T. Rosswall (ed). 1980
Nitrogen Cycling in West African Ecosystems

NITROGEN CYCLING IN A SOIL-TREE SYSTEM IN A SAHELIAN SAVANNA. EXAMPLE OF *ACACIA SENEGAL*

F. Bernhard-Reversat and H. Poupon
ORSTOM, BP 1386, Dakar, Senegal

Abstract

The cycling of N in the soil-tree system was studied in a Sahelian Savanna where *Acacia senegal* is largely represented as isolated trees or in clumps of a few trees. The herbaceous stratum is scarce and irregular in the open but it is dense under the trees. The return of organic matter and N from vegetation to soil by the litter was calculated and the herbaceous litter was found to be an important component under the trees, compared to the tree litter. The decay of organic matter seems to be fast, as only the first centimeters of soil show a greater accumulation of organic matter and N than in the open. The accumulation of N and its repartition was measured. The mineralization of organic N in the top soil was studied, and was found to be relatively important under the trees. Most of it occurred in the beginning of the rainy season and a short period of accumulation of mineral N took place at this time; the mineral N content of soil decreases afterwards during the growth of the herbaceous stratum. Mineral N produced was mainly in the form of NO_3-N, and the possibility of N losses during periods of heavy rainfall is discussed.

Introduction

The need for tree conservation in the Sahel, and the role of trees in the Sahelian ecosystem has been emphasized during the recent years. One aspect of the role of trees is their impact on soil nutrients and on nutrient cycling (Gerakis & Tsangarakis, 1970; Jung, 1969). In the present paper we shall study the nitrogen cycle in a soil-tree system in a Sahelian savanna of North Senegal. *Acacia senegal* was chosen because it is present in a great part of the Sahelian zone and is well represented in the study area. Besides, it has some economic importance as a gum tree and is used for re-afforestation.

The study area was described by Bille *et al.* (1972). The mean annual precipitation is 300 mm falling during a three-month wet season. The relief is a succession of dunes and depressions. The trees are scattered on the dunes and slopes, their density being higher in the depressions. The herbaceous stratum is scarce and irregular in the open, but is dense and higher under the trees. The population of *Acacia senegal* was studied for several years in a protected quadrat (Poupon, 1976).

The N cycle study was undertaken recently in the same quadrat. Twelve trees were studied for total N, mineral N, and mineralization in soil. Sampling was done on several trees to obtain mean values of N content of leaves and wood, and for herbaceous biomass and N content. Biomass of trees was estimated with established relationship between tree girth and biomass.

Accumulation of nitrogen in the vegetation

Accumulation of nitrogen in the tree

The biomass of 21 trees was measured by H. Poupon and relationships were established between tree girth and the different parts of tree biomass: twigs, branches, trunk, roots and leaves. The equations were in the form of $\log y = a \log x + b$ where y is the biomass, and x the girth of the tree.

These equations were used to calculate the biomass of the trees under which soil N was studied. Samples of wood and leaves were analysed for N content (N content of root was assumed to be the same as that of wood). Branches and trunk had the same N content of about 0.48 % (standard error, 0.09 for 13 samples). N content of twigs was 0.62 %, N content of leaves was 3.0 % (standard error, 0.29 for 12 samples). The nitrogen contents in the trees are given in Table 1.

Accumulation of nitrogen in the herbaceous standing crop

The biomass of herbs under the trees was measured in 1976 and 1977 at the end of the wet season, in October, and N content was determined. Because of the low precipitation in 1977 (120 mm) the biomass of herbs was weak, but its N content was higher. Nevertheless, the accumulation of N was lower than in 1976.

The following values, for 1976, are assumed to represent a "mean" year. The biomass of aerial parts under *Acacia* was 0.42 kg m^{-2} (standard error, 0.1 for 8 samples) with a mean N content of 1.07 % (standard error 0.3). The biomass of roots was 0.26 kg m^{-2} (standard error, 0.05) with a N content of 1.66 % determined on one composite sample. The total N immobilized was 8.7 g m^{-2} under the trees and 4.7 g m^{-2} in the open.

In 1977, with low rainfall, the aerial biomass of herbs under *Acacia* was only 0.23 kg m^{-2} with 1.33 % N. The root biomass was not measured but we can estimate the total accumulation of N to about 6 g m^{-2}.

Return of nitrogen to the soil

Nitrogen is returned to the soil by tree litter, leaching of leaves and branches by throughfall, herbaceous litter, roots (Table 2). *Acacia* leaves turn yellow before they fall. Yellow leaves taken off the tree or freshly fallen on the soil were analysed, showing a N content of 2 %, i.e., two-thirds of the N content of green leaves. One-third of leaf nitrogen is withdrawn to the tree before leaf-fall. The N content of yellow leaves was used with the leaf biomass to calculate the annual return to the soil by litter. Annual return by tree roots was not measured.

Throughfall was studied during two years to estimate the amount of nitrogen leached from the tree crown. The N content of rain under the tree and in the open was determined. During the wet season of 1976 (from 330 mm of rain), 2.2 g of N m^{-2} was brought to the soil, of which 1.8 g m^{-2} was washed from the tree crown, and 0.4 g m^{-2} was supposed to have come from the atmosphere. Stem flow was measured on some occasions, but the amount of N returned to the soil in this way was small.

In the studied area all the herbaceous species are annual, so it can be assumed that all

Table 1. Accumulation of N in trees

Tree No.		1	2	3	4	5	6	7	8	9	10	11	12
Girth	(cm)	26	27	35	35	38	39	40	47	48	49	49	57
situation[1]		D	D	D	LS	LS	LS	LS	D	LS	LS	LS	LS
Twigs biomass	(kg)	4.0	4.4	9.0	9.0	11.3	12.2	13.1	20.3	21.5	22.8	22.8	34.6
	N(g)	25	27	56	56	70	76	81	126	133	141	141	214
Wood biomass	(kg)	21	23	38	38	45	47	50	70	73	76	76	106
(trunk+ branches+roots)	N(g)	102	109	181	181	215	227	233	335	351	366	366	511
Leaves biomass	(kg)	0.25	0.26	0.39	0.39	0.44	0.46	0.48	0.61	0.63	0.65	0.65	0.83
	N(g)	8	8	12	12	13	14	15	18	19	20	20	25
Total N	(g tree^{-1})	130	140	250	250	300	320	330	480	500	530	530	750
	(g m^{-2})	23	31	44	10	9	31	32	38	49	32	40	23

[1] D = dune, LS = Lower part of slopes.

Table 2. Annual N return to the soil

Tree No.	1	2	3	4	5	6	7	8	9	10	11	12	Open LS
N in tree litter (g m^{-2})	0.44	0.91	1.70	1.40	0.36	0.28	0.94	0.97	1.24	0.78	0.98	0.52	–
Total N return (g m^{-2})	–	–	–	–	10.9	10.8	11.4	11.5	11.7	11.3	11.5	11.0	4.70
Total N return (g tree^{-1})	–	–	–	–	268	359	116	145	119	187	152	354	–

Table 3. Accumulation of N in soil (0–10 cm)

Tree No.	1	2	3	4[1]	5	6	7	8	9[1]	10[1]	11[1]	12	Open D	Open LS
N content (%)	0.28	0.47	0.43	0.64	0.29	0.51	0.55	0.47	0.76	0.53	0.76	0.80	0.17	0.27
N (g m^{-2})	48	80	73	76	49	88	94	80	90	63	90	136	29	46
N (g tree^{-1})	542	456	328	433	1200	2920	959	1010	918	1045	1188	4379	–	–

[1] measured in 1976, others in 1977.

the nitrogen accumulated in the herbaceous standing crop is returned to the soil each year. The mean values of herbaceous biomass and N accumulation were not used for the small trees where they are probably lower (no measurements were made under them).

Nitrogen accumulation in soil

Total nitrogen in soil was first studied by establishing the profile distribution of N content under the tree. This was done under several trees and the general trend observed was that of the example given in Fig. 1. It shows that except in the soil around the trunk, nitrogen was evenly distributed under the tree crown, and that only the surface layer of soil had a higher N content than in the open.

The N content of the 0–10 cm layer was determined every month in a composite sample for each tree studied. The annual means are given in Table 3. A positive correlation ($r = 0.71$) was observed with the tree girth, which indicates that accumulation of nitrogen in the soil increases during the life of the tree.

Nitrogen mineralization in soil

The profile of potential mineralization, measured by three-week incubations of humidified soils, is illustrated by the example given in Fig. 2. It can be observed that mineralization occurs principally in the first 10 cm of soil and that deeper soil has significant production of mineral N only near the trunk.

Mineralization *in situ* was measured in the surface soil under the crown, taking samples at various distances from the trunk (the depth of sampling was 0–7 cm the first year and 0–10 cm in the second year). Measurements were made every four weeks from June to October, and the results are shown in Table 4.

During the wet season, mineral N was produced mainly in the form of NO_3-N. The two years of measurement had different rainfall (330 mm in 1976, 120 mm in 1977). Nevertheless, the amount of mineral N produced was the same, as there was enough rainfall to achieve the mineralization of the mineralizable N present in the soil.

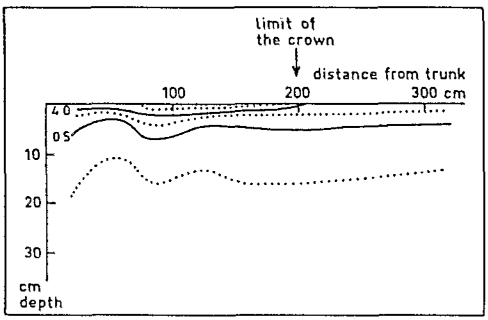

Figure 1. Isolines of total N under an *Acacia* (N o/oo).

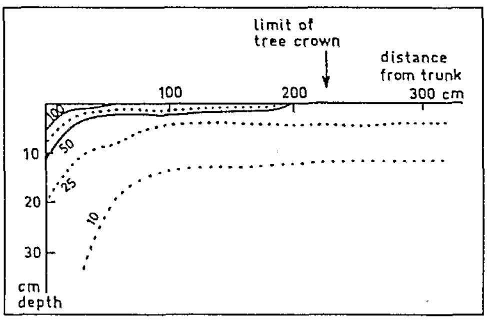

Figure 2. Isolines of mineralizable N under an *Acacia* (NO_3-N µg/g of soil/3 weeks).

Table 4. Mineral N produced in the soil from June to October

Tree No.	1	2	3	4[1]	5	6	7	8	9[1]	10[1]	11[1]	12	Open D	Open LS
$(g\ m^{-2})$	3.6	3.8	4.2	8.4	6.2	5.5	14.9	3.1	8.4	7.0	6.3	9.0	2.2	4.5
$N(g\ tree^{-1})$	41	22	19	48	153	183	152	39	139	86	83	290	–	–

[1] measured in 1976, others in 1977

The results in Table 4 show a great variability, and the relation between N mineralized and the age of the tree (tree girth) is weak. The mean values were 3.7 g N m^{-2} (30 g $tree^{-1}$) for *Acacia* on the dunes, and 8.2 g m^{-2} (142 g $tree^{-1}$) for trees at the foot of the slopes.

Some measurements were made during the dry season and showed a very low production of NH_4-N, probably due to chemico-physical factors (Dommergues *et al.*, 1970). The amount of NH_4-N produced ranges from 0.5 to 1 g m^{-2} for the whole dry season. Some occasional showers occur during the dry months which may bring about a production of mineral N if the soil is moistened, thus in 1976 there was a mineralization of 5 g N m^{-2} for the whole dry season with two showers.

Possible inputs and outputs

Inputs and outputs have not been measured but some observations were made on this subject. Inputs are mainly due to rainfall and to fixation of atmospheric nitrogen by microorganisms. Nitrogen concentration in rain was low and its contribution to inputs was about 0.4 g N m^{-2} yr^{-1}, as previously noted.

Symbiotic fixation could occur in a leguminous tree as *Acacia senegal*. Seedlings grown in the laboratory as well as seedlings found in the field showed numerous nodules. However, the search for nodules on adult tree roots was negative, except in one out of ten trees sampled. It is possible that symbiotic fixation occurs during the first years of tree life, but rarely in adult trees. In the laboratory it was observed that nodulation was inhibited when seedlings were grown in soil taken from under an old *Acacia*, but not in soil taken from the open. In the latter soil, addition of nitrate inhibited nodulation. The active nitrate production in soil under the tree during the wet season could be partly responsible for the absence of nodules in adult trees, but very little is known on this subject. The dryness is perhaps another factor limiting nodulation. Good nodulation was reported by Orchard & Darb (1956) in *Acacia mollissima* forests in a wetter zone, and they observed that nodulation decreased with increasing soil N. Moore *et al.* (1967) found poor nodulation in an *Acacia harpophylla* forest during a dry year, but observed substantial nodulation in wetter years. Non-symbiotic fixation in soil was not investigated.

Outputs by denitrification seem to be possible, at least in the lower part of slopes and in depressions where the soil can be temporarily waterlogged. Losses of mineral nitrogen were observed once during the wet season of 1976, after a heavy rainfall (Bernhard-Reversat, 1977).

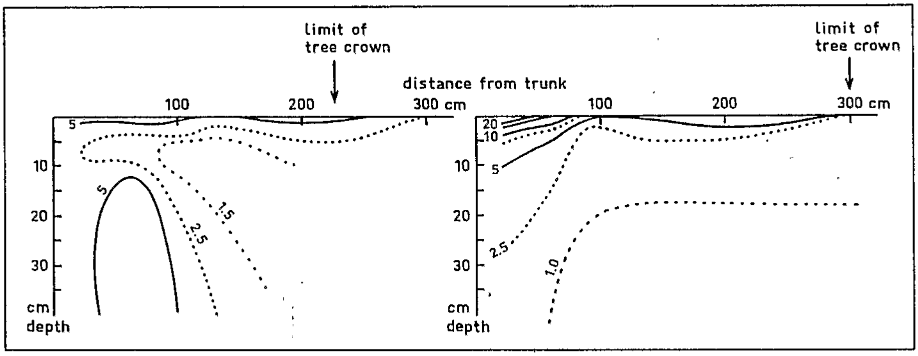

Figure 3. Isolines of NO_3-N under two *Acacia*, A: after the wet season of 1977, B: after a mean wet season, 1975 (NO_3-N $\mu g/g$ of soil).

Leaching losses of nitrogen from the ecosystem are probably not important as water flow in the soil does not go deeper than 2 m, which is the depth of tree roots, according to A. Cornet (pers. comm.), who is studying the water balance in this ecosystem. Nevertheless, nitrate or soluble organic nitrogen may be leached below the bulk of the herbaceous roots after a heavy rainfall, particularly during a year as 1977 where the herbaceous standing crop was low and the amount of mineral N in it was smaller than the amount produced by mineralization. This could be the explanation for the nitrate distribution observed in a profile established after the 1977 wet season under *Acacia*, and shown in Fig. 3.

Conclusions

Taking the mean for adult *Acacia* situated in the lower part of slopes, the annual flow of nitrogen from vegetation to soil was about 12 g m^{-2}, which is a relatively high value, comparable to some forest ecosystems. It can be assumed that dense *Acacia* stands, like plantations, should have an active N cycle. An important part of the nitrogen flow passes through the herbaceous stratum, and is then available to cattle.

Compared to the nitrogen cycle outside the cover of trees, the nitrogen flow is 2.5 to 3 times greater under the tree, as shown in Table 5. The annual turnover of soil N is 10 % in the open, and 14 % under the tree. The higher N accumulation in herbs under the tree is not only due to a higher biomass, but also to a higher N content.

Table 5. Main flows and stocks of N under *Acacia* and in the open for a year with mean rainfall (means for the lower part of slopes)

	Acacia	Open
N immobilization in vegetation (g m^{-2})	32.6	4.7
N return to the soil (g m^{-2} yr^{-1})	11.3	4.7
Total N in soil (g m^{-2})	86.0	46.0
N mineralized (g m^{-2} yr^{-1})	11.5	4.9

If the year 1976, with mean rainfall, is compared to a year with low precipitation, as 1977, it appears than N flow from vegetation to soil is lowered:

	1976	1977
return by tree leaves	0.8	0.8
return by throughfall	1.8	0.6
return by herbaceous litter	8.7	6.0
Total	11.3	7.4

The production of mineral N in soil was about the same for the two years, as the soil was humid for a sufficient number of days to achieve the mineralization of the mineralizable N. Only if this number of days is not reached should the mineral N production be decreased. However, a succession of several dry years with low herbaceous growth should result in a decrease of mineralizable N.

In conclusion, rainfall is the main environmental factor influencing the nitrogen cycle in the system studied:

- by limiting vegetation growth and thus nitrogen utilization and return,
- by controlling mineral N production in the soil, more or less strongly according to the amount of precipitation,
- eventually by causing denitrification or leaching of mineral N in the soil.

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T. Rosswall (Editor)

Proceedings of a workshop arranged by the SCOPE/UNEP International Nitrogen Unit in collaboration with MAB (Unesco) and IITA
at
the International Institute for Tropical Agriculture, Ibadan, Nigeria
11–15 December, 1978