The role of biological activity (roots, earthworms) in medium-term C dynamics in vertisol under a *Digitaria decumbens* (Gramineae) pasture

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Abstract

The natural abundance of ^{13}C was used to estimate the turnover of the soil organic matter in a vertisol re-grassed with *Digitaria decumbens* (C4 plant) following intensive market gardening (C3 plants). In addition, the experimental design allowed us to determine the respective roles of roots and earthworms (*Polypheretima elongata*) in soil C stock restoration in *D. decumbens* pasture.

The C stock increased from 31 to 37 Mg C ha^{-1} in 5 years and the δ^{13}C increased from -18.1‰ in market gardening soil to -15.5‰ in the 5-year-old pasture soil in the upper 20 cm. Below the 20 cm soil layer, the C stock and the δ^{13}C did not change significantly in 5 years. The net gain of 6 Mg C ha^{-1} was the balance of a loss of 5 Mg C ha^{-1} derived from market gardening and a gain of 11 Mg C ha^{-1} derived from *D. decumbens*. Effects of earthworms on the C dynamics were not discernible. © 2001 Elsevier Science B.V. All rights reserved.

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1. Introduction

Soil organic matter (SOM) plays an important role in soil fertility and productivity (Feller et al., 1996), and is a critical factor for the reduction of soil erosion through aggregate stabilization. In addition, the preservation of OM in soil mitigates greenhouse gas emissions (CO_2) into the atmosphere (Cole et al., 1996). Regional, continental or global models are useful to understand the SOM dynamics according to land use changes and management practices (Cole et al., 1996). These models require a thorough knowledge of the distribution of C among the SOM functional pools in different soils and under different land uses practices (Paustian et al., 1997).

Though vertisols constitute only 4.4% of soil surface in the tropics and store only 2.2% of the total organic C in tropical soils (Eswaran et al., 1993), they are fertile and used intensively for agricultural production (Ahmad, 1996). Furthermore, they have a high C storage capacity under natural vegetation (10 kg C m^{-3} on 1 m, Batjes, 1996). They have been studied extensively for their physical and hydraulic properties (e.g.

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Cabidoche and Voltz, 1995). However, so far, there have been few studies focusing on the organic characteristics and biological activities in these soils (Dalal et al., 1995).

In Martinique (West Indies), land use patterns greatly affect C stocks in vertisols. For example, 15 years of intensive market gardening significantly decreased SOM stock and soil aggregation and increased soil erosion (Albrecht et al., 1992). There is now a need to increase soil organic stocks in order to preserve the soil resources. Pastures seem to be one of the best agrosystems for enhancing the SOM stock in cultivated soils (Fisher et al., 1994; Cole et al., 1996). Indeed, some pastures have higher soil C stocks than forests (Choné et al., 1991; Lugo and Brown, 1993; Neill et al., 1996) and, Scharpenseel and Becker-Heidmann (1997) have calculated that the mean residence time (MRT) of C derived from pasture was longer than the MRT of C derived from forest in an Australian vertisol. In Martinique, planting a *Digitaria decumbens* pasture on a cultivated vertisol increased the C stock from 31 to 37 Mg C ha^{-1} (0–20 cm) within 5 years (Chevallier et al., 2000). This high storage value could be explained partly by the heavy clayey soil and the high plant inputs. Furthermore, the increases in spatial microvariability of the soil C content and in the C/N ratio, in parallel to the soil C content, suggest that the increase in C content arises mainly from the incorporation of plant debris (Chevallier et al., 2000). Nevertheless, we do not know how significant the C inputs from *D. decumbens* are to stock C in this vertisol, nor do we know about the dynamics of the different C pools in the young pasture. In the present study, we used the natural abundance of ^{13}C to estimate the turnover of the SOM present under culture (C3+C4 plants) and the SOM derived from *D. decumbens* (C4 plant).

Soil C stocks are influenced by roots and faunal activities. Roots are the major C source in soil (Balesdent and Balabane, 1996), and can also stimulate SOM mineralisation (Choné et al., 1991; Ladd et al., 1994). Earthworms, which dominate soil fauna in the humid tropics (Lavelle, 1997), can influence both short and long term C dynamics; the former through C assimilation and the latter through protection of SOM against mineralisation in their casts (Lavelle and Martin, 1992). For vertisols, C stocks were also influenced by root biomass, micro-organisms and faunal activi-

ties (Blanchart et al., 2000). But so far, there is less understanding about the respective contributions to C dynamics of roots and earthworms.

The aim of our experiment was to establish the respective roles of roots and earthworms in pasture soil C stock restoration. Our main objectives were: (i) to calculate and compare the mean residence times (MRT) of C in soil with and without root and litter inputs; (ii) to estimate the net storage of C over 5 years in relation to the amount of C inputs from *D. decumbens*; and (iii) to determine the influence of earthworms (*Polypheretima elongata*, which is the main earthworm species in natural pastures of the region) on soil C stock restoration.

2. Materials and methods

2.1. Site and soil characteristics

The experiment was located in the southeastern part of Martinique, French West Indies (14°25′N/60°53′W). The area is characterised by a humid tropical climate. The mean daily temperature is stable (26–28°C) throughout the year, and rainfall mainly occurs from July to December with a mean annual amount of 1400 mm. The soil (20-m elevation with a 5% slope) was classified as smectitic Leptic Hapludert (USDA classification; Soil-Survey-Staff, 1975) or Eutric Vertisol (FAO-UNESCO-ISRIC, 1988) developed on andesite. Cation exchange capacity (CEC) values ranged from 35 to 40 cmol kg^{-1} (exchangeable Ca: 55%, exchangeable Mg: 32.5%, exchangeable Na: 10% and exchangeable K: 2.5% of the CEC). The pH (water) varied from 6 to 6.5 across the area. Soil depth was around 1 m. The soil was clayey in texture, with mineral particles <20 μm comprising 70–80% of total mineral content in the top 20 cm.

2.2. Experimental design

The experimental design consisted of three plots, which had been under continuous sugarcane (C4 plant) production until 1970, followed by fallow (native pasture) until 1978. At that time, the first plot, MG, (0.3 ha) was used for intensive market gardening for the production of melons, tomatoes, yams — C3 plants; the second plot, P, (0.3 ha), was converted to

pasture and planted with a tropical grass *Digitaria decumbens* (Pangola grass), a C4 plant; and the third plot, Pr (0.4 ha), was used for intensive market gardening until 1991. At the end of 1991, Pr was converted into a *D. decumbens* pasture. Like P, Pr was fertilised ($100 \, kg \, N \, ha^{-1}$ per year) and irrigated (rain plus irrigation amounted to about 120 mm per month) and grazed by sheep (2 animals ha^{-1}, breed: Martinik). The annual above ground yield of *D. decumbens* was around $25 \, t \, DM \, ha^{-1}$ (Mahieu, personal communication). In 1992, three sub-plots were installed in the Pr plot to distinguish between the effects of roots and earthworms on the dynamics of C storage when a plot was converted from cultivation to pasture. As replication was not practical, special care was taken to choose subplots with comparable physico-chemical parameters. Spatial variability of soil carbon and clay contents (0–30 cm) and soil depth was assessed by the use of geostatistics in Pr (ORSTOM SECI, 1994) and the three experimental sub-plots of $50 \, m^2$ ($5 \times 10 \, m$) were located in a relatively homogenous zone inside Pr to allow valid comparison. The C content varied from 13.5 to $15.5 \, g \, C \, kg$ per soil, the clay content from 50 to 55%, and the soil depth from 0.5 to 0.8 m. Due to the presence of toxic pesticides and the presence of cattle in the field, these plots were isolated by wire netting. The following treatments were applied to the subplots:

- Treatment P_0E_0 (control): a few months after the establishment of the pasture by planting *D. decumbens*, grass was killed with a herbicide (Glyphosate at a rate of $360 \, g \, l^{-1}$, $10 \, l \, ha^{-1}$). The herbicide was applied every 2 months. Earthworms were killed with a pesticide (carbofuran) which is known to affect earthworms at various rates depending on the species and the type of soil (Lee, 1985). Due to the low hydraulic conductivity in vertisols, we chose to apply high doses of $10 \, kg \, ha^{-1}$ a.i. The product (Trademark Furadan) was spread on the soil surface every 2 years.
- Treatment P_+E_0 (with plants only): the vermicide Carbofuran was used at the same rate and at the same time as in treatment P_0E_0. Plants were allowed to develop and were cut regularly.
- Treatment P_+E_+ (with plants and earthworms): plants were allowed to develop and were cut regularly, as in treatment P_+E_0. Earthworms were inoculated into this subplot because the indigenous

population was low as this area had previously been under market gardening cultivation. A U-shaped trench 30 cm wide and 30 m long, was dug out around the plot, down to the bedrock. After excavating the soil, a relatively thick plastic film was used to line the trench, and the soil was put back in the trench. This was meant to prevent the escape of earthworms. Earthworms (*Polypheretima elongata*, Megascolecidae) were collected in an irrigated pasture where the population density was known to be very high. About 4.500 earthworms were collected over a period of 30 days and placed in 100 soil-filled containers lined with plastic film to allow easy removal of contents. The containers were evenly distributed on the plot, inverted on the ground and covered with a mulch to avoid heating. This introduction technique was chosen in order to avoid predation by birds and exposure to sunlight, and to limit soil disturbance. After 1 week earthworms had left the containers and entered the soil. Containers were removed and their contents were hand-sorted to verify the absence of earthworms. As a consequence, a density of 90 earthworms m^{-2} was introduced into this sub-plot.

2.3. Samples for C and ^{13}C content analyses

From 1993 to 1997, 96 soil C profiles were determined every year from Pr (in 10 cm soil layers down to 30 cm depth) as described by Chevallier et al. (2000). At the same time, six soil C profiles were determined from the three sub-plots in Pr (P_0E_0, P_+E_0, P_+E_+) (in 10 cm soil layers down to 60 cm depth). In 1997, three additional profiles of ^{13}C natural abundance were determined (in 10 cm soil layers down to 60 cm depth) in each experimental plot. ^{13}C natural abundance was determined for the three replicate samples from the 0–10 to 10–20 cm soil layers, but for deeper layers, only one composite soil sample per soil layer was analysed.

In 1997, *D. decumbens* litter, living leaves, roots and stems+stolons were dried and ground to powder. Then, the C and ^{13}C contents of these different plant tissues were measured.

2.4. Soil and biological analyses

The soil was oven dried at 60°C, then crushed and sieved to 200 μm. Total C and N were measured

with a Carbon Nitrogen Sulfur Analyser, NA 1500, (Carlo–Erba). The $^{13}C/^{12}C$ ratio was measured with an isotopic mass-spectrometer (Sira 10, Fisons) with an internal precision of about 0.015‰ (Girardin and Mariotti, 1991).

Root biomass, integrating both living and dead roots, was measured once under Pr in three soil profiles. Soil samples, monoliths of $10\,cm^3$ for each 10 cm soil layer were taken down to 60 cm depth. The soil samples were dispersed in a NaOH solution (pH 10) and sieved at 200 μm. The plant and mineral particles >200 μm were separated by flotation in water. From optical observations it was concluded that almost all plant debris were of root origin.

Earthworm biomass was assessed in Pr every year at the end of the rainy season by hand-sorting monoliths measuring $30\times30\times30\,cm$. Earthworm biomass in MG and P was only measured in 1997.

2.5. Calculations

P_0E_0 had no C input and it was therefore possible to estimate the mean residence time (MRT) of C in soil in this treatment. A first order kinetics equation was fitted to values of the C content at different dates:

$$C_{P_0E_0} = A_0 e^{-kt} \tag{1}$$

where $C_{P_0E_0}$ is the C content in P_0E_0 at date t, A_0 the initial C content and $1/k$ the MRT.

The carbon isotope ratio $^{13}C/^{12}C$ is greater in plants with a C4 photosynthetic cycle (*D. decumbens*) because C4 plants discriminate less against ^{13}C in favour of the lighter isotope ^{12}C present in atmospheric CO_2 than C3 plants (market gardening plants) do. The isotopic composition of SOM is comparable with that of the plant material from which it is derived. The $^{13}C/^{12}C$ ratio is expressed in $\delta^{13}C$‰ units (Balesdent et al., 1987). In the present study, soil C was denoted as follows:

- C_{MG} for C derived from the SOM present under market gardening culture, i.e. C derived from market gardening and sugar cane plants. The soil C under P_0E_0 is also derived from market gardening and sugar cane plants so it is the same as C_{MG} ($C_{P_0E_0}=C_{MG}$).
- $C_{D.dec}$ for C derived from *D. decumbens*.

After the determination of C_{total} (the total C content of the sample), $\delta^{13}C_{sample}$ (the $\delta^{13}C$ value of this sam-

ple), $\delta^{13}C_{MG}$ (the $\delta^{13}C$ value of the SOM in MG) and $\delta^{13}C_{D.dec}$ (the $\delta^{13}C$ average value of the different *D. decumbens* tissues), $C_{D.dec}$ and CM_G were calculated as follows:

$$C_{D.dec} = C_{total} \frac{(\delta^{13}C_{sample} - \delta^{13}C_{MG})}{\delta^{13}C_{D.dec} - \delta^{13}C_{MG}};$$
$$C_{MG} = C_{total} - C_{D.dec}$$

The C stock (Mg C ha^{-1}) of a soil layer was calculated using the following equation:

$$S = bdeC \times 10$$

where S is C stock (Mg C ha^{-1}), bd the bulk density (t m^{-3}), e the thickness of the soil layer (m) and C the soil C content (gC kg per soil). In vertisols, the bulk density varies widely depending on the level of soil moisture which governs shrinkage or swelling, on the size of the sample, and on the proportion of cracks in the sample. Bulk density is best estimated when the soil moisture approximates the soil water holding capacity, and for these vertisols, the bulk density at this moisture content is then ca. 1.0 (Mg m^{-3}) (Ndandou, 1998). This value was used for C stock calculations and consequently if the thickness of a layer is 10 cm, 1 g C kg soil^{-1}=1 Mg C ha^{-1}.

3. Results

3.1. C content and $\delta^{13}C$ of D. decumbens

C content and $\delta^{13}C$ of the different plant tissues were respectively 380 g C kg^{-1} and −11.2‰ for litter, 467 g C kg^{-1} and −11.1‰ for leaves, 433 g C kg^{-1} and −11.2‰ for roots, and, 440 g C kg^{-1} and −11.3‰ for stems and stolons. The $\delta^{13}C$ was quite homogeneous among the different plant tissues with an overall average of −11.2‰.

3.2. Soil C stocks and $\delta^{13}C$ under market gardening (MG) and P_0E_0

C stocks under MG in 1997 and P_0E_0 in 1993 were similar, but in 1997 the C stock under P_0E_0 was smaller than in 1993 in the upper 20 cm of soil (Fig. 1a). This difference is due to the loss of C_{MG} stock from the bare soil (P_0E_0) in 5 years. It was 3.3 and 5.2 Mg C ha^{-1} at 0–10 and 0–20 cm depths,
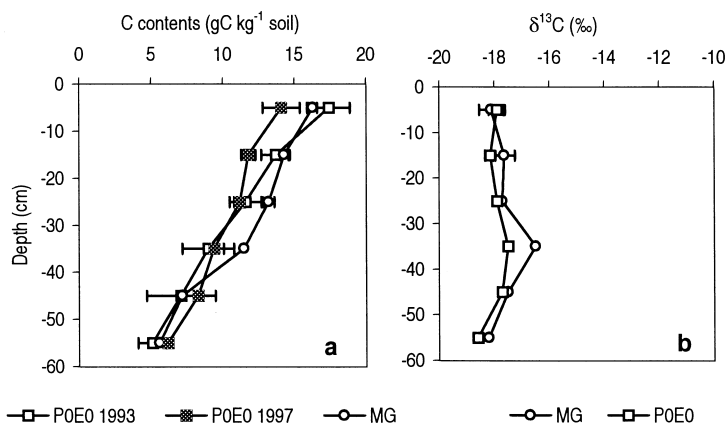
Fig. 1. C content (a) and δ^{13}C (b) profiles in a cultivated soil (MG), and a bare soil for 5 years (P$_0$E$_0$) Error bars: 95% confidence intervals.

respectively, and it represented a loss of 17 and 19% of the initial C stocks for the two layers. The mean residence time (MRT) of C$_{MG}$, calculated from Eq. (1) was 14.7 years for 0–10 cm and 21.4 years in 10–20 cm soil layers (Fig. 2).

The δ^{13}C profiles under P$_0$E$_0$ and MG were similar with a mean value of around −18‰ (Fig. 1b) and the δ^{13}C values showed little variation, ranging from −16.5 to −18.6‰, along the profile.

3.3. C stocks and δ^{13}C values of Pr, sub-plots P$_+$E$_0$, P$_+$E$_+$, and P

The C stocks in Pr and the sub-plots P$_+$E$_0$ and P$_+$E$_+$ were similar in 1993 and in 1997 (Fig. 4a and
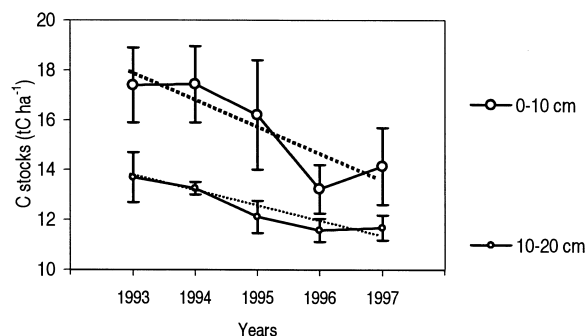

Fig. 2. C loss kinetics in the sub-plot P$_0$E$_0$ (bare soil without earthworms). C loss kinetics equation in the 0–10 cm soil layer depth: $C_t = 17.9\,e^{-007t}$, $r^2 = 0.88$; C loss kinetics equation in the 10–20 cm soil layer depth: $C_t = 13.6\,e^{-005t}$, $r^2 = 0.95$.

b). There was a similar trend in C increase from 1993 to 1997 in the sub-plots with plants, P$_+$E$_0$ and P$_+$E$_+$ and Pr.

The δ^{13}C values of P$_+$E$_0$, P$_+$E$_+$ and Pr soils were not different and they were higher than the δ^{13}C value of P$_0$E$_0$ soil. The differences in δ^{13}C values between these soils and P$_0$E$_0$ soil ranged from +2.0 to +2.8‰ and from +1.0 to +2.4‰ at 0–10 and 10–20 cm depths, respectively (Fig. 4c). In the 20–30 cm soil layer, the differences were smaller (+1–1.7 δ units) and in deeper soil layers the differences were much smaller, from 0.2 to 0.6 (Fig. 3b and Fig. 4b). Thus, in 5 years, the C inputs from *D. decumbens* led to an increase of soil C and ^{13}C stocks chiefly in topsoil (0–20 cm).

Average values of δ^{13}C in MG and P$_0$E$_0$ (−18.0‰ at 0–10 cm and −17.8‰ at 10–20 cm, Table 1) were used to calculate the percentage of the remaining C$_{MG}$. On this basis, 5 years of *D. decumbens* pasture led to a C$_{D.dec}$ storage ranging from 11.7 to 12.9 Mg C ha^{-1} in the 0–20 cm soil layer. C$_{MG}$ losses were calculated as the difference between the stock of C$_{total}$ in 1993 and the stock of C$_{MG}$ in 1997; the C$_{MG}$ loss was 2.4 in P$_+$E$_0$, 4.1 in P$_+$E$_+$ and 6.5 Mg C ha^{-1} in Pr in the 0–20 cm soil layer. These amounts were close to the value of the C$_{MG}$ loss in P$_0$E$_0$ (5.2 Mg C ha^{-1}). Since the C stocks in 1993 (Fig. 4a) and the C losses were close in all treatments, the MRT of C$_{MG}$ in P$_+$E$_0$ and P$_+$E$_+$ must be equal to the MRT of the C$_{MG}$ in P$_0$E$_0$. Since there was no statistical difference (two-tailed *t*-test) in C total and δ^{13}C between the Pr, P$_+$E$_0$ and
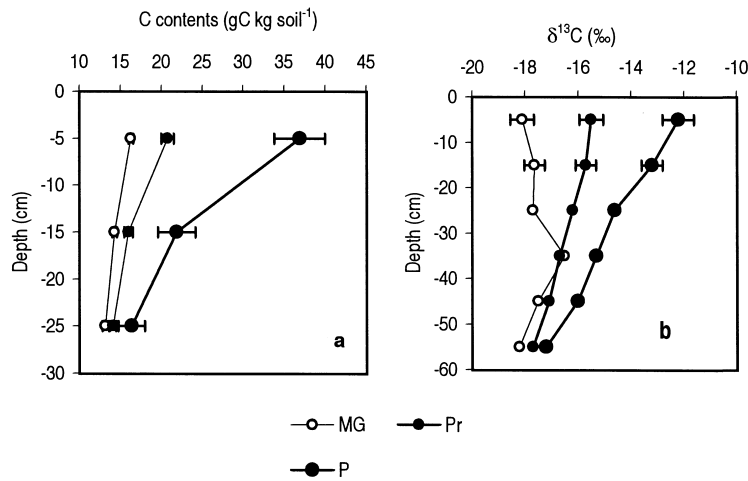
Fig. 3. C content (a) and $\delta^{13}C$ (b) profiles in a cultivated soil (MG), in a 5-year-old pasture (Pr), and in a 17-year-old-pasture (P). Error bars: 95% confidence intervals.

P_+E_+ soils, we considered the observed differences in C_{MG} and $C_{D.dec}$ amounts between these soils as non-significant and attributed them to calculation and rounding errors.

3.4. Root biomass

In plot Pr, 76% of the root biomass was located in the top 20 cm of soil (Table 2). This represented on average 12.4 t DM ha^{-1} or 5.3 Mg C ha^{-1}.

3.5. Earthworm biomass

The earthworm biomass in plots MG, P_0E_0 and P_+E_0 was nil or very small (Table 3). In P_+E_+ and Pr soils, the earthworm biomass was higher but had not yet reached the value measured by Loranger (unpublished data) in P soils. There was a decrease of about 50% in the earthworm population since the inoculation of earthworm 5 years earlier. This decrease could be explained by a low soil C content at the beginning
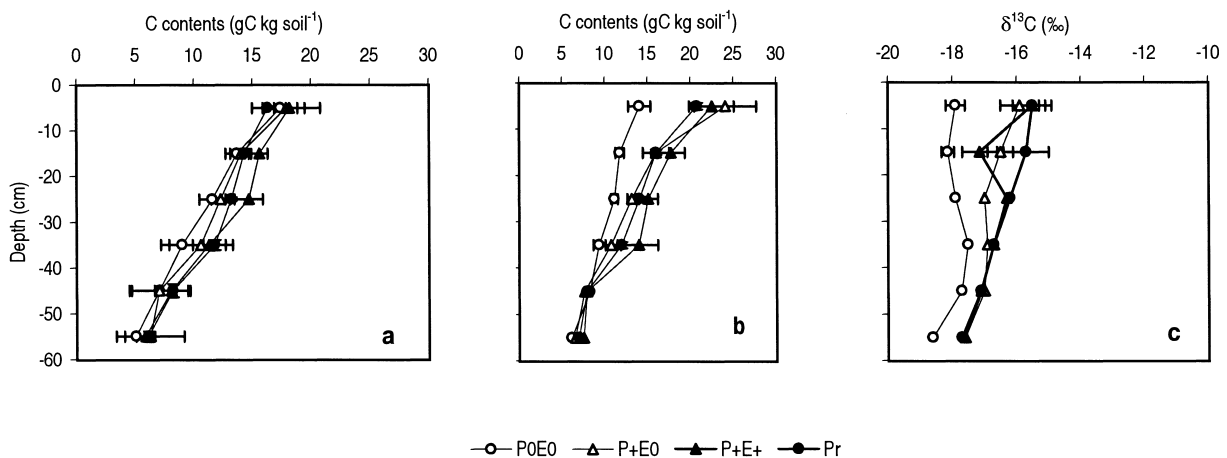

Fig. 4. Variation in C content profiles, between 1993 (a) and 1997 (b) and $\delta^{13}C$ profiles in 1997 (c) in sub-plots P_0E_0, P_+E_0, P_+E_+ and Pr.

Table 1
C stocks (means±s.d.) in 1993 and 1997[a]

Soil layers (cm)	P_0E_0					Pr				
	1993	1997				1993	1997			
	C_{total}	C_{total}	$\delta^{13}C$	$C_{D.dec}$	C_{MG}	C_{total}	C_{total}	$\delta^{13}C$	$C_{D.dec}$	C_{MG}
0–10	17.4±1.5	14.1±1.3	−17.9±0.3	–	14.1±1.3	16.3±0.3	20.8±0.8	−15.5±0.8	7.6	13.2
10–20	13.7±1.0	11.8±0.5	−18.1±0.2	–	11.8±0.5	14.3±0.3	16.0±0.5	−15.7±0.9	5.3	10.7
	P_+E_0					P_+E_+				
	1993	1997				1993	1997			
	C_{total}	C_{total}	$\delta^{13}C$	$C_{D.dec}$	C_{MG}	C_{total}	C_{total}	$\delta^{13}C$	$C_{D.dec}$	C_{MG}
0–10	17.9±2.9	24.1±3.6	−15.9±0.6	7.4	13.4	18.2±1.3	22.5±2.6	−15.5±0.5	9.6	12.9
10–20	14.0±0.9	16.0±1.5	−16.5±0.4	3.3	12.7	15.6±0.7	17.8±1.6	−17.0±0.7	2.1	15.7

[a] $\delta^{13}C$, C derived from *D. decumbens* ($C_{D.dec}$), C derived from the SOM present under market gardening (C_{MG}) in 1997.

Table 2
Root biomass in Pr (s.d.: standard deviation) and percentage of root biomass in each soil layer

Soil layers (cm)	Mean (t DM ha^{-1})	s.d. (t DM ha^{-1})	Distribution (%)
0–10	8.3	1.8	51
10–20	4.1	2.2	25
20–30	1.8	0.2	10
30–40	1.0	0.1	6
40–50	0.6	0.2	4
50–60	0.6	0.1	4

Table 3
Earthworm, *Polypheretima elongata*, biomass (g m^{-2}) in each plot (mean±standard deviation)

Plots	Dates			
	1994	1995	1996	1997
Pr	6±10.4	53.34±37.31	50.6±28.44	nd[a]
P_+E_+	35.7±38.4	27.85±18.48	32.81±23.88	42.28±21.82
P_0E_0	0.07±0.13	0.68±0.03	0.59±0.29	3.11±1.31
P_+E_0	0.05±0.08	1.22±0.96	0.34±0.45	0.07±0.07
MG	nd	nd	nd	3.64±8.91
P	nd	nd	nd	58.75±57.06

[a] Not determined.

of the experiment, i.e. a low amount of nutrients for the earthworms, inducing a high mortality of animals.

4. Discussion

Changes in C and ^{13}C contents between 1993 and 1997 occurred chiefly in the upper 20 cm reflecting lower C inputs in deeper soil layers. Litter was not incorporated into deep soil layers (>20 cm) and C inputs from roots were small because only 24% of the total root biomass was located below 20 cm depth. This was not the case in grass-legume pasture with deep-rooted grass established in South American savannahs, where C storage in soil and fine roots occurred to 100 cm depth (Fisher et al., 1994). This difference with our

study could be explained by a greater number of developing roots in soils because of older (14 years) pastures, and by the greater depth of soils. The C_{MG} losses below 20 cm were negligible. Since there was no change in SOM in deeper layers in 5 years, the C dynamics will be discussed only for the 0–10 and 10–20 cm soil layers.

4.1. C_{MG} losses in P_0E_0

Loss of C_{MG} could be caused by soil erosion and SOM mineralisation. Although bare vertisol could be very susceptible to water erosion (Albrecht et al., 1992), C_{MG} losses were similar under P_0E_0 and under Pr where soil erosion was probably limited because of protection by the plant cover. The C losses due to soil erosion were probably not significant over 5 years and the greater part of C losses in P_0E_0 was due to SOM mineralisation. Nevertheless, in P_0E_0 the C_{MG} losses could have been underestimated because of C inputs from weeds despite their control by chemicals. Inputs from weeds were estimated at 0.15 Mg C ha^{-1} per year in a bare soil in southern England by Jenkinson and Coleman (1994). These C inputs could have balanced the C losses by erosion in P_0E_0.

In P_0E_0, the C loss estimates allowed calculation of the MRT of C in soil. The calculated MRT (14.7 years) for C_{MG} in the 0–10 cm soil layer is similar to the value (15 years) found by Trouvé et al. (1991) for sandy soils (less than 7% of clay) under perennial plants in Congo and in Côte d'Ivoire (Fig. 1). Moreover, the MRT of C_{MG} in soil was found to increase with depth, and was similar to the MRT (from 17.5 to 19.2 years in the 0–5 cm layer and 31.4 years in the 5–10 cm layer) of C derived from forest after pasture on an oxisol in Amazonia (Bernoux et al., 1998).

4.2. C dynamics under pasture

4.2.1. C_{MG} losses

The similarity in C_{MG} losses between soil with living roots and soil without could be due to the different effects of roots on soil C losses: protection against erosion on the one hand and stimulation of C_{MG} mineralisation on the other (Choné et al., 1991; Ladd et al., 1994).

The CM_G stocks observed in 1997 were similar in P_+E_+ and in P_+E_0, suggesting that the effect of P. elongata on C_{MG} mineralisation was not significant. The influence of earthworms on C mineralisation cannot be conclusively quantified in the present study for two reasons: (i) the wide variations in soil C content (Chevallier et al., 2000); and (ii) the lack of precise computation of C turnover by isotopic analyses at natural abundance level (Veldkamp and Weitz, 1994). However, the role of earthworms in protecting SOM against mineralisation is still the subject of much debate. Gilot (1997) has measured smaller C mineralisation (−5%) in plots with Millsonia anomala than in plots without M. anomala after 3 years in a shrub savannah on a ferralsol in Ivory Coast. No SOM protection in the long-term was however evident in richer SOM soil (Lavelle, 1997). Zhang and Hendrix (1995) reported enhancement (+20%) of total C efflux when earthworms (Lumbricus rubellus or Aporrectodea caliginosa) were present in microcosms. Lavelle and Martin (1992) showed that the earthworm casts stimulated mineralisation in the short term but limited it in the long term. This would explain why, over the years, there is no discernible influence of earthworms on the C_{MG} losses from the overall soil profile.

4.2.2. Inputs and outputs of $C_{D.dec}$

The $C_{D.dec}$ inputs were litter and roots. The amount of inputs was difficult to estimate because leaf and root growth processes are concomitant throughout the year. Although, the effect of grazing on annual net primary productivity of pasture is still hotly debated (McNaughton et al., 1998), we did not consider sheep droppings and sheep forage intake, as the results between the enclosed plots (P_+E_0, P_+E_+) and the pasture were similar (Table 1).

4.2.3. Estimation of the C inputs from D. decumbens litter

The above ground production of a D. decumbens pasture was 25 t DM ha^{-1} per year in a long-term pasture at our study site (Mahieu, personal communication). This value is close to the 26 t DM ha^{-1} per year value reported by Vicente-Chandleur et al. (1974, in Crowder and Chheda, 1982) from a D. decumbens pasture in Puerto Rico. So, annual C inputs in our experiment were 11 Mg C ha^{-1} per year.

4.3. Estimation of C inputs from roots

Two methods of calculation were used to estimate root C input into soil:

1. The annual root turnover was multiplied by the mean root biomass in soils (Picard, 1979). The pasture being regularly irrigated and fertilised, the root biomass was probably constant all over the year and equal to $5.3 \, \text{Mg C ha}^{-1}$ (0–20 cm). The annual root turnover was considered to be between 0.4 (Robertson et al., 1994) and 4.7 (Picard, 1979) according to different authors. If we assumed an annual root turnover of 1–2, the root C inputs would be of $5–11 \, \text{Mg C ha}^{-1}$ per year.

2. The above-ground production was known and according to different authors, the ratio 'above-ground production/below-ground production' is between 0.25 (Polglase and Wang, 1992) and 2.32 (Seagle et al., 1992). If values of 1–1.5 are chosen, the C inputs from total roots ranged from 11 to $16 \, \text{Mg C ha}^{-1}$ per year. Furthermore, if root distribution is taken into account, since 76% of the total root biomass was in the 0–20 cm soil layer, the C inputs from roots would be between 8 and $12 \, \text{Mg C ha}^{-1}$ per year for the 0–20 cm layer.

The C inputs from above ground were estimated at $11 \, \text{Mg C ha}^{-1}$ per year and the root input ranged between 5 and $12 \, \text{Mg C ha}^{-1}$ per year. Therefore, the total C inputs derived from the pasture ranged between 16 and $23 \, \text{Mg C ha}^{-1}$ per year in the 0–20 cm soil layer. These values are higher than those quoted by Tiessen et al. (1998): $2–15 \, \text{Mg C ha}^{-1}$ per year for savannahs and fallow in West Africa. The difference could be explained by modes of production, extensive in West Africa and intensive in Martinique. However, plant productivity was less in the initial years of plant growth compared to plant productivity in long-term pastures. The total C input in 0–20 cm soil was then probably over-evaluated, and a value of $15 \, \text{Mg C ha}^{-1}$ per year or $75 \, \text{Mg C ha}^{-1}$ in 5 years is probably more realistic.

4.4. $C_{D.dec}$ storage

As the δ^{13}C values of SOM were similar in P_0E_0 and in MG in this study, contrary to the conclusions of Mary et al. (1992) or Agren et al. (1996), the δ^{13}C of SOM did not seem to be affected by SOM miner-

alisation. Then, the δ^{13}C increases observed between MG and Pr were solely due to C input from *D. decumbens*, which had a higher δ^{13}C (−11‰) than the δ^{13}C (−18‰) of the SOM present under market gardening. In five years under pasture, $C_{D.dec}$ storage ranged from 10.6 to $12.8 \, \text{Mg C ha}^{-1}$ in the 0–20 cm soil layer. These values were about 15% of the estimated total C inputs from *D. decumbens* ($75 \, \text{Mg C ha}^{-1}$). Thus, 85% of the C input is mineralised within 5 years, assuming that erosion under pasture is negligible. These results are similar to those presented by Dalal et al. (1995) and Saffigna et al. (1989), who, respectively, calculated a 16% storage of C input from plants in a vertisol and a 14% C input from *Sorghum* residue. A 5-year study by Ayanaba and Jenkinson (1990) found a smaller C storage of 8% of the C input from ^{14}C labelled corn leaves in a tropical sandy soil. Reduced C storage from corn leaves, as compared to the combined inputs from root, litter and droppings, could be explained by the chemical composition of leaves which contain less lignin than roots (Balesdent and Balabane, 1996). It could also be explained by the better protection that a clayey soil (vertisol) affords against SOM mineralisation compared to the protection afforded by a sandy soil (e.g. Feller and Beare, 1997). Nevertheless, C inputs from litter on the soil surface were mineralised rapidly, and a small quantity of these were incorporated into the soil. Grazing and the presence of earthworms did not measurably modify $C_{D.dec}$ storage in soil in the present study.

5. Conclusion

Conversion of an intensively cultivated vertisol to a *Digitaria decumbens* pasture resulted in the storage of $6 \, \text{Mg C ha}^{-1}$ in the upper 20 cm of soil. This net gain was the result of a loss of C_{MG} of $5 \, \text{Mg C ha}^{-1}$ and a gain of $C_{D.dec}$ of $11 \, \text{Mg C ha}^{-1}$ (Fig. 4). The mean residence time of the C_{MG} was 15 years in the 0–10 cm soil layer and 21 years at 10–20 cm. The $C_{D.dec}$ mineralisation was high, ca. 85% of total C inputs into soil. After 5 years of pasture, the C stock was still less than the C stock in a 17-year-old pasture. The quantity of C inputs and the amount of C actually incorporated into the soil have not been measured and further research is needed to clarify this point.

After 5 years, earthworm activities did not show any influence on C dynamics at the soil profile scale.

Acknowledgements

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