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The respective roles of roots and earthworms in restoring physical properties of Vertisol under a *Digitaria decumbens* pasture (Martinique, WI)

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Abstract

Sloping Vertisols having large exchangeable sodium contents are erodible. In Martinique, French West Indies, intensive market gardening during 15 years decreased their organic matter content, biological activity (roots, earthworms, mesofauna, microorganisms), soil porosity, and increased soil losses due to erosion. Conversely, old irrigated pastures (*Digitaria decumbens*, Pangola grass) on these soils maintained organic matter content, biological activity, soil porosity and aggregate stability. A research programme was set out in 1991 in the south-eastern part of Martinique in order to study the respective roles of grass roots and earthworms in the restoration of the properties of a degraded Vertisol. Plots with and without plants, with and without earthworms were tested and physical properties were followed during 4 years and compared with properties existing under market crops and old pastures. The restoration of physical properties was more rapid and more important in treatments with plants than in treatments without plants. Plants played a dominant role through rhizosphere effects and possible carbon rhizodeposition. The effect of earthworms was less important. Earthworms particularly increased the stability of aggregates of 200–500 μm size, and decreased clay dispersion.

Keywords: Polypheretima elongata; Aggregation; Erodibility; Porosity; Pastures; Vertisol

1. Introduction

Vertisols developed in the south-eastern part of Martinique usually exhibit exchangeable sodium percentage (ESP) values above 10%. They are thus physically fragile and susceptible to erosion (Albrecht et al., 1992) as observed in other areas worldwide (Dalal and Bridge, 1996; Freebairn et al., 1996). These soils were extensively used for sugar cane (*Saccharum officinarum* L.) cropping during three centuries. In the last 20 years, irrigation led to the development of both pastures and market gardening crops. These land-use changes induced strong modifications of soil biological and physical properties. Market gardening cropping decreased the biomass of plant roots, microbes and earthworms (*Polypheretima elongata*, Megascolecidae) as well as the soil mesofauna diversity and carbon content thereby decreasing structural porosity and aggregate water-stability and thus increasing soil susceptibility to erosion. Conversely, such negative impacts were not observed in Vertisols under irrigated artificial pastures (*Digitaria decum-*

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bens). Comparatively to market gardening crops, soil under pastures present high root, microbe and earthworm biomasses, a high mesofauna diversity, a high carbon content, a high structural porosity, a relatively high aggregate stability and a relatively low sensibility to erosion (Albrecht et al., 1992; Chotte et al., 1992; Rossi, 1992; Loranger et al., 1998; Blanchart et al., 2000; Cabidoche et al., 2000).

The establishment of a pasture on a Vertisol degraded by many years of intensive market cropping could be an option for the restoration of physical and biological soil properties.

Grass roots and earthworms may significantly improve soil physical properties. Roots mainly act through soil enmeshment, carbon inputs, and the stimulation of microbial biomass (Ladd et al., 1994; Angers and Caron, 1998). Tropical earthworms strongly increase aggregation and porosity without soil organic matter increase in kaolinitic soils (Martin, 1991; Blanchart et al., 1997). Recently, Chevallier et al. (2001) showed that the restoration of soil carbon stocks in a Vertisol under pasture was caused by abundance of grass roots, and that earthworms had no discernible effects on soil organic matter (SOM) dynamics.

The objective of this paper is two-fold. Firstly, it is aimed at determining the rate of restoration of soil physical properties of a Vertisol under irrigated pasture (*P. elongata*). Secondly, the experimental study is focused on assessing the respective roles of grass roots and earthworms in this restoration. The physical properties considered here are: aggregation, aggregate stability, structural porosity, and susceptibility to erosion.

2. Materials and methods

2.1. Study site

The experiment was located in the south-eastern part of Martinique, French West Indies (14°25′N/60°53′W) (humid tropical climate, mean annual rainfall of 1400 mm especially during the rainy season from June to December, mean daily temperature of 26–28 °C). The soil developed on andesite. It keys out as a smectitic Leptic Hapludert (USDA classification) or Eutric Vertisol (FAO-UNESCO classification). The soil had a clayey texture dominated by fine particles (fraction <20 μm amounting to 70–80%). Smectite was the dominant clay mineral. CEC values ranged from 35 to 40 cmol kg^{-1} and exchangeable sodium percentage (ESP) was about 10% in the upper 10 cm.

2.2. Experimental design

The experimental design consisted of three plots, which had been under continuous sugarcane production until 1970, followed by fallow (native pasture) until 1978 (Chevallier et al., 2000). At this time, the first plot, MG (0.3 ha) was used for intensive market gardening; the second plot, P (0.3 ha), was converted to pasture and planted with a tropical grass *D. decumbens* (Pangola grass); 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. Both pastures, P and Pr, were fertilised (100 kg N ha^{-1} per year), irrigated and grazed by sheep (2 sheeps ha^{-1}). In 1993, three sub-plots (5 m × 10 m each, i.e., 50 m^2) were installed in the Pr plot in order to distinguish between the effects of roots and earthworms (*P. elongata*) on the dynamics of C storage and physical properties. As replication was not feasible, special care was taken to choose subplots with comparable physico-chemical properties. Spatial variability of soil carbon and clay contents (0–30 cm) and soil depth was assessed by the use of geostatistics in Pr (200 sampling points), and the three experimental subplots were located in a relatively homogeneous zone inside Pr to allow valid comparison. In this area, initial soil C content varied from 13.5 to 15.5 gC kg^{-1} soil, initial clay content from 50 to 55% and soil depth from 0.6 to 0.8 m (ORSTOM Martinique, 1994, unpublished data). Experimental sub-plots were as given further.

- Treatment P_0E_0 (no plants, no earthworms)—plants were killed each 2 months by the application of glyphosate (360 g l^{-1}, 10 l ha^{-1}) and earthworms were killed each 2 years by the application of a pesticide (carbofuran, Trademark Furadan, 10 kg ha^{-1} a.i.). Carbofuran is an insecticide known to be particularly harmful to earthworms (Lee, 1985) and to other non-target soil organisms (Todd et al., 1992);
- Treatment P_+E_0 (with plants only)—earthworms were killed each 2 years by the application of car-

bofuran, and plants were allowed to develop and were cut regularly to simulate grazing;

- Treatment P_+E_+ (with plants and earthworms)—plants were allowed to develop and were cut regularly. Earthworms (*P. elongata*) collected from an old irrigated pasture were introduced at a density of 90 ind m^{-2} (i.e. a biomass of 90 g m^{-2}). 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. 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. Containers were evenly distributed on the plot, inverted on the ground and covered with a mulch to avoid heating. This technique avoided predation by birds and exposure to sunlight, and limited soil disturbance. After 1 week, earthworms left the containers and entered the soil.

Due to the presence of toxic pesticides in the sub-plots and to the presence of cattle in the field (Pr), these sub-plots were isolated by wire netting.

In these four plots (P_0E_0, P_+E_0, P_+E_+ and Pr), during 4 years (t0 to $t+4$) at the end of the rainy season (December) and for the upper 40 cm of soil (0–10 cm, 10–20 cm, 20–30 cm and 30–40 cm), we studied root biomass, earthworm biomass (0–30 cm), soil carbon content, soil structural porosity, aggregate stability and soil erodibility. Soil properties in these plots were then compared with soil properties in MG (market gardening plot) and P (old pasture).

2.3. Root biomass

Three soil samples (1 l volume) were taken once a year in December, at each depth (0–10 cm, 10–20 cm, 20–30 cm and 30–40 cm) and in each plot. Soil was dispersed in water and 10 min before sieving (at 200 μm) a few drops of NaOH solution (pH 10) was added. The plant and mineral particles >200 μm were separated by flotation in water. Roots (mainly live and dead roots and other organic debris) larger than 200 μm were then oven-dried and weighed. Root biomass was calculated and expressed in g kg^{-1} soil.

2.4. Earthworm biomass

Three soil samples (30 cm × 30 cm × 30 cm) were taken every year in each plot. Earthworms (*P. elongata*) were hand-sorted, kept in formalin and weighed.

2.5. Soil carbon content

Six soil samples were taken once a year in December, at each depth (0–10 cm, 10–20 cm, 20–30 cm and 30–40 cm) and in each plot. Soil was air-dried, crushed at 200 μm and soil carbon content was analysed by using a micro-analyser CNS (Carlo Erba NA 1500).

2.6. Soil structural porosity

Soil structural porosity was measured through the measurement of specific air volume. Soil clods (ca. 500 cm^3) whose wet masses were measured, were immersed in kerosene of accurately known density (Monnier et al., 1973). After one night, clods were taken out and excess of kerosene was removed using a filter paper in a standardised procedure. Volume of the samples was then calculated using Archimedes' principle (kerosene's displacement measured using a weighing balance). Clods were then oven-dried at 105 °C until constant weight and water content calculated. The structural porosity or air-filled porosity was calculated as the total pore volume minus water volume (McGarry and Malafant, 1987). Five replicates were measured for each plot and each depth, only the last year $(t+4)$.

2.7. Aggregate stability

Soil samples were collected once a year in December, at each depth (0–10 cm, 10–20 cm, 20–30 cm and 30–40 cm) and in each plot. Soil was air-dried, crushed at 2 mm and aggregates between 1 and 2 mm were subjected to water-stability test (Albrecht et al., 1992). Aggregates were immersed in water for 16 h before being shaken for different times (0, 0.1, 0.5, 1, 2, 6, 12 and 18 h). Aggregates >500 μm and 200–500 μm that withstood shaking were separated by sieving, oven-dried and weighed. The size distribution of aggregates <200 μm was obtained with a laser-granulometer (Malvern, Mastersizer/E). The cumulative curves of aggregate distribution were drawn in order to obtain the D50 (diameter corresponding to 50% of aggregates on the cumulative curves). The percentages of water-stable aggregates WSA (>500 and >200 μm) were calculated for the different shaking times and corrected by the sand amount. Clay dispersion indices (Id) (i.e., the percentage of dispersed clay) were also calculated for the different shaking times.

2.8. Soil erodibility

A rainfall simulator (Asseline and Valentin, 1978) was used to measure the sensitivity of soil surface to erosion. Three soil surfaces were successively tested: soil surface with plants, soil surface with plants removed, and gently hoed soil surface after vegetation removal. For each soil surface, three rainfall intensities were used (55, 80 and 150 mm h^{-1}). Rainfall events lasted 30 min; they were applied on a wet soil surface in order to get rapidly a maximal run-off. Turbidity of run-off water and run-off were measured to calculate soil losses (Asseline and Valentin, 1978).

2.9. Statistical analyses

Statistical analyses (ANOVA, *t*-tests, correlations) were performed using the STATVIEW software. The dataset was also subjected to a Principal Component Analysis (PCA) with the ADE-4 software (Thioulouse et al., 1997). PCA was realised for the whole dataset and for the set of the 0–10 cm depth data.

3. Results

3.1. Biological properties

Earthworm biomasses largely differed between MG (<1 g m^{-2}) and P (ca. 100 g m^{-2}). Eradication of earthworms in P_0E_0 and P_+E_0 was successful, as inferred from their very small biomass (Fig. 1). In P_+E_+ where earthworms were introduced at a density of 90 ind m^{-2} (i.e., a biomass of 90 g m^{-2}), biomass rapidly declined, then increased slowly to reach a mean value of 42 g m^{-2}. The development of earthworm population in Pr plot was discernible after 2 years of experiment (mean biomass: 53 g m^{-2}).

Grass root biomasses also differed between plots (Fig. 2). They were less than 5 g kg^{-1} soil in the upper 10 cm in MG and P_0E_0 and around 20 g kg^{-1} soil in P_+E_0, P_+E_+, Pr, i.e., where *D. decumbens* was not killed. This latter was almost equal to the ones measured in the long-term pasture P.

Mean soil C content (gC kg^{-1}; 0–10 cm) was ca. 16 in MG and 36 in P. After 4 years ($t + 4$), soil carbon contents (gC kg^{-1}; 0–10 cm) differed between sub-plots: 14.1 in P_0E_0, 23.5 in P_+E_0, 22.8 in P_+E_+ and 24.8 in Pr (Fig. 3). The differences between the last three plots were not significant ($P < 0.05$).

3.2. Aggregate stability

The percentage of water-stable aggregates WSA >500 μm (in the absence of mechanical shaking) in

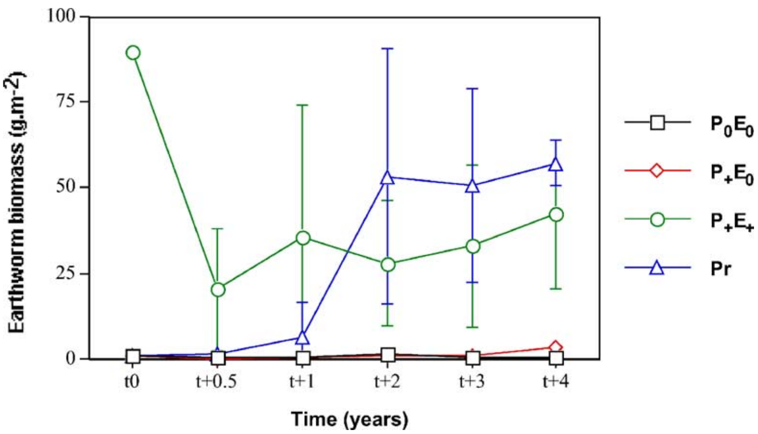


Fig. 1. Evolution with time of earthworm biomass (g m^{-2}) in the different plots (mean and standard error, $n = 3$).

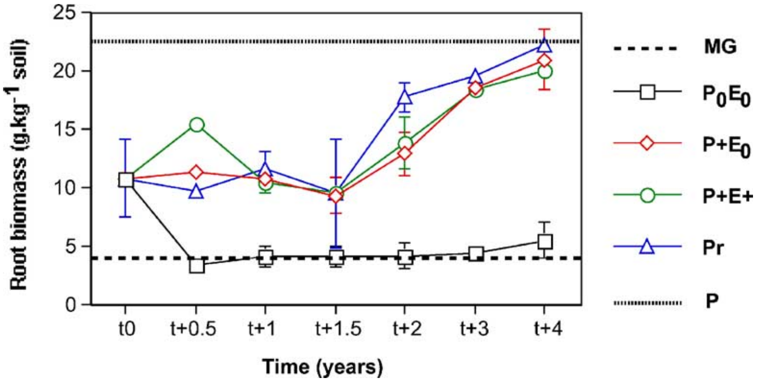


Fig. 2. Evolution with time of root biomass ($g\,kg^{-1}$ soil) in different plots (0–10 cm) (mean and standard error, $n = 3$). Comparison with mean values measured under old pasture (P) and market crops (MG).

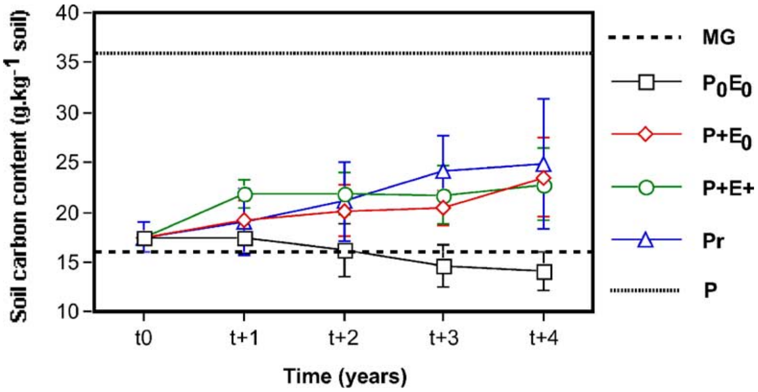


Fig. 3. Evolution with time of soil carbon content ($gC\,kg^{-1}$ soil) in different plots (0–10 cm) (mean and standard error, $n = 3$). Comparison with mean values measured under old pasture (P) and market crops (MG).

the different plots (0–10 cm) varied from 31.5% in MG to 77.2% in P. After 4 years, WSA (%) was 56.1 in P_0E_0, 70.0 in P_+E_0, 70.6 in P_+E_+ and 71.5 in Pr (Fig. 4). WSA did not significantly differed between P_+E_0, P_+E_+ and Pr, but was significantly larger than in P_0E_0. Dispersion indices Id (in absence of mechanical shaking) (0–10 cm) did not vary during the first two years (Fig. 5). After 4 years Id in P_+E_+ and Pr were close to the values measured in P. The largest Id values were measured in P_0E_0 and P_+E_0. However, they were not significantly larger than the ones observed in P_+E_+ and Pr. Values of D50 (in absence of mechanical shaking, 0–10 cm) regularly increased (except for P_0E_0) from an initial mean value of 290 μm. At the end of the experiment, D50 was significantly larger in P_+E_0 (743 μm), P_+E_+ (737 μm) and Pr (773 μm) than in P_0E_0 (600 μm), and almost equal to the one measured in P (815 μm).

3.3. Soil erodibility

Soil losses as measured under rainfall simulation, largely differed between plots (Fig. 6). Under a 30 min rainfall with an intensity of 150 $mm\,h^{-1}$ and for a gently hoed surface, soil loss was as high as 1452 $g\,m^{-2}$ in MG, and 1323 $g\,m^{-2}$ in P_0E_0 after 3 years. The lowest soil loss was observed in P (534 $g\,m^{-2}$). In P_+E_0, P_+E_+ and Pr soil loss after 3 years was 900, 839 and 742 $g\,m^{-2}$, respectively.

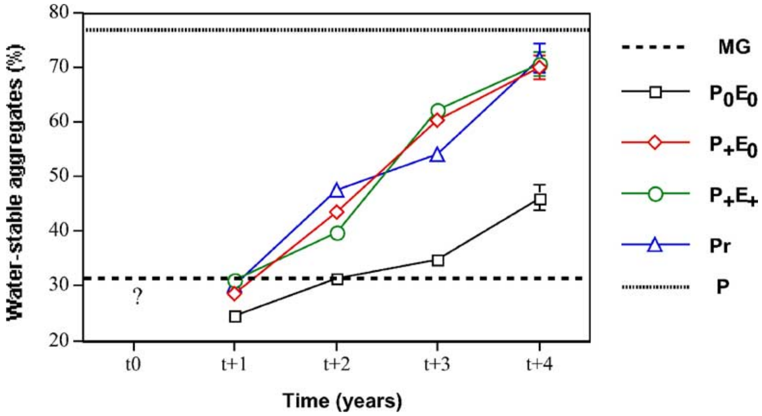


Fig. 4. Evolution with time of water-stable aggregates >500 μm (%) in different plots (0–10 cm) (mean and standard error, $n = 3$ at time $t + 4$). Comparison with mean values measured under old pasture (P) and market crops (MG).

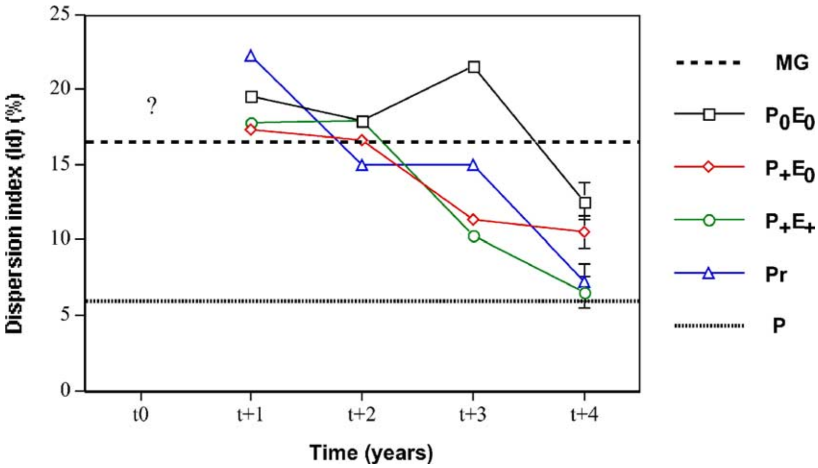


Fig. 5. Evolution with time of dispersion indices Id (%) in different plots (0–10 cm) (mean and standard error, $n = 3$ at time $t + 4$). Comparison with mean values measured under old pasture (P) and market crops (MG).

3.4. Structural porosity

The installation of a pasture after many years of market gardening induced an increase in the structural porosity. In the upper 10 cm of soil, the air specific volume was 0.051 $cm^3\,g^{-1}$ in MG, but 0.105 $cm^3\,g^{-1}$ in P (Fig. 7). Four years after the installation of the sub-plots, the air specific volume significantly ($P < 0.05$) decreased in P_0E_0 (0.032 $cm^3\,g^{-1}$), but increased in other sub-plots: 0.064 $cm^3\,g^{-1}$ in P_+E_0 and in P_+E_+, and 0.061 $cm^3\,g^{-1}$ in Pr. These differences between plots decreased with depth and between 30 and 40 cm the mean value measured in MG (0.011 $cm^3\,g^{-1}$) was significantly lower than the values measured in other plots.

3.5. Correlation between factors

ANOVA and statistical analyses showed that physical soil properties (water-aggregate stability, erodibility) and soil organic carbon content were firstly affected by depth effect, and then by treatment and time effects. PCA performed on the 0–10 cm dataset (excluding depth effect) separated on the first axis

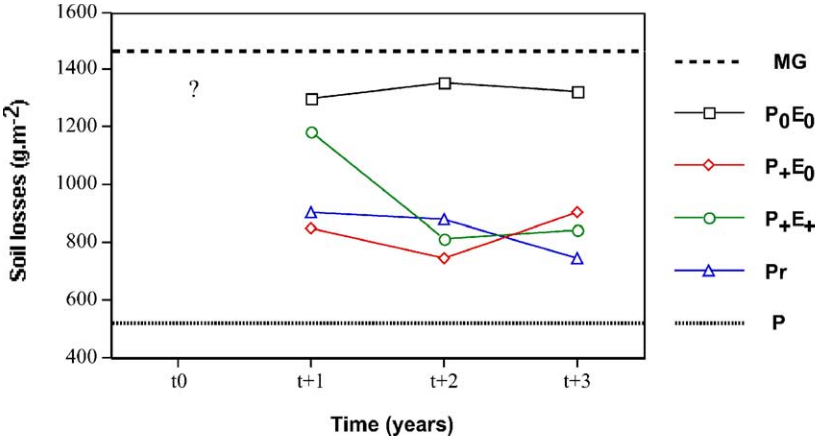


Fig. 6. Evolution with time of soil losses ($g\,m^{-2}$) (rainfall intensity $150\,mm\,h^{-1}$, duration 30 min, gently hoed soil surface) in different plots (0–10 cm). Comparison with mean values measured under old pasture (P) and market crops (MG).

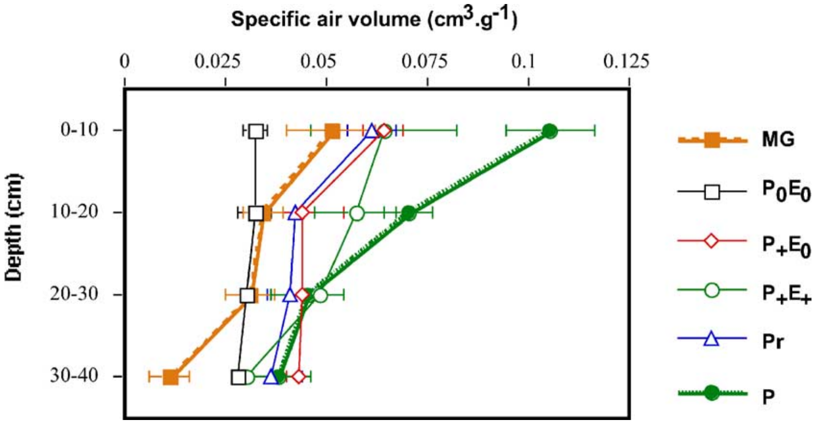


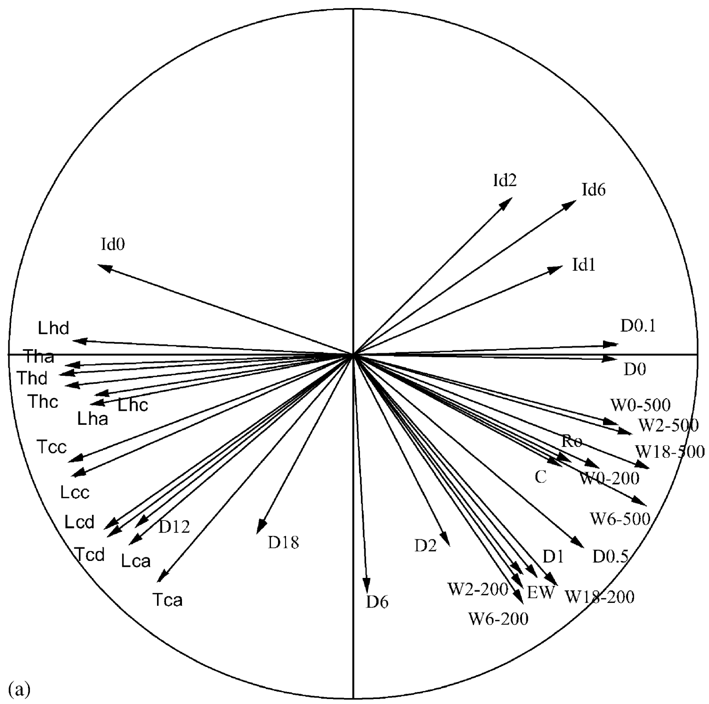
Fig. 7. Profiles of soil structural porosity (specific air volume) in different treatments at the end of the experiment (mean and standard error, $n = 5$).

(48% of total variance): (i) the plots at t0 and $t + 1$ characterized by large values of: Id (without mechanical shaking), turbidity and soil loss, D50 (after 12 and 18 h shaking), and (ii) plots (except P_0E_0) at $t + 3$ and $t + 4$ characterized by large values of: Id (after 1, 2 or 6 h shaking), D50 (from 0 to 2 h shaking) and WSA (all shaking times) (Fig. 8a and b). These latter plots were also characterized by large root and earthworm biomass, as well as high organic carbon content. The second axis (17% of variance) discriminated: (i) plots without earthworms (P_0E_0 and P_+E_0) characterized by large Id, and (ii) plots with high earthworm biomass (P_+E_+ and Pr at $t + 3$ and $t + 4$) characterized by large D50 (more than 30 min shaking), turbidity and soil loss (for a soil surface with vegetation removed and for 55 and 80 $mm\,h^{-1}$ rainfall intensity), as well as large percentages of water-stable >200 μm aggregates (Fig. 8a and b).

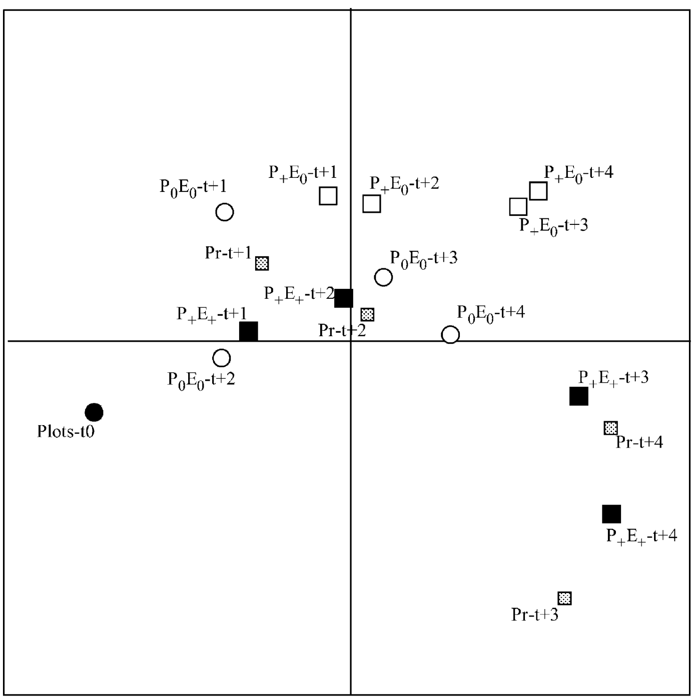
4. Discussion

4.1. *Efficiency of root and earthworm manipulations*

The effect of soil biota on soil properties has often been studied in experiments based on inoculation


Id2
Id6
Id0
Id1
Lhd
D0.1
Tha
Thd
D0
Thc
Lhc
Lha
W0-500
W2-500
Ro
W18-500
Tcc
C
W0-200
Lcc
W6-500
Lcd
D12
D18
D2
D1
D0.5
Tcd
Lca
W2-200
EW
W18-200
Tca
D6
W6-200

(a)


P+E0-t+1
P+E0-t+2
P+E0-t+4
P0E0-t+1
P+E0-t+3
Pr-t+1
P0E0-t+3
P+E+-t+2
P+E+-t+1
P0E0-t+4
Pr-t+2
P0E0-t+2
P+E+-t+3
Plots-t0
Pr-t+4
P+E+-t+4
Pr-t+3

(b)

or exclusion of soil biota, either in the laboratory (microcosms, artificial cores) or in the field (Jastrow and Miller, 1991; Lavelle et al., 1999). This is especially true for earthworms (e.g., Blanchart, 1992; Alegre et al., 1995; Blair et al., 1997; Blanchart et al., 1997; Derouard et al., 1997; Villenave et al., 1999), which have been introduced at large scale in order to improve soil structure and fertility. In the present field experiment, manipulation of roots (of *D. decumbens*) and earthworms (*P. elongata*) was successful. Treatment without plants/roots (P_0E_0) had only a limited root biomass, which was maintained at low level during the experiment. As expected, root biomass increased in treatments with plants, and reached values as large as 20 g kg^{-1} soil in the top 10 cm, and 35 g kg^{-1} soil in the upper 40 cm). Earthworm killing was successful: biomass in treatments without earthworms (P_0E_0, P_+E_0) was maintained at very low level. It is very likely that other non-target soil organisms were also affected by pesticide application. The natural colonization of earthworms in Pr was low in the first two years of experiment, and then rapidly increased. Earthworm introduction in P_+E_+ was not as successful as expected. Earthworm biomass rapidly decreased in the first months of experiment. This decrease might be due to a lack of food, as organic matter content was low at the beginning of the experiment. Nevertheless, the mean worm biomass in P_+E_+ was higher than in treatments without earthworms, and in Pr during the first 2 years of experiment.

4.2. Restoration of physical properties in recent pasture Pr

Establishing a pasture on a Vertisol degraded under intensive market crops readily increased soil porosity, water-stable aggregation, and decreased soil erodibility. This land use change increased the biomass of plant roots and earthworms, and soil organic matter content. In the recent pasture Pr, earthworm biomass significantly increased in 2 years after the beginning of the experiment, but was still half of that measured under an old pasture after 4 years. Grass root biomass regularly increased; after 4 years, it was close to that of an old pasture. The restoration of soil C content was described in details by Chevallier et al. (2001): the installation of a pasture Pr resulted in the storage of 6 MgC ha^{-1} (in 5 years) in the upper 20 cm of soil. Water-stability of aggregates, as measured by WSA and D50, did not increase during the first year, but regularly increased afterwards. The decrease of Id readily occurred only after 4 years. These resulted in a rapid decrease of turbidity of run-off water, and soil loss. As assessed by the various parameters tested here, the rate of restoration differed between the biological and physical properties. The decrease of soil erodibility was faster than the restoration of biological properties, porosity and water-stability of aggregates. After 4 years, root biomass, water-stability of aggregates and dispersion index (ID) reached values similar to those measured under old pasture, whereas C content, earthworm biomass, soil loss and porosity did not reach the levels observed under pastures. Soil erodibility thus rapidly decreased after pasture installation; likely because of intense soil cover, root development and absence of soil tillage. Moreover, the increase of aggregate stability was faster than the one of soil C content, as previously reported (Angers, 1992; Jastrow, 1996). This suggests that a part of the pool of organic matter may rapidly participate in both micro- and macroaggregation in clayey soils rich in smectite (Six et al., 2000). The most often cited organic matter which influence aggregate stability are water-extractable carbohydrate, and POM (Particulate Organic Matter which are debris >50 μm) (Jastrow, 1987; Besnard et al., 1996).

4.3. Effects of grass roots

The presence of grasses/roots was the predominant factor associated with the restoration of soil physical

Fig. 8. PCA performed on the 0–10 cm dataset. (a) Correlation circle of variables, on axis 1 and 2. C, carbon content; Ro, root biomass; EW, earthworm biomass; T, turbidity of run-of water (second letter indicates soil surface); c, surface with cut vegetation; h, gently hoed surface; third letter indicates rainfall intensity: $a = 55\,\mathrm{mm\,h^{-1}}$, $d = 80\,\mathrm{mm\,h^{-1}}$, $c = 150\,\mathrm{mm\,h^{-1}}$); L, soil losses (same letters than for turbidity); Id, dispersion index (following number indicates shaking duration in h); D, D50 (following number indicates shaking duration in h); W, water-stable of aggregates (the first number indicates shaking duration in h, the second number indicates the size of stable aggregates: 200 or 500 μm). (b) Projection of treatments at each time (years after beginning of experiment t0) on axes 1 and 2.

properties. Actually at the end of experiment, water-stable aggregation (WSA, D50) and soil porosity did not significantly differed between P_+E_+ or Pr and P_+E_0. Yet, these parameters were significantly different from those measured in the treatment without plants/roots (P_0E_0). The restoration of physical properties under pasture, in the Vertisol studied here, was strongly related with grasses/roots development. Indeed, root biomass and physical properties, on the one hand, were correlated with, on the other hand ($P < 0.05$): soil loss (negative relationship), D50 and WSA >500 μm (without shaking) (positive relationship). This confirms the role of grass roots in the modification of soil structure at both micro- and macroscale (Van Noordwijk et al., 1993; Dorioz et al., 1993; Angers and Caron, 1998). Roots, and associated fungal hyphae, affect soil structure through carbon input, stimulation of microbial (bacteria, fungi) activity, soil particle enmeshment (“sticky string bag”), and stabilization of large aggregates (Oades, 1993; Kandeler and Murer, 1993; Amézqueta, 1999). In the Vertisol studied here, Chevallier et al. (2001) have demonstrated that grass roots were responsible for the increase of soil C stock. Thus the restoration of soil C content under a new pasture was directly linked to root development. In other words, recent-sequestrated C had a pasture grass origin. The positive effect of labile organic matter on structure development in Vertisol was shown recently (McGarry, 1996). Here, C content was closely related to soil aggregation and soil erodibility (Albrecht et al., 1992; Feller et al., 1996); water-stable aggregates 5–20 μm were associated with organic debris or colonies of bacteria producing extracellular polysaccharides (Achouak et al., 1999; Blanchart et al., 2000). Thus soil structure at a microscale was affected by land use. Yet, plant roots may affect macroaggregation as well through organic debris and colloids while microaggregation was mainly influenced by extracellular polysaccharides produced by soil bacteria (Albrecht et al., 1998). According to Six et al. (2000), clayey soils rich in swelling clays under native vegetation exhibit two hierarchic levels of aggregation: C-depleted microaggregates are bound together by organic binding agents within C-rich macroaggregates. No aggregate hierarchy was, however, observed in Vertisols of Martinique (Feller et al., 1996).

4.4. Effects of earthworms

The effect of earthworms on the restoration of physical properties in the Vertisol of Martinique was not as clear as that of roots. The unique significant difference between treatments with earthworms (P_+E_+, Pr) and without them (P_+E_0, P_0E_0) concerns the dispersion index (for shaking duration up to 6 h) (Figs. 5 and 8a,b). The presence of *P.elongata* in soil reduced clay dispersion while its absence increased Id, as previously reported (Shipitalo and Protz, 1988; Hindell et al., 1994). Besides, earthworm biomass was correlated more strongly with WSA >200 μm than with WSA >500 μm. This suggests that earthworms might partly control the stability of aggregates 200–500 μm, while roots might controls the stability of aggregates larger than 500 μm. Following the assumption that WSA reflects macro-aggregate stability whereas dispersion clay reflects micro-aggregate stability (Amézqueta, 1999), the results presented here suggest that *P. elongata* may affect both micro- and macroaggregation in the Vertisol studied here. The size of stable macro-aggregates (200–500 μm) affected by earthworms was smaller than the size of globular casts created by *P. elongata* (>5 mm). It was thus difficult to explain the mechanisms by which *P. elongata* may stabilize 200–500 μm aggregates. Though able to use a wide variety of organic substrates (Lattaud et al., 1997), this species seemed here to feed preferentially on large organic debris. Casts were enriched with organic fragments of mean diameter above 50 μm in a soil under market gardening crop, while they were not enriched in such fragments in a soil under pasture (Duboisset, 1995, unpub. data). It is thus possible that these organic fragments are partly responsible for the binding of clay particles in casts, and thus for the stability of sub-aggregates composing casts. The observed but not important effect of earthworm on aggregate stability and clay dispersion could thus be explained by the specific properties of earthworm casts (polysaccharide content, cations, porosity, microbial activity. . .) and by a modification of C dynamics or localization in soil. Actually it is known that casts of geophagous species are less stable when wet, but more stable when dried, than other soil aggregates (Marinissen et al., 1996; Blanchart et al., 1999). In the case of *P. elongata*, dried casts were less stable (regarding D50) than non-ingested aggregates (Blanchart et al., 1999). The specific effect of earthworms on C dynamics or localization in the Vertisol studied here was not discernible too (Chevallier et al., 2001). *P*. *elongata* affected neither the C stock restoration nor the turnover of SOM at a profile level.

The consequence of an increased earthworm biomass was positively correlated with turbidity of run-off water and soil loss for soil surface with vegetation removed (for rainfall intensities of 55 and 80 mm h^{-1}). This may indicate a participation of earthworm casts in the reduction of soil loss.

The results presented here strongly differ from the ones obtained in kaolinitic soils, where geophagous earthworms were shown to play a major role in both the formation and stabilization of macroaggregates (Blanchart et al., 1999).

The amount of burrows (from 1 to 3 mm diameter) created by *P*. *elongata* was not measured here. Yet, these burrows may affect the movement of water into the subsoil (Robertson et al., 1994; Friend and Chan, 1995) even if *P*. *elongata* burrows are often filled in with casts and are not as continuous as burrows of *Heterporodrilus mediterreus* in Vertisols of Australia (Friend and Chan, 1995). Here, most of structural porosity was built up by tubular pores with a diameter of 10–30 μm which may have been created by Actinomycetes and it was shown that *P*. *elongata* had a negative effect on the formation of these pores (Cabidoche et al., 2000). Here, the presence of *P*. *elongata* thus resulted in an increase of macroporosity and a decrease of fine structural porosity.

5. Conclusion

In clayey smectitic soils, aggregate formation is known to be dominated by clay–solution interaction whereas biotic processes and factors are often poorly considered either in structural formation or in aggregate stabilization (Dalal and Bridge, 1996; McGarry, 1996; Oades, 1993). The results presented in this paper show that these processes and factors are of great importance in controlling physical properties, especially macroaggregation (>200 μm), in a Vertisol having high ESP (exchangeable sodium percentage).

It thus seems possible to restore physical properties of Vertisols, which have been degraded after many years of intensive farming, through the installation of intensive pastures. Such restoration leads to reduce soil loss by erosion. In that way, it may contribute to support a sustainable use of these soils, if pasture could be planned within a cropping system. The installation of pastures indeed favoured the restoration of some important physical properties through the development of grass root in soil, C storage and secondly through earthworm activity.

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