

Nitrogen cycling in tree plantations grown on a poor sandy savanna soil in Congo

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Abstract

Fast growing *Eucalyptus* trees are grown in Congo for industrial purposes, on a very poor sandy savanna soil. The sustainability of such land use is questionable, particularly regarding nutrient availability. Among the lacking nutrients, nitrogen (N) deserves special attention as N status is supposed to be improved by N-fixing trees. To assess N changes in tree plantations, N cycling was studied in *Eucalyptus* and *Acacia* stands and compared to the native savanna.

Nitrogen accumulation in vegetation and soil, together with N flows in the ecosystem, were estimated. It was assumed that the difference between N amounts in *Acacia* stands and in *Eucalyptus* stands was an estimate of the amount of N fixed symbiotically in the former.

The results showed that 800–1000 kg N ha⁻¹ were accumulated during 7 years in *Acacia* stands. Nitrogen fixation was higher in *Acacia auriculiformis* than in *Acacia mangium*.

Nitrogen cycling through litter fall was high in *Acacia* stands, up to 170 kg ha⁻¹ per year, and low in *Eucalyptus* and *Pinus* stands. However, in *Eucalyptus* stands, slow litter decay and reduced N release from decaying litter resulted in a relative accumulation of organic N in the forest floor.

Decrease in N content was observed in organomineral fractions under the trees. In top-soil (0–10 cm) N mineralization was higher in tree stands than in savanna and total N decreased significantly under 7-year-old *Eucalyptus*. Under older *Eucalyptus*, decreasing N content of organic matter was shown by the increase in C/N ratio. Under *Acacia*, soil N increase was significant in the older stands studied but not in the younger ones, and fixed N accumulated in trees and in the forest floor first. The implications of these observations are discussed.

Keywords: Nitrogen; Symbiotic fixation; Mineralization; Litter; Soil organic matter; *Eucalyptus*; *Acacia*; *Pinus*

1. Introduction

Poor soils are usually devoted to afforestation, which is assumed to enhance their fertility. Trees are

expected to improve soil organic matter status and to increase soil nutrient content either by nutrient absorption in the deep layers of soil and release in litter fall, or by increasing the retention of nutrient input in relation to increased exchange capacity (Kellman, 1979). However, soil nitrogen (N) content deserves special attention as it originates from atmospheric N either through fixation, mainly biological, or rain. Tropical savanna soils are known to have a low N

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content and their improvement by tree plantation is questionable. Although numerous studies are now available on the N cycle in tropical forest (Bernhard-Reversat, 1974; Robertson and Rosswall, 1986; Vitousek and Sanford, 1986; Maggs, 1991), little is known about changes in N cycling when tree plantations take the place of the original ecosystem. Some studies have been concerned with litter and soil N (Bernhard-Reversat, 1988; Theodorou, 1990; Lugo et al., 1990; Purwanto, 1992; Lisanevork and Michelsen, 1994) and others with the nutrient biogeochemical cycle (Bernhard-Reversat, 1986; Loumeto, 1986; Loubelo, 1990; Pande and Sharma, 1993).

In Southern Congo, savanna soils are very poor in N and nutrients. In general, their use for agricultural purposes is limited to cultivation near settlements, where groundnuts and cassava are grown for no more than 1 or 2 years. Since 1978 this savanna has been planted, mainly with *Eucalyptus*, which is grown industrially and cut when 7 years old for wood exploitation. Australian *Acacia* and tropical pines are grown for experimental purposes.

Effects of fast growing tree plantations on soil fertility are often questioned (Poore and Fries, 1985). Nutrient output occurs through logging, and the sustainable management of the plantation requires knowledge of nutrient cycling. To assess the main changes in N cycling when tree plantations are grown on a poor savanna soil, and to generate data on plantation sustainability, N cycling was studied in two *Eucalyptus* hybrids, and two Australian *Acacia* species as an alternative possibility involving symbiotic N fixation. Also some measurements were carried out in a tropical pine plantation. Previous work investigated soil organic matter dynamics (Bernhard-Reversat, 1993) and amounts of N in biomass (Loubelo, 1990; Bernhard-Reversat et al., 1993).

2. Materials and methods

2.1. Site and tree stands

Plantations have been established on undulating hills close to Pointe Noire (Congo), which is located at a latitude of 4° 48' South and a longitude of 11°

54' East. Elevation ranges from 40 to 180 m above sea level. Mean annual precipitation is 1250 mm, with 4 dry months from June to September. Mean annual temperature is 25°C. The highly desaturated ferrallitic soil (French classification) is unvaryingly sandy, with low levels of nutrients, especially N (Jamet and Rieffel, 1976). A soil survey was carried out by Malvos and Ranger (1983) which showed the apparently great homogeneity of the area to be planted.

Two *Eucalyptus* hybrids, one called PF1 (*Eucalyptus alba* × undetermined parents with predominance of *Eucalyptus urophylla* and *Eucalyptus grandis*) and one referred to as HS2 (*Eucalyptus tereticornis* × *Eucalyptus saligna*) (= *grandis*), and two Australian *Acacia* species, *Acacia mangium* and *Acacia auriculiformis*, were studied. *Pinus caribaea* was added to the study for some measurements. The *Eucalyptus* plots were situated in plantations of Unité d'Afforestation Industrielle du Congo (UAIC), and the *Acacia* and *Pinus* plots were in CTFT-Congo (now CIRAD-Forêt, France) plantations. Sylvicultural practices were similar for all species. The trees were planted after tillage to a depth of 20 cm, and fertilization in the planting hole. No fertilization occurred later. Manual or mechanical weeding was performed during 2 or 3 years after planting. Fires in tree plantations were accidental and did not occur in the studied plots. Plots were all larger than 1 ha, and approximately 50 × 50 m were used for experimentation. The characteristics of plots are given in Table 1. The PF1 plot was studied for only 1 year, after which it was logged. *Acacia* and *Eucalyptus* biomass was approximately the same when trees were 7 years old (Bernhard-Reversat et al., 1993).

Table 1
Some characteristics of the tree stands

Tree species	Plot	Year of planting	Age (years)	Spacing (m)
<i>Eucalyptus</i> PF1	79-36	1979	7–8	5 × 5
<i>Eucalyptus</i> HS2	79-14	1979	7–9	5 × 5
<i>Acacia mangium</i>	80-12	1981	7–10	3.5 × 3.5
<i>Acacia mangium</i>	83-12	1984	5–7	3.5 × 3.5
<i>Acacia auriculiformis</i>	80-11	1981	7–10	3.5 × 3.5
<i>Acacia auriculiformis</i>	83-13	1984	6–7	3.5 × 3.5
<i>Pinus caribaea</i>	80-2	1980	10–11	3.5 × 3.5

Tree stands were compared to the native herbaceous savanna on which they were grown. Savanna vegetation is dominated by *Loudetia togoensis* and *Ctenium newtonii*. Some *Anona senegalensis*, a savanna shrub, are scattered among the herbaceous layer but there are no trees in the savanna, which is burnt annually, although it is not cultivated.

2.2. Methods

The accumulated N in stands was divided into the following pools: aerial biomass including leaves and stems, root biomass, forest floor biomass, and the 0–10 cm layer of the mineral soil.

The following N flows were taken into account: input through biological fixation, litter fall, and N mineralization in soil. To estimate N fixation, the total N difference method was used: the amounts of N that built up in stands during a given time in N-fixing trees were compared to non-N-fixing trees.

2.2.1. Measurements of N in litter

Litter fall (litter which falls from trees in a given time) was collected each week in ten randomly set litter traps (0.25 m²) during 1 year under *Eucalyptus* PF1 and during 2 years under *Eucalyptus* HS2, *A. mangium* and *A. auriculiformis*.

Forest floor litter (litter that accumulate on the ground) was collected in 10–12 randomly chosen quadrats (0.25 m²) and was separated into five fractions by hand-picking and sieving: leaves, twigs, flowers + fruits > 4 mm, fragments 0.5–4 mm, and one organic matter fraction < 0.5 mm obtained by flotation in water. These measurements were done

every 3 months for 1 year under *Eucalyptus* HS2 and *A. mangium* and for 2 years under *A. auriculiformis* and savanna. Samples were taken only once under *Eucalyptus* PF1.

Litter from litter traps and forest floor samples was dried at 75°C, weighed for each quadrat in order to calculate mean amounts and standard error (Bernhard-Reversat, 1993). Nitrogen determinations in litter fall were done on composite samples from litter collected in the ten traps for 4 weeks in succession. For the forest floor N, determinations were done on composite samples of each fraction from all the quadrats at each sampling date.

A decomposition coefficient, based on the ratio between litter fall and litter accumulation, was calculated by Bernhard-Reversat (1993) for forest floor fractions, and the same calculation was applied to N in the same fractions, using N amounts in place of dry matter amounts, in order to estimate N release from litter.

2.2.2. Measurements of N in vegetation

Aerial and root biomass and their N content were determined previously in *Acacia* stands by Bernhard-Reversat et al. (1993). Aerial biomass and N was measured in *Eucalyptus* using a similar method by Loubelo (1990). Root biomass in *Eucalyptus* was not measured; a rough estimate was obtained using the root/total biomass ratio found for *Acacia*.

In savanna, biomass and N were measured each month. Aerial biomass was measured on six plots of 1 m² each, and below-ground biomass was sampled in the same plots in the 0–10 and 10–20 cm layers using a 56.6 cm² cylinder. Samples were dried for

Table 2

Nitrogen input to the soil through litter fall (leaves, reproductive parts, i.e. fruits and flowers, twigs; kg ha⁻¹ per year), and nitrogen accumulated in forest floor litter (kg ha⁻¹)

Species and plot	Age (years)	Leaves	Reproductive parts	Twigs	Total	Forest floor
<i>Eucalyptus</i> PF1, plot 79-36	7–8	33	0	4	37	93
<i>Eucalyptus</i> HS2, plot 79-14	7–9	30	0	3	33	118
<i>Acacia mangium</i> , plot 83-12	5–7	134	17	13	164	215
<i>Acacia auriculiformis</i> , plot 83-13	6–7	110	34	8	152	283
<i>Acacia auriculiformis</i> , plot 80-11	7–9	85	33	16	134	
<i>Pinus caribaea</i> , plot 80-2	10–11	21	1	2	24	76
Savanna (aerial parts)					34	0

Table 3
Annual decomposition coefficient of litter dry matter (DM) and annual disappearance coefficient of litter nitrogen (N)

Litter fraction	<i>Eucalyptus</i> HS2		<i>Acacia mangium</i> , 1983		<i>Pinus caribaea</i>	
	DM	N	DM	N	DM	N
Leaves > 4 mm	0.61	0.37	0.96	0.85	0.57	0.47
Leaves + fragments 0.5-4 mm	0.35	0.12	0.69	0.65	0.42	0.30
Total litter > 0.5 mm	0.24	0.10	0.76	0.91	0.46	0.32

weighing and N determination. The average annual maximum was taken for N accumulation in vegetation.

2.2.3. Measurements of N in soil

In each stand, total soil N was measured every 4 weeks in one sample made from mixing eight to ten soil cores 0-10 cm deep, for at least 2 years, except under PF1 where ten samples were taken on 1 day. Soil N below a depth of 10 cm was measured on four samples only.

Mineral N and mineralization were measured on the same samples as total N, and incubations were carried out either 3 weeks in vitro at 30°C for each sampling date, or 4 weeks in situ during the wet season only, according to previously described procedures (Bernhard-Reversat, 1988). In situ incubations were performed in four replicates, and the mean value was used, but frequent deterioration of incubation tubes and a great variability gave weak estimations of mineralization.

As no seasonal trends were observed in soil N data, comparisons were made between stands using the *t*-test on monthly (4 weeks) values.

Also, in vitro incubation of one 0-10 cm soil sample for each stand was carried out on subsamples

with varying water content during 3 weeks to assess the influence of soil humidity.

Sampling of the soil profile down to a depth of 60 cm was done once and in vitro N mineralization was measured.

Particle-size fractionation of soil organic matter was carried out in the 0-2 cm layer of soil according to the method described by Feller (1979) and Bernhard-Reversat (1981). This soil layer was chosen because of its high yield in organic matter, compared to the 0-10 cm layer where it was diluted in sand. Fractionation was achieved by sieving in water and flotation of organic particles, and centrifugation of the resulting suspension to collect the clay + silt fraction.

2.2.4. Nitrogen determination

Total N in litter and soil was determined by the Kjeldahl method, ammoniacal N by the Nessler

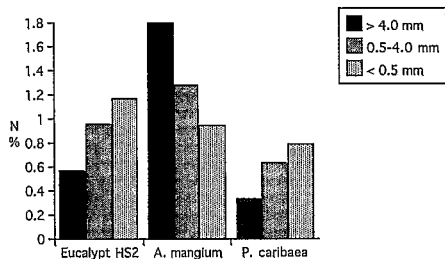


Fig. 1. Nitrogen content of particle-size fractions of forest floor litter.

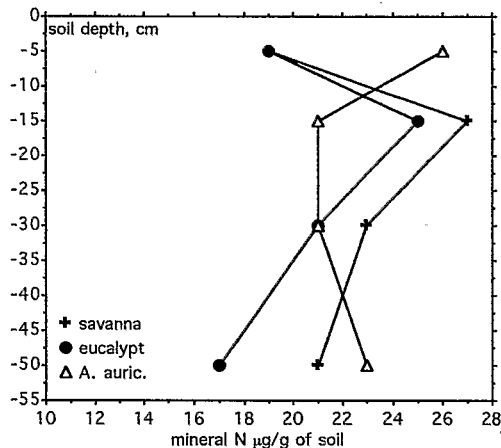


Fig. 2. N potential mineralization: mineral N content of soil (0-10 cm) after 3 weeks in vitro incubation.

Table 4

Mean mineral N content in the 0–10 cm layer of soil before and after in vitro and in situ incubations, expressed as percent of total N

	Initial content			After in vitro incubation			After in situ incubation		
	Mean	n	Significance	Mean	n	Significance	Mean	n	Significance
Savanna	1.0	38	a	3.7	38	a	1.7	23	a
<i>Eucalyptus</i> HS2	1.2	14	ac	4.6	14	b	1.9	8	a
<i>Acacia mangium</i> 80	2.2	21	b	4.1	21	ab			
<i>Acacia mangium</i> 83	1.7	24	bd	4.0	24	ab	3.4	12	b
<i>Acacia auriculiformis</i> 80	2.0	26	b	4.0	26	ab	3.3	16	b
<i>Acacia auriculiformis</i> 83	1.4	13	cd	4.3	13	b	3.1	8	b

n, number of measurements. Different letters in a column indicate significant differences.

method and nitric N by the phenol–disulphonic acid method (Bremner, 1965).

3. Results

3.1. Nitrogen input through litter fall and accumulation in the forest floor

Nitrogen content was low in *Eucalyptus* leaf litter (0.65% and 0.67% for PF1 and HS2 respectively) and pine leaf litter (0.32%). Nitrogen content was 1.62% and 1.51% in *A. mangium* and *A. auriculiformis* leaf litter respectively. Nitrogen content of live leaves (Loumeto, 1990; Bernhard-Reversat et al., 1993) compared to leaf litter emphasized the change in N content that occurred in leaves before leaf fall. Nitrogen was withdrawn from leaves towards twigs and branches, especially in *Eucalyptus* where this process reached 63% of leaf N, whereas it accounted only for 37% and 44% of leaf N in *Acacia*.

Nitrogen input to the soil through litter fall (Table 2) showed great variation among stands. Under *Acacia* it was 4–5 times higher than under *Eucalyptus*, and 6–7 times higher than under *Pinus*. In savanna, the amount of N in aerial parts, 34 kg ha⁻¹, could not be counted as input to the soil because annual fires resulted in N loss.

The range of N accumulation values in the forest floor is narrower (Table 2). Comparison between N release and dry matter decomposition coefficients (Table 3) emphasizes the low rate of N release by *Eucalyptus* litter, and to a lesser extent by *Pinus* litter. This trend was also suggested by the increas-

ing N content of litter fractions with decreasing size (Fig. 1).

3.2. Nitrogen in soil

3.2.1. Nitrogen mineralization

Nitrogen mineralization was first measured in the 0–10 cm soil layer (Table 4), as the process usually decreases sharply beneath this depth according to other studies (Bernhard-Reversat, 1982, 1988; Abbadie and Lensi, 1990). However, results of some in vitro measurements in deeper layers under *Eucalyptus* and savanna were inconsistent with this assumption (Fig. 2).

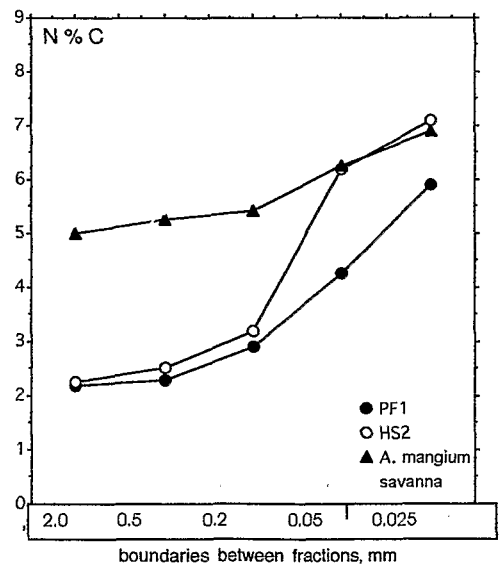


Fig. 3. Nitrogen content of particle-size organic matter fractions, expressed as N% of carbon content.

Table 5
Mean amount of nitrified N, percent of total mineralised N, in the 0–10 cm layer of soil during the first 2 years of measurement

Vegetation	In vitro	In situ
Savanna	100	4
<i>Eucalyptus</i> HS2	15	3
<i>Acacia mangium</i>	97	53
<i>Acacia auriculiformis</i>	100	68

Initial mineral N content was higher in *Acacia* stands than in *Eucalyptus* stands and savanna. Potential mineralization rate, expressed as percent of total N, was higher in *Eucalyptus* soil than in other soils. Trends towards higher mineralization rates in *Acacia* soil compared to savanna soil were not significant. However, in situ incubation resulted in different trends with higher values under *Acacia* stands. It might be related to the ability of *Acacia* soils to mineralize N at lower water content than *Eucalyptus* soils, which was suggested by an in vitro experiment (Fig. 4).

It was noteworthy that, unlike savanna and *Acacia* soils, *Eucalyptus* soils did not exhibit any consistent nitrification of mineralized N (Table 5).

3.2.2. Total soil N

Total N in soil did not exhibit any difference between the various tree stands and savanna below a depth of 20 cm.

Table 6
Soil total N (%) with significance of the difference versus savanna, soil C/N ratio and soil C (%)

Depth (cm):	C		N		Data number	Significance	C/N	N		
	0–10	0–10	0–10	10–20				20–40	40–60	
	Mean ^a	Mean ^a	Mean ^a	Mean ^b	Mean ^b	Mean ^b				
Savanna	7.3 (0.1)	0.46 (0.01)	41	–	15.8	0.40	0.30	0.30		
<i>Eucalyptus</i> PF1, 7–8 years	7.1	0.42	10	–	16.9	–	–	–		
<i>Eucalyptus</i> HS2, 7–9 years	7.1 (0.2)	0.40 (0.01)	24	< 1%	17.5	0.28	0.23	0.29		
<i>Eucalyptus</i> PF1, 15 years	10.6	0.49	3	–	21.7	–	–	–		
<i>Acacia mangium</i> , 7–9 years	9.3 (0.4)	0.58 (0.02)	29	< 1%	16.5	–	–	–		
<i>Acacia mangium</i> , 6–7 years	7.0 (0.3)	0.46 (0.01)	21	n.s.	15.2	–	–	–		
<i>Acacia auriculiformis</i> , 7–9 years	9.2 (0.4)	0.59 (0.01)	31	< 1%	15.6	0.40	0.30	0.27		
<i>Acacia auriculiformis</i> , 6–7 years	7.1 (0.2)	0.50 (0.02)	13	n.s.	14.2	–	–	–		
<i>Pinus caribaea</i> , 10 years	5.9	0.37	4	–	16.0	–	–	–		

^a Standard error of the mean in parentheses.

^b Mean of three measurements.

n.s., not significant.

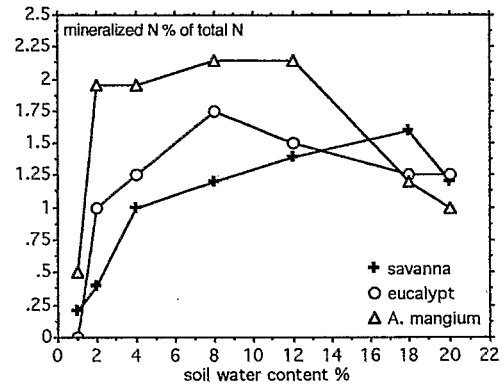


Fig. 4. Soil water content effect on N mineralization during 3 weeks of in vitro incubations of the 0–10 cm layer of soil.

In the older stands of *Acacia*, when 7–8 years old, N and C had increased significantly compared to savanna (Table 6) with an average annual increase of 20 kg ha⁻¹. Younger stands, observed when 5–7 years old, did not show any significant difference compared to savanna.

In 7–9-year-old *Eucalyptus* stands, total C in the 0–10 cm layer of soil was the same as under savanna, whereas total N content had decreased significantly (Table 6). The resulting C/N ratio was higher under *Eucalyptus* compared to savanna. Some measurements made in older PF1 plantations (15 years old) showed a still increasing C/N ratio, although N content had also increased.

Table 7
Nitrogen content of the various pools of the savanna and tree stands (kg ha^{-1})

	Savanna	<i>Eucalyptus</i> PFI	<i>Eucalyptus</i> HS2	<i>Acacia mangium</i>	<i>Acacia auriculiformis</i>
Aerial biomass	30	109 ^a	147 ^a	663	783
Root biomass	27	16 ^b	21 ^b	169	69
Forest floor litter	0	93	118	215	283
Soil 0–10 cm	610	556	530	600	650
Total	670	770	820	1650	1790
Increase/savanna		100	150	980	1120
Increase/ <i>Eucalyptus</i>				850	990

^a Loubelo (1990).

^b Estimation.

Measurements of particle-size organic matter fractions (Fig. 3) emphasized the decrease in N content in organomineral fractions under *Acacia* stands, and in all the fractions under *Eucalyptus* when compared to savanna.

3.3. Total N in the ecosystem and estimation of N fixation

Amounts of N in pools are given in Table 7. They show few differences between the two *Eucalyptus* hybrids. There is some uncertainty concerning N mass in *Eucalyptus* roots. Qualitative observations of *Eucalyptus* root systems which were extracted by UAIC showed a similar organization to *Acacia* root system. However, according to unpublished data on fine roots (0–20 cm deep), fine root biomass was lower for *Eucalyptus* HS2 (3.2 t ha^{-1} , SE 0.3) than for *A. auriculiformis* (6.5 t ha^{-1} , SE 0.4).

To calculate N fixation, the average value of N amounts in PF1 and HS2 stands was subtracted from the amount of N in each stand of *Acacia*. Nitrogen in water was not investigated and it was assumed

that output was equal at all sites, as was input through rainfall.

The results show that 850 and 990 kg N ha^{-1} might have been symbiotically fixed during the 7 years of growth in *A. mangium* and *A. auriculiformis* respectively. A difference ranging from 100 to 150 kg ha^{-1} between *Eucalyptus* stands and savanna was observed. Numerous nodules were observed on roots in the litter and the 0–10 cm layer of soil under *Acacia*, but their efficiency was not tested.

The mean annual symbiotic fixation was 120 and 140 kg N ha^{-1} in 7-year-old *Acacia* stands (Table 8).

4. Discussion and conclusions

4.1. Changes in N input: N fixation

It was assumed that the difference between *Acacia* and *Eucalyptus* stands was mainly due to symbiotic fixation. The total N difference method was compared to the ^{15}N natural abundance or ^{15}N tracer

Table 8
Some annual N flows in 7-year-old tree stands (kg ha^{-1} per year)

	<i>Acacia mangium</i>	<i>Acacia auriculiformis</i>	<i>Eucalyptus</i> HS2
(1) symbiotic nitrogen fixation	120	141	0
(2) immobilization (wood + root biomass)	86	83	13
(3) litterfall	170	173	30
(5) total uptake: (2) + (3)	256	256	43
(4) total available (3) + (1)	290	314	30
(7) forest floor accumulation	0	0	14
(8) soil accumulation	0	6	-11

methods of Mariotti et al. (1992) and Gauthier et al. (1985) and was shown to give approximate results in young trees, although, in the first study, soil and litter were not taken into account. Danso et al. (1993), who reviewed the available data on biological fixation in trees, stated that this method leads to errors which affect the accuracy of estimates as usually a different species serves as a control. However, they stated that differences from other methods are small in low-N sandy soils because of the small contribution of soil N. In the present study, the low level of N in sandy soil, and the fact that both soil and vegetation were taken into account in applying the total N difference method, might lower the possible error in calculation of fixed N during the 7-year period. However, poor agreement with other methods might be noted for estimation of annual rate of fixation in adult trees because of reabsorbed N from decomposing leaves.

Non-symbiotically fixed N, together with fire protection, was assumed to play part in the observed increase in N amount in *Eucalyptus* stands compared to savanna. Although not measured, N fixation was expected to occur in savanna (Dobereiner, 1978), as suggested by the sustainability of the ecosystem, although traditional annual fires result in large annual N losses, which prevent accumulation in the system, as shown by Cook (1994).

More N appeared to be fixed in *A. auriculiformis* compared to *A. mangium*; this difference is in agreement with the results of Galiana et al. (1990) showing a slightly higher N_2 -potential fixation in young plants of the first species.

Annual symbiotic N fixation was estimated on an average basis. However, in *Leucaena*, N fixation was shown to decrease sharply from 1 to 6 years after planting (Van Kessel et al., 1994, in Dommergues, 1994), and this trend was ascribed to the inhibitory effect of mineral N accumulation in the soil. The numerous nodules that occurred in our studied stands did not suggest such a trend. Mineral N storage in soil might be prevented by the sandy texture, and the mean mineral N content of the 0–10 cm layer of soil in older *Acacia* stands was low (12 and $13.6 \mu\text{g g}^{-1}$), even though it was higher than in savanna ($4.6 \mu\text{g g}^{-1}$). However, the average value of annual symbiotic fixation might differ from the actual one.

The mean annual symbiotic fixation was 120 and 140 kg N ha^{-1} in 7-year-old *Acacia* stands. When inoculated with a selected *Rhizobium* strain, young legume trees in good experimental conditions are able to fix higher amounts of N. Sanginga et al. (1988) observed a symbiotic fixation of 134 kg ha^{-1} for a 6-month period in *Leucaena leucocephala*, and higher amounts of up to 580 kg ha^{-1} have been quoted for *Sesbania rostrata* (Ndoye and Dreyfus, 1988). However, in the present study no inoculation was performed and the trees nodulated with native strains. Abrams et al. (1990) found that about 100 kg ha^{-1} per year were fixed in adult *Prosopis* in the field, a value comparable to the present results. Few data are available on N fixation in adult trees grown in field conditions.

Our results suggest (Table 8) that N fixation covered about 50% (47% and 55%) of annual uptake by the trees. Apart from one low value in *Sesbania sesban*, the range of values given in the review by Danso et al. (1993) was 35–76%, with an average of 55%. However, in tropical legume crops, N fixation usually covers 85–90% of plant uptake (Robertson and Rosswall, 1986).

4.2. Changes in N flows: litter fall and mineralization

4.2.1. Flows through litter and its decomposition

Nitrogen input through litter fall (Table 3) under *Acacia* was comparable with the value found in tropical forest (Vitousek and Sanford, 1986) and with other leguminous tree plantations (Montagnini et al., 1993); it was 4–5 times higher than under *Eucalyptus*, and 6–7 times higher than under *Pinus*. This low level of N in litter fall could be ascribed to low soil N. Lisanewok and Michelsen (1994) reported a lower N input of 21 kg ha^{-1} per year in a 40-year-old *Eucalyptus globulus* stand. Data for *Pinus caribaea* plantations suggested low N cycling through litter fall, and Spain and Le Feuvre (1987) stated that the N content of leaf litter was 0.25%.

The N release coefficient showed low N availability for microbial activity in *Eucalyptus* litter, which might be assigned to high tannin content, quoted in a further study, together with low N content. According to Constantinides and Fownes (1994), mineral-

ization in litter is mainly related to initial N content rather than to tannin content.

Thus, the amount of N in the forest floor was only 2–2.5 times greater under *Acacia* than under *Eucalyptus*, although 4–5 times more N was added through litterfall under *Acacia*. Besides, it can be assumed that differences in forest floor N will decrease with the aging of stands as forest floor amount increases under *Eucalyptus*.

Nutrient release rate is expressed by some authors as residence time, i.e. the ratio of nutrient accumulation versus nutrient input. As expected for the present study, residence time was longer for *Eucalyptus* (3.2) and *Pinus* (3.0) than for *Acacia* (1.4 and 1.8).

4.2.2. Change in soil N mineralization

Compared to savanna, N mineralization in tree stands was improved. Increased mineralization has been ascribed by some authors to higher soil nutrient content and resulting lower tannin levels (Maggs, 1991). However, in the present study, exchangeable cation content in top soil decreased under tree plantations compared to savanna, and a high amount of tannin was brought to the soil by *Eucalyptus* litter. (Tannin content of leaf litter was 3.9–4.6% in *Eucalyptus* and only 0.7% in *Acacia*, measured by the Folin–Ciocalteu method; Bernhard-Reversat and Schwartz, in preparation.) Other tree-related factors, such as microclimate or available C from litter might be involved.

It was notable that, unlike what was observed in savanna and *Acacia* soils, no mineralized N or only a very small part of it was nitrified in *Eucalyptus* soil, although numerous observations in the tropics (De Rham, 1973; Wetselaar, 1980; Pereira, 1982), including observations on *Eucalyptus camaldulensis* plantations on sandy soils in Senegal (Bernhard-Reversat, 1987), have emphasized the nitrification of the entire mineralized N. In other Congolese *Eucalyptus* PF1 plantations grown on clay soil, soil samples that were collected for in vitro incubations showed that all mineralized N was nitrified. Some authors have assigned nitrification inhibition to P limitation (Ruess and Seagle, 1994), while the C/N ratio was reported by Polglase et al. (1992) to control nitrification in temperate Australian *Eucalyptus* forests. The lack of nitrification under *Eucalyptus* in the studied sandy soil might rather be ascribed to an

inhibitory effect of litter extracts, which might be inactivated by adsorption on clay particles. Such an inhibitory effect was shown to occur in *Melaleuca*, a closely related genus, by Boquel and Suavin (1972). Antibiotic compounds are also known to occur in *Eucalyptus* (Murata et al., 1990). However, while measuring N mineralization in a great number of samples widely spread over the plantation area, a few samples were shown to exhibit nitrification, but no relationship was found with clay content; pH, which is another known nitrification related factor, showed small variation.

Whatever the cause of the lack of nitrification under *Eucalyptus*, this process prevented nitrate leaching from soil and improved N conservation in this N-poor system.

4.3. Changes in soil N storage

Decrease in total soil N content was observed under 7-year-old *Eucalyptus* stands. Data on a 15-year-old stand suggested further N accumulation. However, it was linked to an increase in C/N ratio. An increase in soil N content under old *Eucalyptus* plantations was quoted by Purwanto (1992) for *Eucalyptus deglupta*, and by Loumeto (personal communication, 1993) for an 18-year-old PF1 stand, where C/N ratio also increased compared to savanna and to younger stands.

Increase in C/N ratio in *Eucalyptus* stands highlights the decreasing N content in organic matter build up under *Eucalyptus*. It occurred in all particle-size fractions, although organic turnover in sandy soils was shown to occur mainly in light fractions by Feller et al. (1991). These results were in agreement with the observed low N release from litter, with the increased soil mineralization rate which provided N uptake for wood growth. The same trend in increasing soil C/N ratio was observed by Madeira et al. (1989) when comparing *Eucalyptus globulus* plantations to natural *Quercus* stands, and by King and Campbell (1993) when comparing *E. grandis* to Miombo forest and pine plantations. Besides, a rapid substitution of native soil organic matter by tree derived soil organic matter when trees were grown on savanna was shown by Martin et al. (1990) and Trouvé et al. (1994) on the studied site. Thus, the low N content of *Eucalyptus*

litter, and also pine litter, resulted in decreasing N content of soil organic matter.

Even in *Acacia* stands, with a high N input through litter fall, a lag time, although shorter than in *Eucalyptus*, was required before soil N changed. It appeared that N accumulated in the forest floor first. However, there were not enough available *Acacia* stands in the studied area to enhance data on N accumulation in soil. Other studies on young leguminous tree plantations also failed to demonstrate significant increases in soil N (Montagnini and Sancho, 1990).

The pattern of N accumulation, which suggested a time lag before soil N accumulation occurred, can be compared with the Thornley and Cannell (1992) model for tree plantations.

4.4. Changes in N economy

It was not possible to study N in water, and it was assumed for calculation purposes that output and input were the same in all sites, yet the above observations suggest that N loss through leaching, which is known to occur mainly as nitrate N, was reduced in *Eucalyptus* stands where no nitrification occurred. Reduced leaching can also be expected under *Acacia* because of the large quantity of fine roots allowing nitrate absorption by the vegetation.

It was notable that some common features were observed in the functioning of tree stands. Increased N mineralization and decreased N content in the organomineral organic matter fraction appeared to characterize tree stands when compared to savanna. However, comparison between *Eucalyptus* and *Acacia* stands highlighted differences, as soil N uptake by plants resulted in soil depletion only under the former. Under *Acacia*, N supply to the soil by symbiotic fixation occurred in the coarse light fractions of organic matter, as suggested by the N content of particle-size fractions.

In *Eucalyptus* and *Pinus* plantations, the low level of soil N might result in feedback which maintains or accentuates N limitation, as stated by Vitousek and Howarth (1991), and result in very low amounts of N being brought into the biogeochemical cycle. However, some processes improve N use in *Eucalyptus* stands by lowering losses: withdrawal before leaf fall resulted in small losses with litter

fall, even though live leaf content was comparatively high. Besides, N accumulation in litter on soil and the lack of nitrification prevented leaching from soil with rainfall. In *Eucalyptus* stands, an overall increase in N bulk as compared to savanna resulted from the above retention processes together with input through rainfall and non-symbiotic fixation.

In *Eucalyptus* stands, output of N with clear felling and log harvesting was estimated to be 100 kg ha⁻¹ by Loumeto (1986). During the same period of time (7 years), the increase in the stand was about 100 kg ha⁻¹. Thus, provided the remaining plant parts (leaves, twigs, bark, forest floor, roots) were managed to prevent losses, N requirement for further tree growth could be maintained. In a natural logged *Eucalyptus* stand, losses by prescribed burning were balanced by symbiotic fixation in leguminous understorey vegetation (Hopmans et al., 1993).

Acacia was shown to fix a large amount of N, and the resulting storage occurred mainly in tree biomass and in forest floor. For several years after planting, soil N and soil organic matter did not increase, whereas high litter production occurred. Besides, soil exchangeable K, Ca and Mg content decreased in tree stands compared to savanna (unpublished results). Thus, short-lived *Acacia* plantations cannot be used for poor sandy soil improvement unless management practices enhance N and C storage in soil.

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