0–5 cm layer of soil was sampled under five trees (three *Acacia* and two *Balanites*) and at three places in the open. For each sample the incubation was conducted as previously described.

The organic matter content, expressed as mg C/g soil, and the total nitrogen content (as mg N/g soil) of the samples are given in Table 2.

Table 2. C and N content of soils sampled for fractionation

Soil n°	Cover	mg C/g soil	mg N/g soil
A 1	<i>Acacia</i>	8.9	1.00
A 2	<i>Acacia</i>	8.2	0.76
A 3	<i>Acacia</i>	7.8	0.72
B 1	<i>Balanites</i>	8.6	0.81
B 2	<i>Balanites</i>	3.8	0.39
O 1	Open	1.5	0.12
O 2	Open	4.2	0.34
O 3	Open	1.6	0.16

Table 3 shows the repartition of organic matter in the various fractions and nitrogen mineralization in each fraction. Although the low level of organic matter content of two of the "open" soils (O1–3) leads to less accurate measurements, the reliability of the results has been checked by the correspondence between the sum of the fraction and the reconstituted and control soils.

The results show a relatively constant repartition of N mineralization, the largest part being produced by the "silt + clay" fraction. The absolute values ($\mu\text{g/g}$ of soil), related in a given fraction to the organic matter content of the whole soil, are far more variable.

Table 3. N mineralization during incubation of 20 days in the various fractions and participation of the fractions to the total soil C

Soil	L 1 + M 1			L 2 + M 2			SC		
	N mineralized		C % total C	N mineralized		C % total C	N mineralized		C % total C
	$\mu\text{g/g soil}$	% total		$\mu\text{g/g soil}$	% total		$\mu\text{g/g soil}$	% total	
A 1	17.8	22	36	13.8	17	28	49.7	61	36
A 2	13.6	25	40	8.7	16	25	32.4	59	35
A 3	8.8	17	41	7.8	15	22	34.9	67	35
B 1	7.0	14	42	8.3	16	18	36.5	70	39
B 2	3.7	12	20	2.9	7	20	24.2	80	59
O 1	1.4	10	20	0.7	5	16	11.3	84	64
O 2	9.5	23	20	6.5	16	13	24.5	60	67
O 3	3.0	16	15	3.2	16	14	13.0	68	71

N mineralization may also be expressed as per cent of the N content of the fraction in order to point out the apparent N stability in the fraction. Table 4 shows that this value ranges from 9 to 14% in the Silt + Clay fraction and from 3 to 10 in the light fractions, except in two samples of "open" soil for the L1 fraction. The C/N ratio of each fraction is also given.

Table 4. Mineral N produced expressed as per cent of total N in the fraction, and C/N ratio

Soil	N min. % total N			C/N		
	L 1	L 2	SC	L 1	L 2	SC
A 1	6.9	6.8	12.8	11.6	11.9	7.9
A 2	6.1	5.4	13.1	14.9	14.9	10.9
A 3	4.1	4.8	11.4	17.0	14.3	10.1
B 1	3.0	6.7	9.0	16.0	11.8	8.5
B 2	6.3	7.0	10.7	14.6	12.1	8.0
O 1	10.1	6.8	11.4	13.9	13.2	9.2
O 2	18.2	9.4	13.9	18.0	15.3	10.1
O 3	17.2		11.0	17.0		12.4

3. Effect of depth

Several analysis of soil organic matter in relation to depth have shown that the C content is relatively high in the 0–2 cm layer of soil and then decreases sharply. This repartition is characteristic of semi-arid or arid soils, as emphasized by CHARLEY and COWLING (1968). Unpublished results have also pointed out the higher susceptibility to degradation of the organic N of the 0–2 cm of soil compared with the lower layers.

Table 5. Soil C and N content in relation to depth under *Acacia* and mineralization in 20 days

Depth/cm	C mg C/g soil	N mg N/g soil	N mineralized	
			$\mu\text{g/g soil}$	% total N
0–1.5	10.5	1.20	114	9.5
1.5–5	8.4	0.78	56	7.1
5–8	4.7	0.54	28	5.2

The fractionation of organic matter was carried out on samples taken under an *Acacia* at the following depths: 0 to 1 or 2 cm (referred to as the 0—1.5 cm layer) 1 or 2 cm to 5 cm (1.5—5 cm layer) and 5 to 8 cm. Their C and N content are in Table 5. No attempt was made to study deeper layers because the organic matter content was too low.

Table 6 and 7 show the results of measurements on the fractions for each layer.

Table 6. N mineralization in the fractions and C content in relation to depth under *Acacia*

Depth cm	N mineralized						C % total C in soil layer		
	L 1 + M 1		L 2 + M 2		SC		L 1	L 2	SC
	$\mu\text{g/g soil}$	% total*)	$\mu\text{g/g soil}$	% total*)	$\mu\text{g/g soil}$	% total*)			
0—1.5	32	28	18	16	62	54	48	30	22
1.5—5	10	18	10	18	35	62	30	31	39
5—8	3.5	12	3.9	14	20	72	21	19	60

*) per cent of total N mineralized in the soil layer

Table 7. N mineralization expressed as per cent of total N in the fractions and C/N ratios in relation to depth under *Acacia*

Depth, cm	Mineralized N, % total N			C/N		
	L 1	L 2	SC	L 1	L 2	SC
0—1.5	9.4	10.5	16.0	16.2	17.9	5.8
1.5—5	7.4	7.2	10.3	15.2	15.2	8.4
5—8	5.6	7.0	7.2	13.4	13.9	9.2

It may be observed from Table 6 that while the participation of the light fraction 1 in the global mineralization decreases with depth, the participation of the "Silt + Clay" fraction increases, whereas the light fraction 2 does not change. However the apparent susceptibility of N to degradation decreases with depth in all fractions.

4. Effect of pre-incubation of soil

The variation of nitrogen stability with time was appreciated by comparing N mineralization of soil with and without pre-incubation.

For this purpose the soil A₁ was humidified, incubated three weeks at 36 °C, dried and then fractionated. After which, N mineralization was measured as above during a 20 days incubation.

The results are shown in Table 8. The amount of mineral N produced decreases in the second incubation, and more sharply in the light fraction than in the "Silt + Clay" fraction.

Table 8. N mineralization in the fraction of a soil pre-incubated (PI) and of an untreated soil (U)

Soil	$\mu\text{g/g soil}$ (% total)			% total N (C/N ratio)		
	L 1	L 2	SC	L 1	L 2	SC
U	17.8 (22)	13.8 (17)	49.7 (61)	6.9 (11.6)	7.8 (11.9)	12.8 (7.9)
PI	5.0 (13)	4.4 (12)	30.6 (75)	3.2 (12.2)	2.9 (12.0)	7.6 (8.3)

5. Effect of temperature

Most of the incubations were carried out at 32 °C. *In situ* the actual soil temperature during the wet season stays around 32 °C during the night and may reach 45 °C and more during the day at 5 cm depth. In order to assess the effect of this high day-time temperature, incubations were conducted at 32°, 45° and with a day-night sequence of 32°/45 °C.

Table 9 shows that the mineralization is somewhat higher after a 32°/45 °C cycle compared with 32 °C the participation of each fraction being about the same. At 45 °C the nitrification is inhibited, almost completely in the light fraction 1 and but little in the "Silt + Clay" fraction.

Table 9. N mineralization at various temperatures of incubation

Temperature	N	L 1	L 2	SC	
32 °C	NO ₃ -N	21	10	53	μg/g soil
	mineral-N	22	11	49	μg/g soil
	mineral-N	(27)	(13)	(60)	% total
32/45 °C	NO ₃ -N	22	15	56	μg/g soil
	mineral-N	26	15	51	μg/g soil
	mineral-N	(28)	(16)	(55)	% total
45 °C	NO ₃ -N	1	5	45	μg/g soil
	mineral-N	19	20	63	μg/g soil
	mineral-N	(18)	(20)	(62)	% total

Discussion

1. Methodological problems

The fractionation method was chosen to cause the least perturbation of microbial activity. It may be less effective than the density solutions methods or the ultrasonic methods which have been proposed (HENIN et al. 1950, GREENLAND and FORD 1964, EDWARDS and BREMNER 1967) but the microbial population after the fractionation with distilled water seems to have undergone no alteration (FELLER et al. 1980), and inoculation is not necessary before incubation.

The aim of the present study being the comparison between the light and organo-mineral fractions, the "Silt + Clay" fraction has been extracted as a whole (allowing a greater number of samples to be analysed) and the repartition of mineralizable N inside this fraction was not investigated. According to CHICHESTER (1969) and CAMERON and POSNER (1979), N availability for mineralization increases with decreasing particle size.

The loss of nitrogen in water during fractionation is about 25 μg of N per g of soil, and less in the poorest soils.

20 days of incubation may appear to be short, but in the area studied the mean number of rainy days amounts to 13 per year, and it can be assumed that the number of days during which the surface soil is wet ranges from 15 to 25 during the rainy season.

2. Repartition of organic matter in the fractions

As shown in Table 3 the light fractions contain about two thirds of the surface soil organic matter under the trees, and about one third in the open.

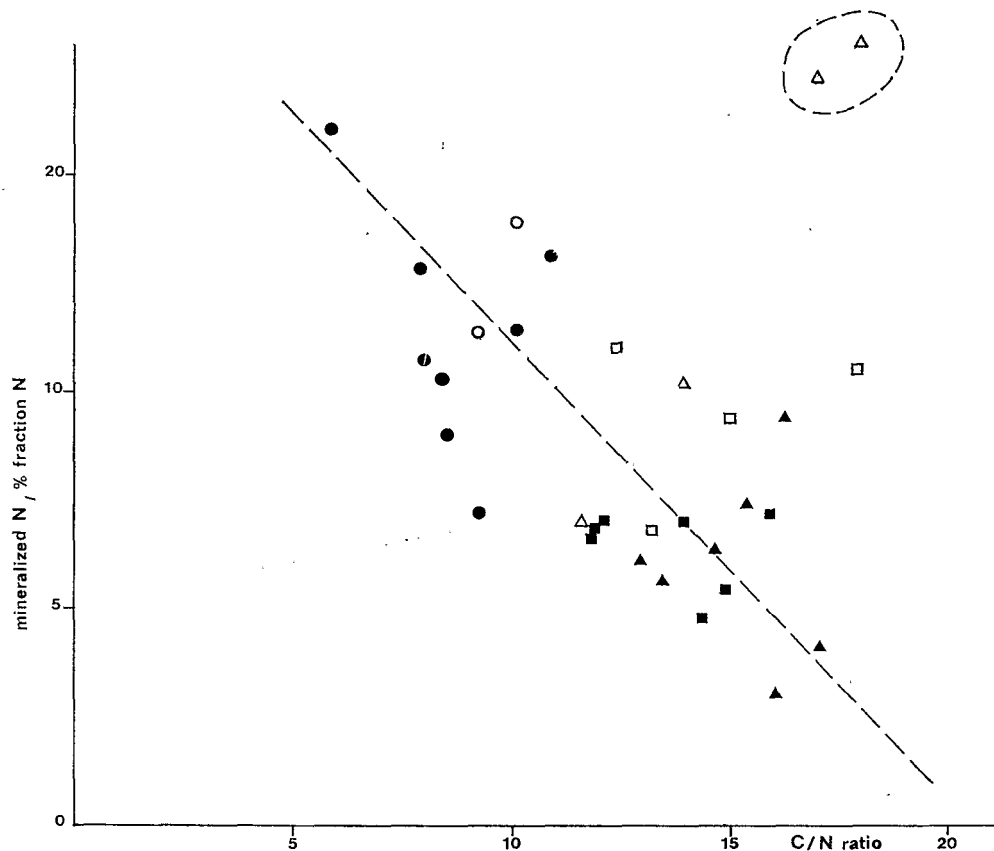


Fig. 1. Relation between the mineralizable N of fractions and their C/N ratio. Light fractions < 200 μ : \blacktriangle \triangle ; Light fractions 50 to 200 μ : \blacksquare \square ; "Silt + Clay" fractions: \odot \bullet ; Black signs: under-tree samples; open signs: "open" samples. (See text — 4 algal crust — for explanation of the points inside the dotted circle). (Instead of 20 at the x-axis read 15.)

According to some results given for temperate and humid tropical soils (BATES 1960, GREENLAND and FORD 1965, CHICHESTER 1969) it appears that an inverse relation would rather be the rule, as organic matter is related to clay content, the percentage of carbon in light fractions being lower in soils with high organic matter content (Fig. 2). In the area concerned the lack of organic matter in "open" soils corresponds with the lack or scarcity of the herbaceous cover, which allows wind erosion and disappearance of litter debris. This fact would partly explain the repartition of C in the fractions.

Under the trees the role of surface litter is shown by the decrease of light fraction C with depth and the increase of "Silt + Clay" C, as shown in Table 5.

3. Participation of the various fractions in the global nitrogen mineralization

Table 3 shows that an amount ranging from 60 to 80 per cent of the mineral N liberated during incubation is produced by the "Silt + Clay" fraction, and this proportion increases with depth.

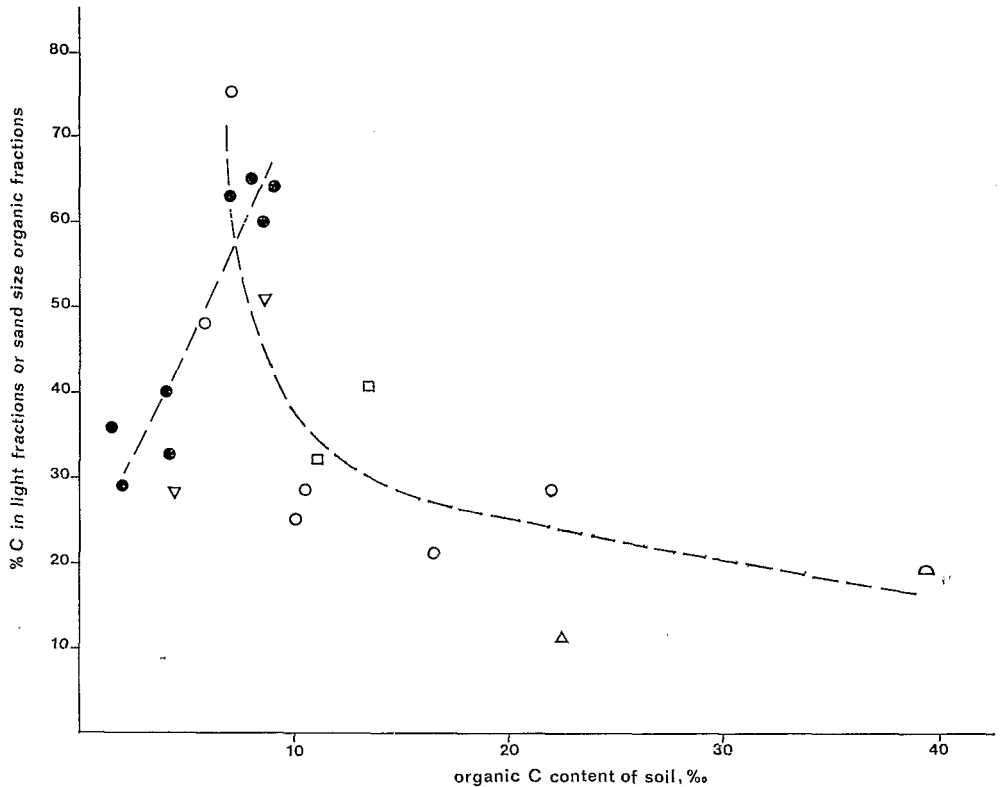


Fig. 2. Relation between the amount of C in light fractions (or sand-size organic fractions) and the amount of organic C in total soil. ○ from GREENLAND and FORD (1964); △ from CHICHESTER (1969); □ from CAMERON and POSNER (1979); ● present work; ▽ calculated from BLONDEL (1971) for soils from Senegal.

This result points out to the fact that fresh organic material is not the principal source of available N for plants in this ecosystem. In another study on a cultivated soil of Senegal, the fraction superior to $200\ \mu\text{m}$ was separated in bigger or smaller than 2 mm, and the bigger fragments did not produce any mineral N during incubation.

Consequently most of the dead plant material will undergo a long degradation cycle before the nitrogen of soil organic compounds and microbial metabolites is liberated as mineral nitrogen.

These results do not agree with those of BLONDEL (1971), working with a similar sandy soil of Senegal under cultivation; beside different definition of the light fraction, in his experiments the alcohol-bromoform treatment could interfere with the microbial activity. However the incubation results are confirmed by culture experiments. No attempt has been made in the present work to estimate the availability of fraction N for plant growth by pot experiments.

GREENLAND and FORD (1965) studying several Australian soils find that the light fraction is a much more readily decomposable material than the remaining soil organic matter. However they state that the amount of mineral nitrogen released depends on the C/N ratio of the organic matter.

4. Nitrogen stability in the various fractions

In most of the analysed samples the nitrogen compounds of the organo-mineral fraction are apparently more readily decomposable than those of the light fractions: about 12 per cent of the nitrogen in the "Silt + Clay" fraction (16 per cent in the surface layer of soil) are mineralized in 20 days, and only 6 to 8 per cent in the light fractions. The difference between the light and organo-mineral fractions increased after a pre-incubation of soil.

However in two of the three "open" samples, the percentage of N mineralized is high in the larger light fraction and mainly produced as $\text{NH}_4\text{-N}$. In the studied area the surface of the soil in the open is frequently covered by a crust of algae when the herbaceous cover is absent or scarce¹). When the soil is fractionated under water, the algae form fibrous tufts which accumulate in the light fraction superior to 200 μm , and to a lesser extent in the 50 to 200 μm light fraction.

The relation between the C/N ratio and the susceptibility of N to mineralization is shown by Figure 1. If the > 200 μm light fractions of the two "open" soils mentioned above are omitted, a loose correlation is observed ($r = -0,62$, $p = 99\%$) which lead to the hypothesis that the nitrogen mineralized in the light fractions is reorganized in microbial biomass on an energy-rich substrate. The 200–2000 μm fraction in a comparable soil has shown the highest biological activity as measured by O_2 consumption (FELLER, personal communication). This hypothesis is also suggested by CAMERON and POSNER (1979) from their finding that under aerobic conditions, the decrease of mineralization with increasing C/N is far less pronounced, because of the much smaller production of new microbial tissues with reduced available energy.

In the presence of algae which probably fix nitrogen the mineral nitrogen demand for microbial activity is lessened and mineral nitrogen released in spite of a relatively high C/N ratio.

However the decrease of the percentage of mineralizable nitrogen after pre-incubation, although no change in C/N ratio occurred, suggests the exhausting of the reserves of easily mineralizable nitrogen compounds. The sharper decrease exhibited by the light fractions emphasizes the higher proportion of nitrogen compounds resistant to mineralization in these fractions relatively to the organo-mineral fraction. As these results were obtained with an "Acacia" soil, the formation of tannin-protein complexes is possible. Moreover this could be involved in the difference in susceptibility to degradation of the larger light-fraction nitrogen in the "open" soils and the "tree-covered" soils.

Several authors consider the particle size to affect directly the accessibility of nitrogen compounds to microbial action (OADES and LADD 1977). In the present work this relation does not appear in the two light fractions, but may account for the difference between light and organo-mineral fractions.

The decrease of nitrogen susceptibility to degradation with depth was observed in the three fractions and cannot be explained by the C/N ratio or the particle size. It has to be related to the nature of nitrogenous compounds and complexes.

Conclusion

This work aimed at an ecological approach of some of the processes involved in nitrogen mineralization in a semi-arid environment.

1) This crust, taken off alone and incubated, produced a great amount of mineral N in the form of $\text{NH}_4\text{-N}$ (200 $\mu\text{g/g}$ soil/2 weeks).

The main result is that in this ecosystem most of the mineral nitrogen available to plants is produced by the organo-mineral fraction, considered to be the most humified. Consequently it may be assumed that a large part of the nitrogen added each year to the soil in dead plant material is released as mineral nitrogen some years thereafter.

This delay could explain that *in situ* the annual amount of mineralized nitrogen exhibits low interannual variation when the primary production and the amount of dead material change drastically in relation to the regime of precipitation.

However, much effort remains to be devoted in the comprehension of these problems, particularly as regards nitrogen resistance to degradation in a semiarid environment.

Acknowledgements

This work originated in a constructive cooperation with C. FELLER. Most of the chemical analysis were carried out at the Analysis Laboratory, ORSTOM-DAKAR, under the control of C. PAY-CHENG.

References

- BATES, J. A. R.: Studies on a Nigerian forest soil. I. The distribution of organic matter in the profile in various soil fractions. *J. Soil. Sci.* **11** (1960), 246—256.
- BERNHARD-REVERSAT, F.: Observation sur la minéralisation in situ de l'azote du sol en savane sahélienne (Sénégal). *Cah. ORSTOM, sér. Biol.* **12** (1977), 301—306.
- and POUFON, H.: Nitrogen cycling in a soil tree system in a Sahelian savanna. Example of *Acacia senegal*. In: Nitrogen cycling in West African ecosystems. SCOPE/UNEP workshop, Ibadan, Dec. 1978 (in press).
- BILLE, J. C., LEPAGE, M., MOREL, G., and POUFON, H.: Recherches écologiques sur une savane sahélienne du Fero septentrional, Sénégal: Présentation de la région. *La Terre et la Vie*. **26** (1972), 332—350.
- BLONDEL, D.: Rôle de la matière organique libre dans la minéralisation en sol sablaux, relation avec l'alimentation azotée du mil. *Agron. Trop.* **12** (1971), 1372—1377.
- BREMNER, J. M.: Nitrogen compounds. In: *Soil biochemistry*, Vol. 1 (A. D. McLAREN and G. H. PETERSON, eds.). Marcel Dekker, New York 1937, 19—66.
- CAMERON, R. S., and POSNER, A. M.: Mineralizable organic nitrogen in soil fractionated according to particule size. *J. Soil Sci.* **30** (1979), 565—577.
- CHARLEY, J. L., and COWLING, S. W.: Changes in soil status resulting from overgrazing and their consequences in plant communities of semi-arid areas. *Proc. Ecol. Soc. Austr.* **3** (1968), 28—38.
- CHICHESTER, F. W.: Nitrogen in soil organo-mineral sedimentation fractions. *Soil. Sci.* **107** (1969), 365—363.
- EDWARDS, A. P., and BREMNER, J. M.: Dispersion of soil particles by sonic vibrations. *J. Soil. Sci.* **18** (1967), 47—63.
- FELLER, C.: Une méthode de fractionnement granulométrique de la matière organique des sols. Application aux sols tropicaux à texture grossière très pauvres en humus. *Cah. ORSTOM; sér. Pédol.* (1980), in press.
- GREENLAND, D. J., and FORD, G. W.: Separation of partially humified organic materials from soil by ultrasonic dispersion. *Trans. 8th Int. Congr. Soil. Sci.* **3** (1964), 137—148.
- HENIN, S., and TURC, L.: Essai de fractionnement des matières organiques du sol. *Trans. 4th Int. Congr. Soil Sci.* **1** (1950), 152—154.
- OADES, J. M., and LADD, J. N.: Biochemical properties: Carbon and nitrogen metabolism. In: *Soil factors in crop production in a semi-arid environment* (J. S. RUSSEL and E. L. GREACEN, eds.). Univ. Queensland Press, Brisbane 1977, 127—160.

Author's address:

F. BERNHARD-REVERSAT, O.R.S.T.O.M., B. P. 1386, Dakar, Sénégal