SOIL ORGANIC CARBON DYNAMICS UNDER EUCALYPTUS AND PINUS PLANTED ON SAVANNAS IN THE CONGO

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Summary—In the Congo, Eucalyptus and Pinus have been planted commercially for 30 yr on savanna. Large differences in the abundance of carbon isotopes of the savanna Gramineae and the trees enabled a study to be made of the soil organic matter (SOM) turnover by means of its carbon isotope composition. The organic carbon content slightly increased with plantation age without any significant differences (90% confidence limit) between plantation types. The δ13C of SOM varies with the plantation age from −14.4‰ in the savanna reference plot to values close to −26.5‰ in the oldest tree plantations. The distribution of δ13C as a function of plantation age was modelled by an exponential function and exhibited no significant variation (90% confidence level) between plantation type. As the relative contribution of organic matter inherited from the savanna and that derived from the tree species was proportional to the δ13C value, the fraction of each organic compartment was evaluated for plantations grouped together without distinguishing between the different tree species. With time, the SOM inherited from the savanna tended to disappear. The half-life was estimated to be 16.5 yr, clearly illustrating the rapid SOM turnover which characterizes the savanna ecosystems in psammitic ferrallitic soils. The fraction of organic C of tree origin progressively introduced into the soils was linearly related to time. The annual increment of organic C was found to be equal to 0.3 mg C g−1 yr−1, but it was clear that the linear evolution of carbon with time could not be extrapolated over more than 30 yr. The various models predicted that after 30 yr there would remain in the soil, 1.8 and 0.8 mg C g−1 of savanna origin and 9.4 mg C g−1 of newly introduced organic C of tree origin respectively.

INTRODUCTION

The carbon isotope composition of terrestrial photosynthetic plants differs from that found in the atmospheric reservoir of CO2 where the current δ13C value is approx. −7.8‰ (Nier and Gulbransen, 1939). This fractionation arises from the preferential incorporation of the lightest isotope during the carboxylation step of the photosynthetic cycle (Park and Epstein, 1961). However, photosynthetic patterns (C3 and C4) produce different stable carbon isotope ratios in plants. The δ13C values of C3 plants such as trees and the majority of temperate herbaceous plants lie between −24 and −34‰, whereas δ13C of C4 plants such as tropical Gramineae range from −9‰ to −16‰ (Bender, 1968, 1971; Smith and Epstein, 1971; Deines, 1980). It is now well known that δ13C values of soil organic matter (SOM) reflect the vegetation cover (Deines, 1980; Cerri et al., 1985; Mariotti and Balesdent, 1990). Under C3 vegetation, the decomposition processes of plant material yield slight variations in the δ13C in the top soil, even if SOM is enriched with 13C (from 1 to 3‰) lower down the soil profile (O’Brien and Stout, 1978; Schleser and Bertram, 1981; Balesdent et al., 1990). This enrichment can be explained in different ways: (i) atmospheric CO2 isotopic decrease during the last 100 yr which is reflected in the vegetation (Marino and McElroy, 1991); (ii) differential mineralization of SOM components; (iii) isotope effects during microbial organic humification (Mariotti and Balesdent, 1990).

In previous studies, 13C:12C ratios have been used as a means investigating paleoclimatic changes in subtropical areas where C3 forest has been substituted by C4 savanna on podzols in the Congo (Schwartz et al., 1986) and changes from C3 to C4 gramineae under arid climatic conditions (Dauree et al., 1985). In agrosystems under a temperate climate, Balesdent et al. (1987, 1988) have studied the SOM turnover in maize (C4) fields developed after previous continuous wheat cultivation. Under a tropical climate in Brazil, Cerri et al. (1985) studied the SOM turnover of Sugar Cane (C4) plantations on a recently cleared primary forest (C3).

In the Congo where Eucalyptus and Pinus have been planted on savanna during the last 30 yr, an opportunity arose of studying the turnover of SOM on the basis of progressive changes in isotopic composition of the SOM due to change of vegetation.
from savanna (mainly C,) to forest (C,). With this intention soil samples were collected in plantation stands of known age and also from a reference plot of the initial savanna. δ 13C measurements allowed us to estimate the replacement of organic matter of the initial savanna by that of trees, so enabling an assessment of the decay rate of the organic matter of savanna origin.

MATERIALS AND METHODS

Study area

The tree plantations were located in the coastal area of the Congo, to the east of the city of Pointe-Noire (4°48'S and 11°51'E) (Fig. 1). The climate is classified as guinean of low-Congo type, and is characterized by a dry fresh season in summer (May–October) and by relatively constant temperatures with an average of 24.8°C FAO/UNESCO, 1975; Jamet and Rieffel, 1976). The soils have developed on plio-pleistocene sands (Dadet, 1969) named 'sables de la série des cirques' which are coarse deposits carried away from the Mayombe mountain chain located 50 km to the east of Pointe-Noire. The soils are classified as 'sols ferrallitiques psammitiques' or as 'Ferralic arenosols' according to the French or the FAO taxonomy (Jamet and Rieffel, 1976; FAO, UNESCO, 1975). They are sandy soils and the maximum clay content reached 7% in the top soil. The pH of the top soil was ca. 5, the values being slightly lower in the plantation stands than in the savanna. The C:N ratio of organic matter ranged from 10 to 14.

In the Congo, a large afforestation programme has been managed for 30 yr by the CTFT (Centre Technique Forestier Tropical) for experimental research and by the UAIC (Unité d’Afforestation Industrielle du Congo) for commercial forestry. The sampling sites were in the CTFT experimental plantations which cover 2000 ha at 15 km to the east of Pointe-Noire. Plantation stands of Eucalyptus and pines (Pinus caribaea) were selected for soil sampling. The chosen Eucalyptus stands were of a hybrid named PFI (a cross between E. urophylla and E. ABL-saligna) which has been planted regularly since 1969.

Sampling strategy

Two methods of sampling were adopted in the plantations. A series of samples were taken from profiles of pits dug at the centre of a limited number of plantations. In addition, top soils (0–5 cm) were sampled in a larger number of stands.

Pit sampling: 120 cm deep soil profiles were dug in three Eucalyptus stands (6, 16 and 19 yr old), in four Pinus stands (11, 13, 18 and 21 yr old) and one in savanna. Samples for isotope analyses were taken every 5 cm down the profile and each one consisting of four subsamples taken with a 50 ml cylinder.

Top soil sampling was performed along a straight line which traversed the tree alignments diagonally. Samples were collected every metre after having discarded the surface litter and consisted of two subsamples collected with a 50 ml cylinder to a depth of 5 cm. Since interpretation difficulties can rise from the dispersion of data due to the spatial variability of soil properties and constituents, we decided to collect samples on two separate sampling occasions.

At the first sampling, 10 samples were collected in the reference savanna plot and in three Eucalyptus stands to determine an optimal sampling strategy. The Eucalyptus tree ages were 5, 10 and 15 yr. The organic C and δ 13C were measured on dried, sieved (at 630 μm) and ground samples. Non-parametric statistical methods were utilized to analyse the distributions according to the Kolmogorov–Smirnov test.
and also to compare the means using the Student t-test (Scherrer, 1984).

Confidence intervals of the means determined by the t-test were found to be too large with 10 samples for each stand. From the t-test, we determined the optimal number of samples to be collected to reach the desired level of precision of 95%. For organic C, the desired precision was 5% about the mean value. Using the formulas of Scherrer (1984), we found that 25 samples had to be collected for each stand. As for the δ13C values, we decided that an acceptable level of precision would be about ±0.3‰ about the mean, and, the estimated optimum number was 21 for each stand.

Therefore at the second sampling, in March 1990, 25 samples were collected in 10 Eucalyptus stands, 10 Pinus stands and in the savanna plot which is an enclave of the initial savanna conserved among the plantations. The samples from each site were air dried and mixed to obtain a representative bulk sample.

Carbon analyses
Carbon contents were determined by conductivity titration after combustion of ground soil samples in pure O2 (Carmagraph Whöfstoff).

The 13C natural abundance of samples was determined by combustion at 850°C of organic carbon. The evolved CO2 was analysed on a mass spectrometer (Finnigan Delta E) fitted with a system equipped for rapid switching between samples and reference.

The results are expressed in δ units (%o) vs PDB international standard as:

\[ \delta^{13}C = \left( \frac{^{13}R_{\text{sample}}}{^{13}R_{\text{standard}}} - 1 \right) \times 1000 \]  
(1)

where

\[ ^{13}R = \frac{^{13}C}{^{12}C} \]  
(2)

Curve fitting of δ13C as a function of the stand age

The δ13C values were fitted as a function of the plantation age using an exponential decay model as expressed by the following equation:

\[ \delta m = \delta f + (\delta s - \delta f) e^{-kt} \]  
(3)

where

\[ \delta m = \delta^{13}C \text{ of organic matter of soil samples} \]
\[ \delta s = \delta^{13}C \text{ of soil organic matter derived from savanna} \]
\[ \delta f = \delta^{13}C \text{ of organic matter derived from trees} \]
\[ k = \text{the decay constant.} \]

Before the introduction of the trees (t = 0), this soil organic C of savanna had an isotope composition δs and δm = δs; for t → ∞, δm tends to δf. With the increasing age of tree stands, the isotope composition changes from this initial value δs to a final value δf, which would reflect the establishment of a new forest ecosystem.

Equation (3) can be easily solved in two ways. The first consists of an iterative procedure using the least squares method (Scherrer, 1984). The second method consists in fixing the value of δf, so that equation (3) can be transformed into a linear equation:

\[ \ln(\delta m - \delta f) = \ln(\delta s - \delta f) - kt \]  
(4)

k and \( \ln(\delta s - \delta f) \) are solved by a linear regression analysis. The confidence intervals of the δs and k parameters have been computed at the probability level of 90% using Scherrer's method (Scherrer, 1984, pp. 650 and 656). The δs and k values of the Pinus and Eucalyptus plantations were judged to be different or not at the 90% confidence limit on the basis of their confidence interval overlap.

Calculation of the fractions of organic carbon derived from the savanna and from trees

δ13C of SOM was intermediate between those of the savanna and the trees. The fractions of organic C derived from savanna and from trees can be directly calculated from these δ13C values if the isotope compositions of the two opposite sources (savanna and trees) are known.

\[ C_t = \text{the total organic C content of the sample, } C_s \text{ and } C_f \text{ are carbon contents derived respectively from the savanna and trees. } \delta m, \delta s \text{ and } \delta f \text{ is } ^{13}C \text{ of organic matter of soil samples, of organic matter derived from savanna and of that derived from trees respectively. As } ^{13}C \text{ is not very different from the total C content (near 1%) the } ^{13}C \text{ balance can be expressed as:} \]

\[ C_t = C_s + C_f \]  
(7)

Then, the soil organic C contents derived from the savanna

\[ C_s = \frac{\delta m - \delta f}{\delta s - \delta f} \times C_t \]  
(8)

RESULTS AND DISCUSSION

Variation of δ13C with profile depth

In the upper 50 cm layer of the savanna soil, the δ13C values were close to those of C4 plants of the savanna (Table 1, Fig. 2). In the deepest layer (from

<table>
<thead>
<tr>
<th>Andropogon</th>
<th>Centaurea</th>
<th>Loudelia</th>
<th>Cyperus</th>
<th>Hyparrhenia</th>
</tr>
</thead>
<tbody>
<tr>
<td>braccae</td>
<td>newtonii</td>
<td>pinnata</td>
<td>spp</td>
<td>spp</td>
</tr>
<tr>
<td>Leaves</td>
<td>-12.0</td>
<td>-13.3</td>
<td>-12.2</td>
<td>-11.3</td>
</tr>
<tr>
<td>Root</td>
<td>-12.0</td>
<td>-13.5</td>
<td>-12.0</td>
<td>-11.4</td>
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</tbody>
</table>
60 to 120 cm) of the savanna soil, the δ13C had significantly decreased (Fig. 2). This had clearly resulted from mixing of old organic matter of tree origin with more recent organic matter derived from the present savanna plants. Similar curve patterns were obtained in Congo indicating transition from a forest landscape to a savanna (Schwartz et al., 1986). As shown in Fig. 2, the Pinus and Eucalyptus plantations had modified the δ13C contents of the upper 50 cm of the profile, particularly in the top soil (0–5 cm). At a given depth, the influence of the plantation trees depended on the age of the plantation. The older the plantation, the lower was the δ13C value of the SOM.

The δ13C data for the subsoil (50-120 cm) indicated a similar pattern in the savanna plot and in the two sampled plantations. The parallelism of the curves indicated that the soils of the Pointe-Noire area had the same ecological history, with evidence of a forest landscape of unknown age. The nonalignment of the δ13C curves and their parallelism can be explained if we suppose that in any area of the savanna before afforestation, erosion processes could have been more or less severe. It is possible that at the site of a savanna pit, a soil layer of 20 cm had been eroded unlike areas now under 6 yr old Eucalyptus and 11 yr old Pinus plantations.

Variation of organic carbon contents and δ13C values of the top soil

In Pinus and Eucalyptus stands, the organic C contents (Table 2) exhibited wide variation ranging from 4.5 mg g⁻¹ to 13.6 mg g⁻¹. The linear relation between organic C and the Pinus stand ages...
Data from Table 2 and the graphs from Fig. 4 clearly show that the $\delta^{13}C$ value decreased with the stand age whatever the tree species. The lowest observed values are close to $-26.5\%$.

The decrease of the $\delta^{13}C$ value with the stand age can be interpreted as the result of the individual decrease of various organic compartments, where each can be modelled by an exponential decay curve (Jenkinson, 1965). But as the dispersion of $\delta^{13}C$ values in the present study was very high, it appeared to be simpler to use a single exponential decay model (equation (3)).

The least-squares method yields decay constant values of 0.041 and 0.062 yr$^{-1}$ respectively for Pinus and for Eucalyptus stands and $\delta\nu$ values of $-13.3$ and $-14.1\%$ for the same two stands. The best evaluated $\delta\nu$ values were found to be $-33.0$ and $-31.5\%$ respectively for Pinus and Eucalyptus stands. These values are much lower than those obtained by measurements of litters and humus, so that the least-squares method does not give reliable $\delta\nu$ values.

Our measurements showed that the organic C isotope composition of Eucalyptus aerial litter and roots ranged from $-31.0$ to $-27.7\%$ respectively. The litter layers of Eucalyptus plantations (16 and 19 yr old) have a $\delta^{13}C$ ranging from $-29.8$ to $-30.9\%$ whereas the $\delta^{13}C$ of the Pinus needle litter was found to be $-29.7\%$. As for the organo-mineral horizons of the top soils, Schwartz et al. (1986) give values ranging from $-27.0$ to $-28.0\%$ for the rain forests in the Congo. It is now well known that the $\delta^{13}C$ values of SOM often increase between 1 and 2% from the surface to median soil horizons (50 cm) in profiles of intertropical (Volkoff and Cerri, 1987;
Fig. 4. Distribution of the $\delta^{13}C$ of organic matter in the top soil of Pinus and Eucalyptus plantations.

The calculation of the fractions of organic C derived from savanna and tree material takes into account the total organic C content, $\delta^{13}C$ of plantation stands and the two opposite 'end members' (savanna and trees).

The savanna in Congo is mostly composed of Loudetia and Hyparhenia spp. Aerial organs and roots of dominant Gramineae and Cyperaceae were collected within the savanna of the Pointe-Noire area. Their isotope compositions (Table 1) ranged from $-11.3$ to $-13.5\%$ and aerial organs were not isotopically different from roots. All data agreed with the C$_4$ plant characteristics. In other savanna sites in Pointe-Noire, Loudima, Niari Valley, Brazzaville areas, $\delta^{13}C$ values between $-13.1$ and $-14.4\%$ have been obtained (unpubl. data and Schwartz et al.).
Fig. 5. Organic carbon derived from savanna in the top soil of Pinus and Eucalyptus plantations.

The fate of organic carbon derived from savanna. The decrease of organic C derived from savanna did not correspond to the decrease of a unique compartment, the variations of the values being not significant differences were found between the two plantation types is similar, and that of 90% of confidence is statistically different between Pinus and Eucalyptus stands. As expected, the organic carbon from savanna decreased with the age of the plantations whereas the organic matter of tree origin tended to increase. Although the decrease of organic C derived from savanna did not correspond to the decrease of a unique compartment, the variations of the values obtained in the reference plot and on 30, 50 and 100 yr old plantations the organic material derived from savanna in the top soil was depleted in 13C in comparison with the savanna top soils which is the average value of the savanna values used - 15.7% which is the average value of the savanna sites in all together.

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amount would represent 1.5% of the initial savanna carbon.

The half-life of organic C derived from the savanna was about 16.5 yr. This low value indicates that the SOM turnover is very rapid in psammitic tropical soils. The same observation was made by Martin et al. (1990) in sandy soils in the 'Côte d'Ivoire' where the variations of organic matter in pure and forested savanna were compared: 52–70% of the initial savanna carbon was lost during the first 16 yr of natural afforestation of the savanna. A slower turnover has been noticed under a temperate climate of Balesdent et al. (1987) who studied the replacement of organic matter originating from wheat by that of maize (C,) on a field continuously cultivated with maize for 13 yr. During this elapsed time, only 22% of the total organic C had turned over.

Incorporation of organic carbon of tree origin

By the linear regression method the following relationship was found between Cf and the plantation ages: 

\[
Cf = 0.30t + 0.37 \quad (r = 0.83) \quad (P < 0.001).
\]

According to this model (Fig. 6), the mean organic C content of 30 yr old plantations would be about 9.4 mg C g⁻¹.

For a longer period, the supposed model could be exponential under the form: 

\[
Cf = Cf_0 \times e^{-\lambda t}
\]

where Cf_0 is the limit value of soil organic C contents and \(\lambda\) the increase constant. Cf_0 could be close to the organic C content of the surface horizons in forest psammitic soils in the Congo ranging from 20.0 to 30.0 mg C g⁻¹ (Jamet and Rieffel, 1976). In such an evolution, the input during the first 20 yr would take place on the linear segment of the curve (Fig. 6).

The relatively rapid incorporation rate of organic matter during the first years of plantations is probably dependent upon the restitution rate of the aerial tree materials. The influence of growth on the organic restitutions is relatively well documented for Eucalyptus (Ashton, 1975; Bernhard-Reversat, 1987; O'Connell, 1987). O'Connell and Menage (1982) studied the restitution annual fluxes in the Eucalyptus stands of Australia. They found that during the first 2 yr, restitutions are essentially constituted by leaves, and the annual litter fall was estimated to be about 2 t ha⁻¹ yr⁻¹. In 6 yr old stands, restitutions were evaluated to be 3.7 t ha⁻¹ yr⁻¹ and for older stands (40 yr old), they still increased but with a larger contribution of twigs and bark which decompose much more slowly than leaves (Ashton, 1975). At Pointe-Noire, in the Congo, experimental devices have been introduced in Eucalyptus stands by Bernhard-Reversat (1988) for measuring the biomass and litter production of Eucalyptus. In 7 yr old stands, the annual litter fall varied between 4.3 and 6.2 t ha⁻¹ yr⁻¹ according to the soil properties. The leaf retention time on the trees is estimated to be 6 months (5 tons of annual litter fall vs 2.5 tons on the tree canopy). Concerning Pinus plantations, Lugo et al. (1988) found no significant differences for the organic restitutions in Pinus and Eucalyptus plantations of same age.

We have shown that Eucalyptus and Pinus plantations of different ages induce changes in the carbon isotope composition of SOM of the Pointe-Noire savanna. Evidently, the isotopic signal is more distinct in the top soil than in the lower soil layers.

The organic carbon isotope composition of the top soil varies within the first 30 yr of a plantation of Eucalyptus and Pinus, from a \(\delta^{13}C\) of SOM derived from C_3 plants to a \(\delta^{13}C\) of SOM derived from C_4 plants. In spite of important variations within organic C content between plots, evidence exists for a process...
of substitution between organic matter inherited from the initial savanna and that derived from trees. No significant differences between the plantation types were found in the disappearance of savanna organic matter, probably by mineralization. In the plantations, the half-life of 16.5 yr of the original organic C reveals a fast turnover of the organic matter in psammitic ferrallitic soils. It is more difficult to interpret the apparent progressive incorporation of organic matter derived from trees because it is clear that the steady-state equilibrium between the different components of the forest ecosystem has not been reached.

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