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Earthworm and enchytraeid activity under different arable farming systems, as exemplified by biogenic structures

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Key words: *Aporrectodea rosea*, conventional system, enchytraeid activity, integrated farming system, soil biogenic structures, tillage

Abstract

A study was conducted in order to compare soil faunal activity in four experimental farming systems using different tillage, chemical input and crop rotation practices: A conventional system with deep-ploughing (CT), an integrated system with reduced tillage and minimum chemical input (IN), a system with reduced tillage and high chemical input (RT) and a system with minimum tillage and high chemical input (MT). In nine experimental fields with two sampling points each, earthworms were sampled and biogenic structures were identified and counted in topsoil profiles (0–14 cm depth). Components of these profiles were identified by morphological features. Quantitative analyses of these morphological features provided information about soil compaction, earthworm and enchytraeid activity and distribution of roots and crop residues in the soil matrix. The dominant species in the earthworm community was the endogeic *Aporrectodea rosea*. Earthworm densities were unexpectedly lowest under reduced tillage (6 specimens per m²), and highest under deep-ploughing (67 specimen per m²), the reverse effect being observed with enchytraeid worms, as ascertained by deposition of their faecal pellets in topsoil profiles. Strong very fine granular structure (STVFGFR) was most frequent in the integrated farming system (IN). We concluded that in the studied site embracing four farming systems,

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enchytraeids play an important role in creating a stable soil structure and porosity at the low level of earthworm densities found in the integrated system (IN).

Abbreviations: MA – structureless massive material; WMFIGR – weak to moderate fine granular structure; STVFGR – strong very fine granular structure (according to FAO, 1977)

Introduction

With the intensification of agriculture over the last four decades, deterioration of soil structure and increases in soil pollution have emerged as major issues. Therefore, new farming management methods have been developed in order to replace conventional management which relies on heavy machinery and high rates of fertilizer and biocide application. Among those new systems, integrated arable farming system is characterised by reduced tillage and low fertilizer and biocide application rate (Vereijken and Viaux, 1990) compared with conventional agriculture.

Many studies have shown that conventional farming practices influence in a negative way the activity and biodiversity of soil fauna, especially earthworms and enchytraeids (Zwart and Brussaard, 1991). Earthworms perform important functions in nutrient cycling and soil structure maintenance in agroecosystems (Lachnicht et al., 1997; Marinissen, 1992; Subler et al., 1997) and studies so far have shown that they are affected negatively by tillage (Clapperton et al., 1997; Edwards and Lofty, 1982; Jordan et al., 1997). Tillage is also detrimental to enchytraeid populations (Parmelee et al., 1990) and the associated negative impacts upon soil structure were stressed by Didden (1990).

Our main objective was to examine the influence of different tillage and chemical input intensities upon soil biological activity by characterising faunal activity in the topsoil (0–14 cm depth). The method used consisted of identifying and counting components in soil horizons fixed into ethyl alcohol. This optical method has only been used in forest humus profile studies (Bernier, 1996) and was applied for the first time to arable soils in this study. Enchytraeid activity was determined by the presence of their excrements (faecal pellets) and data concerning earthworm casts were compared with estimates of earthworm populations. The study was conducted in four farming systems. These are outlined in the study methods.

Materials and methods

This study was conducted in the ITCF (Institut Technique des Céréales et Fourrages) experimental farmland site in Boigneville (France), 70 km south of Paris. The soil is a silt clay loam with 20–25% clay content, overlying limestone at a depth between 0.3 m and 1.20 m. According to the USDA Soil Taxonomy, soils are Ochrepts. Four different farming systems have been conducted since 1991 (Table 1), (i) a system with a high chemical input and a minimum tillage consisting of a single superficial tillage to 10 cm depth prior sowing (MT), (ii) a system with a high chemical input and a reduced tillage consisting of two superficial tillage operations to 10 cm depth for weeding and prior sowing (RT), (iii) an integrated system with a minimum chemical input and a reduced tillage mostly consisting of repeated superficial cultivation to 10 cm depth for weeding (IN) and (iv) a system with a moderate chemical input and a conventional tillage (deep ploughing to 20 cm depth) (CT). In the IN farming system, herbicides and pesticides have been applied after appearance of weeds or pests, but this application was done systematically in the RT and MT systems. In both RT and MT systems, rates of pesticide application are the same but chemical compounds are different (i.e. the organo-chlorine insecticide endosulfan is only applied in the MT system). More information on chemicals used and rates of application can be obtained upon request from the author. Different crop rotations were practised in the four farming systems and the MT farming system was also applied to a wheat monoculture (MT*).

Nine contiguous experimental fields were chosen for the present study: Two different crop varieties (spring pea or winter wheat) within each of the four CT, IN, RT and MT systems and the wheat monoculture MT*. Each experimental field was sampled in March 1998, during a period of high earthworm activity, at two sampling points corresponding to the highest (D) and the lowest (S) depth of limestone observed within each field. Wheat and pea plants were at their greatest growth period. At each sampling point, earthworms were extracted in four 0.25 m² samples surrounding the location chosen for soil profile extraction. We used repeated formalin application followed by hand-sorting the top 30 cm, according to the procedure of Bouché and Gardner (1984). Earthworms were preserved in formaldehyde and identified according to Bouché (1972) and Sims and Gerard (1985). A soil profile consisted in a block 7 × 7 cm in section and 14 cm in depth, which was cut off with a sharp knife. Each profile was divided in visually homogeneous layers 1–4 cm thick which were immediately fixed in 90% ethanol. The eighteen soil profiles were analysed by a micromorphological method devised for humus profiles by Bernier and Ponge (1994). The soil layers were separately spread in Petri dishes filled with 90% ethanol then observed under a dissecting microscope at × 40 magnification. The components of the soil matrix were identified and quantified by a point-count method (Bal, 1970; Jongerius, 1963) using a transparent

film spotted with a 250-point grid, which was laid on the soil layer in alcohol. The percentage in volume of a given component of the soil matrix was calculated by dividing the number of points above it by the total number of points above solid matter. Among 20 categories identified, eight most abundant categories were taken in account for statistical treatment.

The influence of farming systems (MT, RT, IN and CT), crop treatments and limestone depth on earthworm densities (total population and dominant species) was tested by three-way analysis of variance (Sokal and Rohlf, 1995). Differences among the four replicate samples taken at each sampling point were not statistically significant, thus they were added in order to express earthworm densities as numbers of individuals per m² at each sampling point. Numbers of individuals per m² were transformed into $\log(x+1)$ to normalise the data. The two points sampled in each agricultural field were considered as replicates, due to the absence of any significant effect of within-field limestone depth. Between fields, the influence of limestone depth on earthworm densities was tested by a regression analysis. The influence of farming systems (MT, RT, IN and CT) and crop treatments on earthworm densities were analysed by two-way analysis of variance. When interaction between farming systems and crops was significant, data from wheat and pea fields were analysed separately. Homoscedasticity of variance and normal distribution of residuals were previously tested in order to verify whether data fitted with conditions of application of this statistical method. Earthworm biomass was not taken in account because the most abundant species was a small endogeic one, thus the occasional occurrence of a large (anecic) earthworm specimen in a sample could disturb the homogeneity of variance, thereby impeding any statistical treatment. The influence of farming systems, crop of the year and their interaction on the distribution of eight most abundant components of the soil matrix was tested by the analysis of variance as for earthworm densities. A Newman-Keuls test (NKS test) helped to determine homogeneous groups of means. Statistical results were considered significant when $P(F > F_{obs.})$ was less than 0.05. The composition of topsoil layers was analysed by correspondence analysis (Greenacre, 1984) using components of the soil matrix as active variables and farming systems, crops, depth of limestone at sampling points and depth of layers as passive variables.

Results

Earthworm populations

The dominant species in all experimental fields was the endogeic *Aporrectodea rosea* (Savigny, 1826). Another

endogeic species, *Allolobophora chlorotica* (Savigny, 1826) and two deep-burrowing (anecic) species *Lumbricus terrestris* (Linné, 1758) and *Aporrectodea longa* (Ude, 1885) were also present, although at very low densities. Three young individuals (among a total of 497 specimens) could not be identified and thus were not included in data analysis. No surface-dwelling (epigeic) earthworms were found.

Earthworm densities were significantly higher under wheat (40 specimens per m²) than under pea (26 specimens per m²) but because of a significant interaction between farming systems and crops, data from wheat and pea were analysed separately by analysis of variance. The farming system (CT, RT, IN, MT and MT*) influenced significantly ($p < 0.001$) total earthworm and *A. rosea* densities (Table 2). Highest earthworm densities were found in the deep-ploughed system (CT) with 67 specimens per m² as compared with superficially cultivated farming systems (IN, RT and MT) and lowest densities were found in the integrated system (IN) with 5 specimens per m². The small variation in limestone depth within fields had no significant effect on earthworm densities, but regression analysis on the whole sample of fields showed that earthworm densities were positively correlated ($F = 5.86$; $p = 0.028$) with limestone depth. Likewise, we must note that lowest earthworm densities were found at shallowest limestone depth (IN pea field, IN wheat field and RT pea field had only 10, 1 and 7 specimens per m², respectively) (Table 2). With regard to these results, we cannot separate the influence of limestone depth from that of farming practices in the IN system. Comparisons between fields on the deepest soils showed that the MT system had definitely lower earthworm densities than the CT system.

Distribution of main components of the topsoil matrix according to depth

Table 3 lists the 20 components identified in all soil layers. Typical features of soil structure, enchytraeid faecal pellets and earthworm casts are shown in Figure 1. Soil structures were classified according to Soil Survey Staff (1951). Endogeic and anecic earthworm casts were differentiated based on size, less than 1 mm for endogeic earthworm casts, and far more than 1 mm for anecic ones. When the size was intermediary, casts were attributed to an unidentified earthworm category.

Results of correspondence analysis are shown in Figure 2. The first axis explained 31% of the total variance and represented the depth factor. The second axis did not represent any interpretable factor, thus it was not taken into account for the projection of samples and categories. Categories of soil structure were scaled according to depth. Strong very fine granular structure (STVFGFR) was relatively more abundant near the sur-

face, while structureless massive material (MA) was more abundant at 8 cm depth, weak to moderate fine granular structure (WMFIGR) being in an intermediary position. Depth indices (additional variables) were not scaled regularly, indicating that vertical changes in the composition of the soil matrix were more rapid in the top 5 cm.

Enchytraeid faecal pellets were mostly found between 3 and 4 cm depth, at the same depth level as roots (living and dead). Endogeic earthworm casts were in a shallow position (2–3 cm in depth), at the same depth level as partially decomposed plant residues. Anecic earthworm casts were located deeper (4–5 cm), close to living roots. Unidentified earthworm casts were deepest in the soil profile, most of them being found at 12 cm below the soil surface.

Influence of farming systems and crops on the distribution of main components of the topsoil profile

The eight most abundant components present in the soil matrix were structureless massive material (MA), weak to moderate fine granular structure (WMFIGR), strong very fine granular structure (STVFGR), enchytraeid faecal pellets, earthworm casts, living roots and highly or partially decomposed plant (crop) residues. MA was the most abundant component in all profiles, clearly increasing with depth in IN, RT and MT (Figure 3). Beneath 10 cm, differences between fields were insignificant. Conversely, in the top 10 cm, main effects of farming systems on the distribution of MA, as well as the interaction between farming systems and crops of the year, were significant, the lowest amount of this component being in IN and the highest in CT and RT. The analysis of the interaction showed that the farming system effect was stronger than that of crop in IN, RT and MT, the reverse being observed in CT.

WMFIGR, the second most abundant component, was more evenly distributed over depth in the profile (Figure 4). The amount of this structural component was significantly lower in RT than in the other three systems CT, MT and IN. STVFGR was very irregularly distributed throughout and between the profiles (Figure 5). This component was most abundant in the top 4 cm and its amount in the top 2 cm was the most in IN and the least in CT. Enchytraeid faecal pellets made up only a little percentage of soil peds and were significantly more abundant in IN than in the other three farming systems (Figure 6). Data on earthworm casts did not show any significant difference between fields, the within-field heterogeneity being too high (mean percent volume was 0.71 ± 0.12 S.E.).

Living roots were most abundant in the top 4 cm (Figure 7). Beneath 10 cm, they were significantly more abundant under wheat, especially under continuous wheat, than under pea. Although to a lesser extent, the farming system also affected root abundance beneath 10 cm, IN showing the lowest root abundance under the two crops.

The amount of both highly and partially decomposed plant residues decreased with depth in IN, RT and MT systems, contrary to CT where the lowest amount was observed near the surface (Figures 8 and 9), probably due to depth of tillage.

Discussion

Distribution of earthworm populations

The earthworm densities found in our study site were low (less than 75 specimen per m²), although similar low densities have been found in arable soils by Edwards and Lofty (1982) (20 specimens per m² under ploughing in Spring). Our micromorphological study of topsoil profiles supports our sampling results showing low earthworm densities.

Numerous studies showed that conventional tillage strongly affected earthworm populations, when compared with superficial cultivation (Edwards and Lofty, 1982; Marinissen, 1992). On the contrary, we found in our study sites that densities of the endogeic *A. rosea*, the dominant species, were higher under deep-ploughing (CT) than under superficial cultivation (I, RT and MT). Wyss and Glasstetter (1992), who found lower densities of endogeic species under reduced tillage than under deep-ploughing, contrary to anecic species, considered the small body-size of endogeic species as an advantage for their survival in deep-ploughed agricultural soils. Abundance of *A. rosea* in the first top 20 cm was observed whatever the depth of tillage by Wyss and Glasstetter (1992). We can suppose that the burying of crop residues by deep-ploughing (20 cm depth), deeper than superficial tillage, favours this endogeic species by supplying food in enough quantity at their preferential depth. Also, we must emphasise that deep-ploughing consisted of only turning over the first top 20 cm, which resulted in lesser destruction of endogeic earthworms, compared with disking which was used in superficial tillage. The more frequent superficial cultivation of the topsoil used to replace herbicide application in the integrated farming system (IN) could have prevented the establishment of *A. rosea* populations. However, we stress that low earthworm densities are correlated with shallow depth of limestone, probably due to drier conditions than in

deeper soils. Thus, on shallower soils (IN system and RT pea field), the influence of tillage depth on earthworm densities must be far less important than that of limestone depth. Comparing the agricultural systems on deeper soils only, the lower density of earthworms in the MT system than in the RT wheat field could be explained by the application of the organo-chlorine insecticide endosulfan in the MT system. This compound is known to be toxic for the earthworm *L. terrestris* (Haque and Ebing, 1983). Binet et al. (1997) showed that the presence of a well-developed root system also favoured earthworms. Accordingly, we did observe in our study sites that earthworm densities were lowest under the less developed root system of pea than under the well-developed root system of wheat.

The opposite distribution of earthworm and enchytraeid populations

A comparison of the distribution of enchytraeid activity (estimated from micromorphological data) with earthworm population estimates revealed the opposite distribution of these two groups, the highest abundance of enchytraeid faecal pellets being observed in the integrated farming system (IN) and the lowest under conventional tillage (CT). A negative interaction between these two oligochaete groups has been already demonstrated. Górný (1984) reported a decrease in enchytraeid abundance in Dutch polder soils following inoculation with *L. terrestris* and *Aporrectodea caliginosa*, and Haukka (1987) found experimentally an increased mortality of the lumbricid *Eisenia fetida* in the presence of the enchytraeid *Enchytraeus albidus*. Enchytraeids are often found in habitats where conditions are too hard for most other faunal groups (Healy, 1980). This distribution is probably due to their great ecological adaptability but also to their low competitive ability towards other soil-dwelling groups such as earthworms (Healy, 1980). From our results, we can hypothesize that enchytraeid species living in our study sites could be less affected than earthworms by drought occurring seasonally in fields on shallow soils (IN system) and could take advantage of lower densities of earthworms in these fields for their development. In the presence of higher earthworm densities like under deep-ploughing, a possible competition between *A. rosea* and enchytraeids for food, both taxa feeding on plant debris (Bolton and Phillipson, 1976; Kooistra, 1991), could force enchytraeids to occupy other spatial niches (Haukka, 1987). The low activity of enchytraeids found under conventional tillage can also be explained by the negative effect of deep-ploughing on enchytraeid populations (Parmelee et al., 1990). Didden (1990) found that in conventional farming systems, enchytraeids lived at greater depth than in integrated farming systems, so it is possible that enchytraeids were more abundant below the bottom of our soil profiles (14 cm) under conventional

tillage and thus results of their activity were not observed in our samples. The greater activity of enchytraeids in the integrated farming system compared with the two other systems using superficial tillage could be due to rates of fertilizer and biocide application which were markedly lowest in the integrated system. However, further investigations will be required in order to better understand the effects of chemical inputs on these populations.

In the integrated system, where earthworm densities are low, enchytraeids eat earthworm casts and replace them by a crumbly structure made of faecal pellets and channels (Boersma and Kooistra, 1994, Dawod and FitzPatrick, 1993; see also Figure 1) at a higher rate than that of earthworm cast production. It is also possible that a great enchytraeid activity would not be visible where earthworms cast at a high frequency, hereby compacting rapidly enchytraeid structures.

Enchytraeid activity

The distribution of enchytraeid excrements follows that of the strong very fine granular structure (STVFGR). In the integrated farming system (IN), where enchytraeid faecal pellets were most abundant and where earthworm densities were very low, we found the lowest abundance of the structureless massive material (MA). At the opposite, in the deep-ploughing system (CT) where enchytraeid activity was lowest and earthworm densities highest, structureless massive material (MA) was most abundant. From our results, we can assert that, in our study site, enchytraeids have a greater impact on soil structure than earthworms. Our results reinforce the view that enchytraeids increase porosity through their tunnelling activity and their deposition of faecal pellets (Didden, 1990; Van Vliet et al., 1993). Didden (1990) observed an increase in soil aggregates corresponding to the size of enchytraeid faecal pellets.

Enchytraeids also play an important role in nutrient-cycling processes as a consequence of very high mineralization rates measured in their faecal pellets (Marinissen and Didden, 1997). Their activity increases also porosity and creates micro-sites of high fertility which ultimately influences the distribution of plant roots. In our study, enchytraeid faecal pellets were more abundant at the same depth as roots were. Lagerlöf et al. (1989) found that the vertical distribution of enchytraeids reflected the distribution of roots as this has been observed with earthworms too (Binet et al., 1997; Edwards and Lofty, 1978). Although this has been rarely reported, enchytraeid activity can be greater than that of earthworms in spite of a lower biomass, as ascertained by their respiration rate in agroecosystems (Golebiowska and Ryszkowski, 1977). In our study site, enchytraeids play an

important role in the maintenance of soil structure and their high rate of activity may compensate for the low density of earthworms we found in the integrated agricultural system.

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Legends of figures

Figure 1. Photographs of some components of the soil matrix in topsoil profiles. Scale 1 mm represented by a black line at the right bottom of each picture. Photo. 1: Structureless massive material (MA). Photo. 2: Weak to moderate fine granular structure (WMFIGR). Photo. 3: Strong very fine granular structure (SRVFGR). Photo. 4: Enchytraeid faecal pellets on earthworm casts within an earthworm burrow. Photo. 5: Endogeic earthworm casts. Photo. 6: Anecic earthworm casts.

Figure 2. Analysis of correspondences: Projection of soil components (active variables) and depth levels (passive variables) along the first axis. Depth levels in cm are mentioned on the left side and soil components on the right side of the axis.

Figure 3. Distribution of structureless massive material (MA) according to depth in the four farming systems. Sampling points D and S are represented by black and white symbols, respectively. Crops are wheat (●), wheat monoculture (◆) or pea (▲).

Figure 4. Distribution of weak to moderate fine granular structure (WMFIGR) according to depth. Symbols as for Figure 3.

Figure 5. Distribution of strong very fine granular structure (STVFGR) according to depth. Symbols as for Figure 3.

Figure 6. Distribution of enchytraeid faecal pellets according to depth. Symbols as for Figure 3.

Figure 7. Distribution of living roots according to depth. Symbols as for Figure 3.

Figure 8. Distribution of highly decomposed plant residues according to depth. Symbols as for Figure 3.

Figure 9. Distribution of partially decomposed plant residues according to depth. Symbols as for Figure 3.

Table 1. Management of farming systems

Farming system	Crop rotation ^a	Cultivation	Tillage prior sowing ^b	Sowing ^c	Intercrop weeding ^d	Chemical input ^e
MT	Pea-Soft wheat	Minimum tillage	Superficial disk-harrowing	Direct drilling	Herbicide (glyphosate)	>4 kg/ha
MT*	Soft wheat	Minimum tillage	Superficial disk-harrowing	Direct drilling	Herbicide (glyphosate)	>4 kg/ha
RT	Pea-Hard wheat-Soft wheat	Reduced tillage	Superficial disk-harrowing	Direct drilling	Herbicide (glyphosate) + single shallow cultivation	>4 kg/ha
IN	Pea-Hard wheat-Soft wheat	Reduced tillage	Superficial disk-harrowing	Sowing + cultivation	Shallow cultivation (repeated 3 times)	<2 kg/ha
CT	Pea-Hard wheat-Soft wheat	Conventional tillage	Deep ploughing	Sowing + cultivation	Herbicide (glyphosate)	3–4 kg/ha

^a Hard wheat=*Triticum durum*, soft wheat=*T. aestivum*, both as winter wheat, pea=spring pea.

^b Deep ploughing to 20 cm depth, and superficial disk-harrowing to 10 cm depth. Date of tillage prior sowing of spring pea and winter wheat is in February and in October, respectively.

^c In pea crops, soil is compacted after sowing.

^d Interculture weeding in October.

^e Chemical inputs means biocides (herbicides, insecticides and fungicides) and N or PK fertilizers.

Table 2. Analysis of variance of total earthworm and *Aporrectodea rosea* densities according to crop treatment. Means from the same homogeneous group (SNK procedure) are followed by the same letter. Wheat monoculture (MT*) was not taken into account for comparisons between farming systems

		MT	RT	IN	CT	<i>F</i> ratio
Wheat	<i>Aporrectodea rosea</i> (number per m ²)	20.5b	58a	1c	73a	121.22*
	Total earthworms (number per m ²)	21b	63a	1c	74a	119.61*
	Depth D/S	120/75	100/70	70/40	120/75	
Pea	<i>Aporrectodea rosea</i> (number per m ²)	28a	4b	8b	56a	18.65*
	Total earthworms (number per m ²)	28a	7b	10b	60a	13.11*
	Depth D/S	120/75	75/40	75/40	120/90	

* $P(F > F_{obs.}) < 0.001$.

Table 3. List of components of the topsoil matrix identified by morphological features. Abbreviations used in figures and text were between brackets

Soil material	Plant material	Miscellaneous
Soil surface crust	Partially decomposed plant residues	Mineral
Structureless massive material (MA)	Highly decomposed plant residues	Waste
Weak to moderate fine granular structure (WMFIGR)	Fresh plant residues	Enchytraeids
Strong very fine granular structure (STVFGR)	Living roots	Unidentified components
Ped fragments	Dead roots	
Enchytraeid faecal pellets	Pea nodules	
Endogeic earthworm casts		
Anecic earthworm casts		
Unidentified earthworm casts		
Millipede faecal pellets		

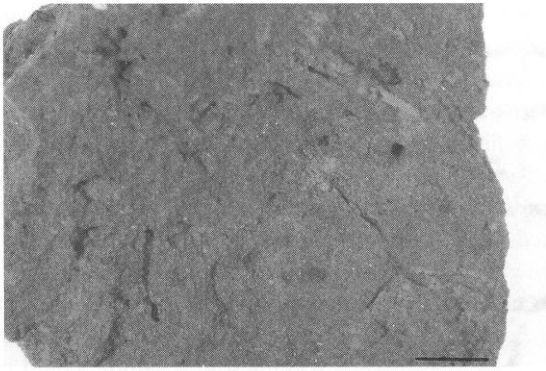


Photo. 1

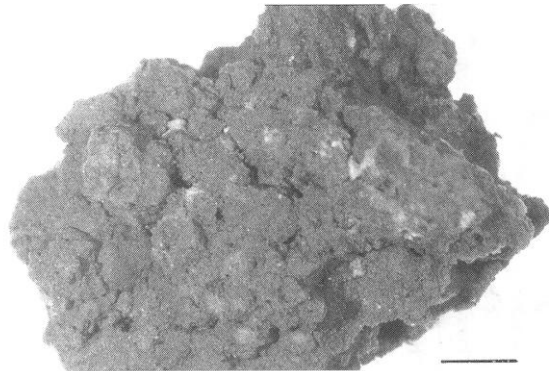


Photo. 2

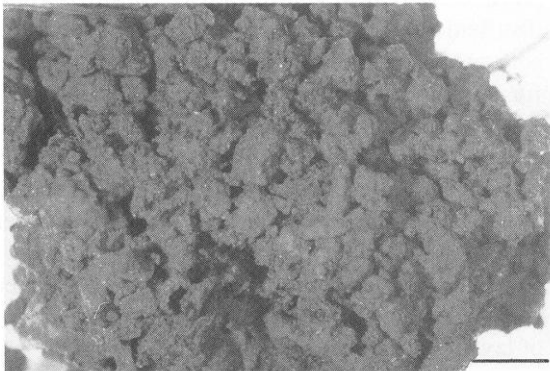


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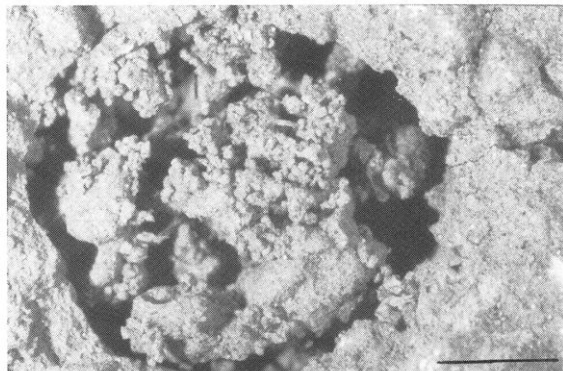


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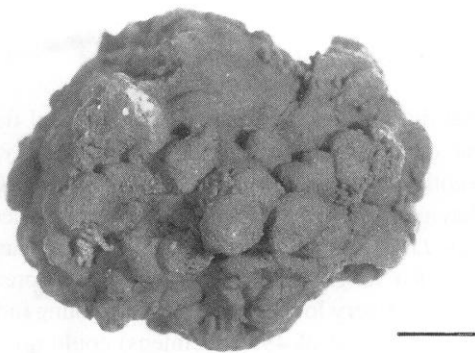


Photo. 5

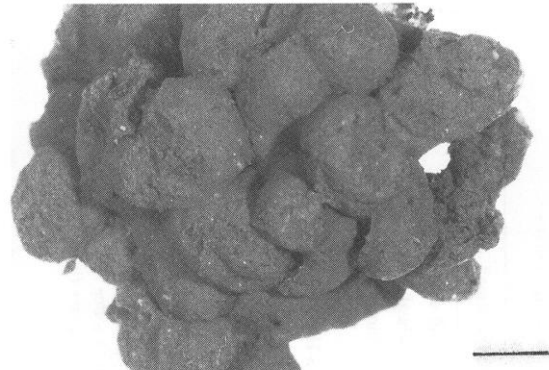


Photo. 6

Fig. 1

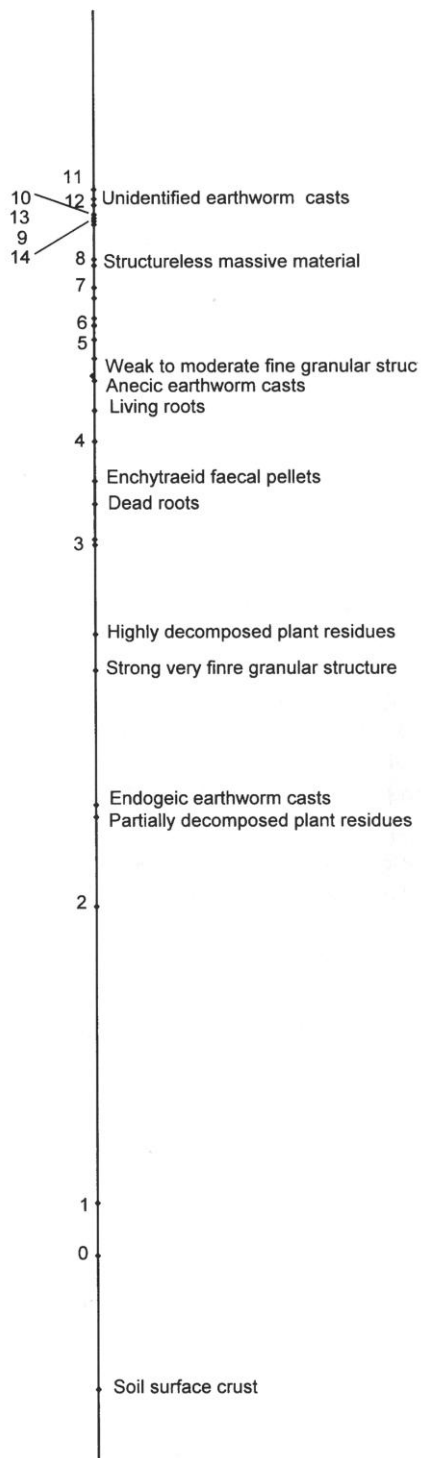


Fig. 2

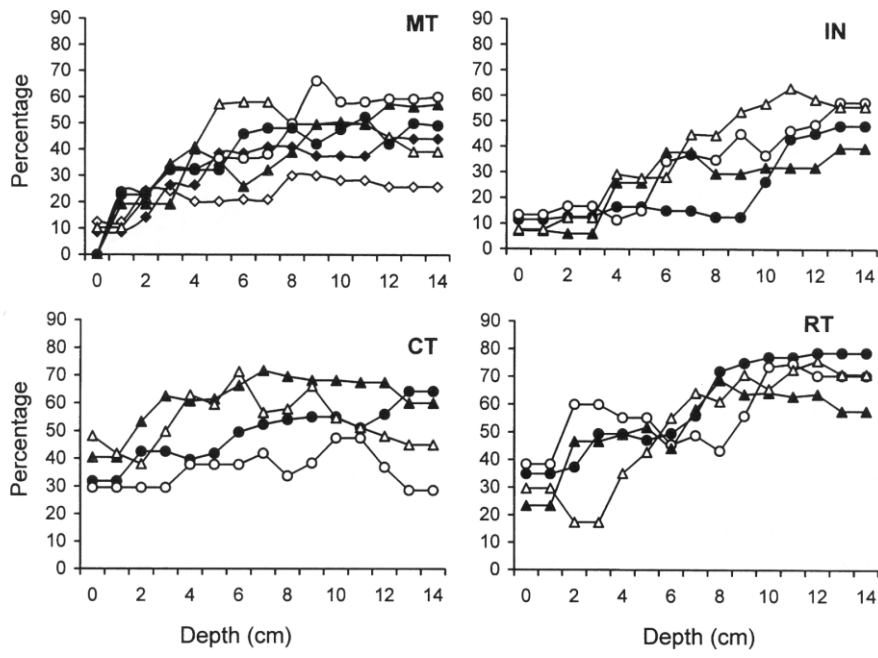


Fig. 3

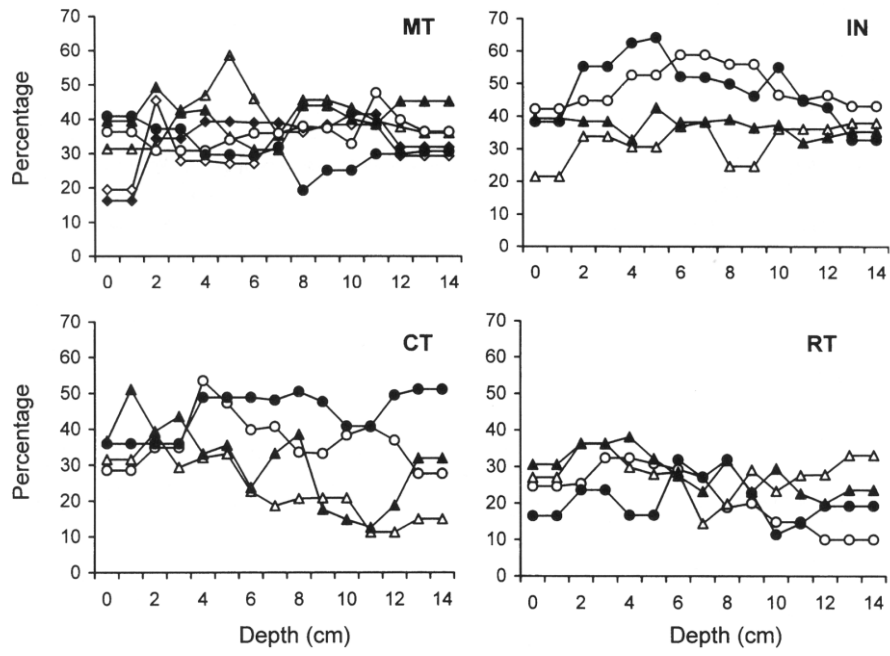


Fig. 4

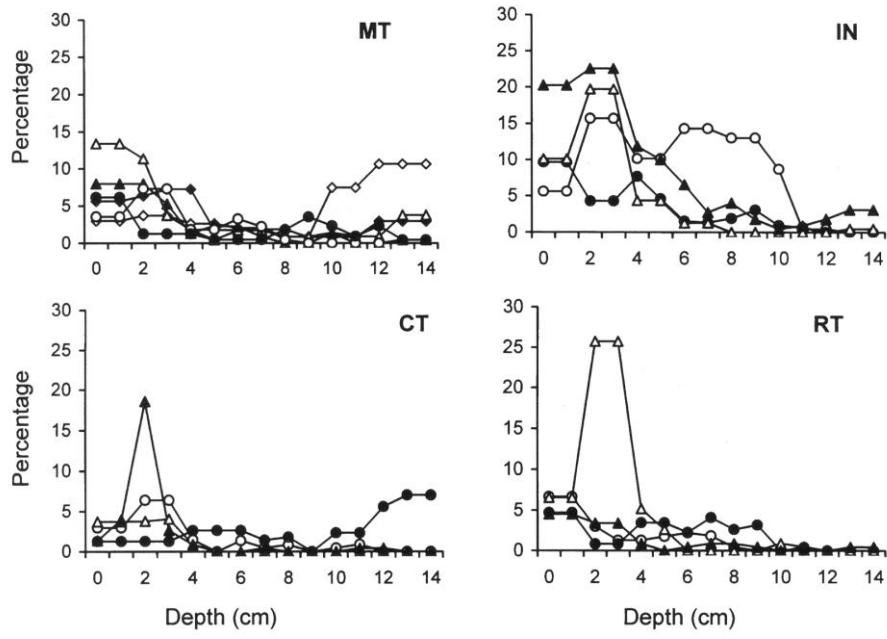


Fig. 5

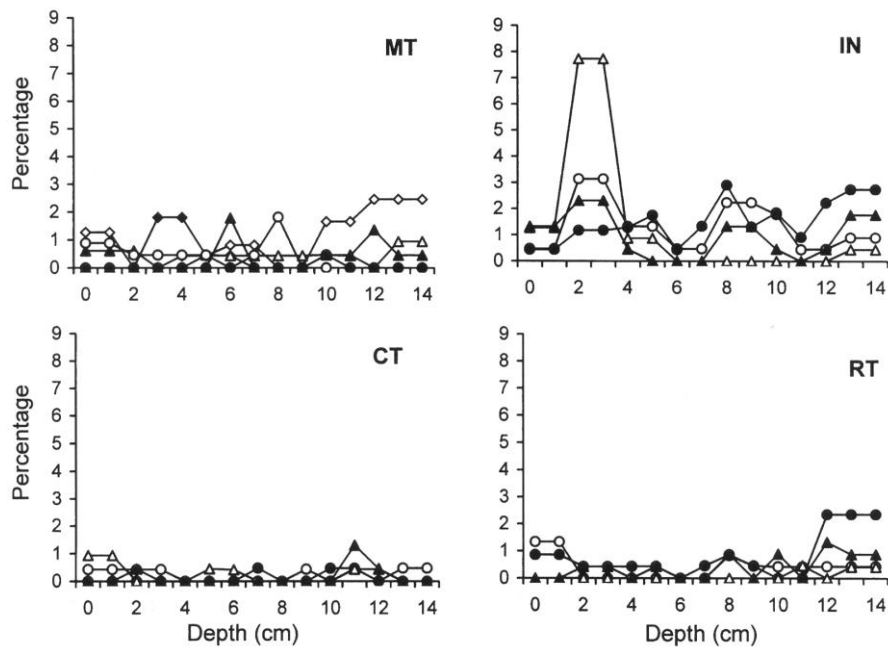


Fig. 6

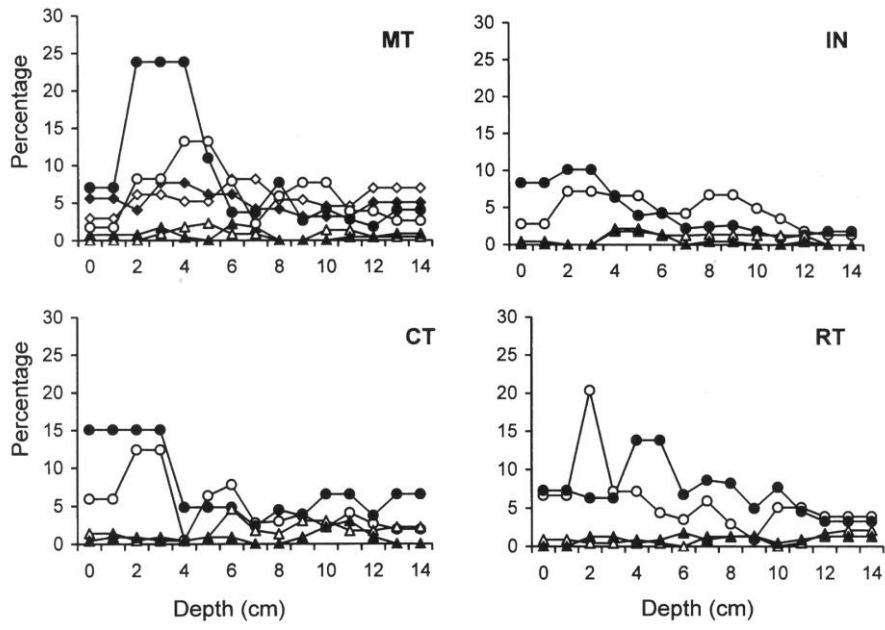


Fig. 7

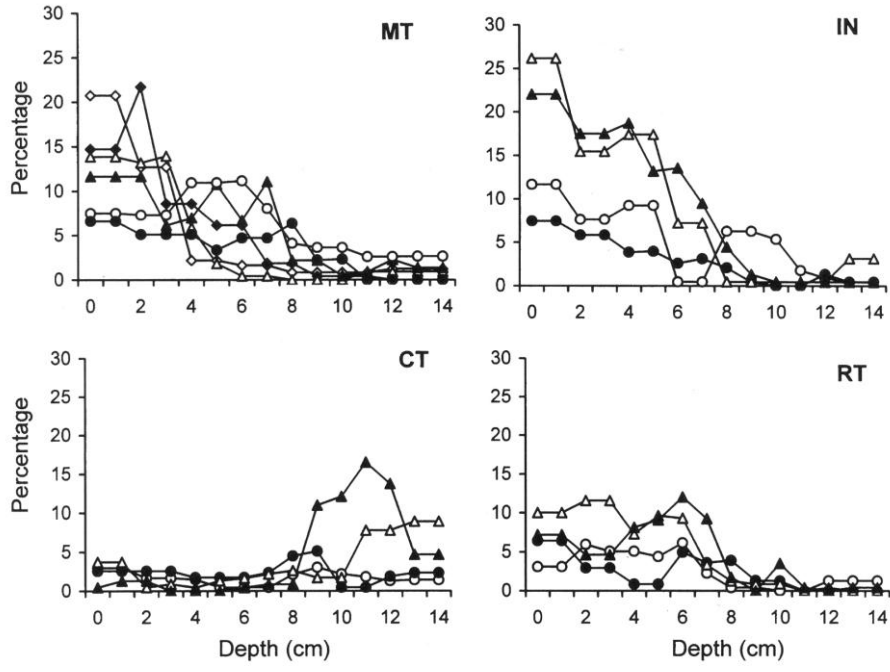


Fig. 8

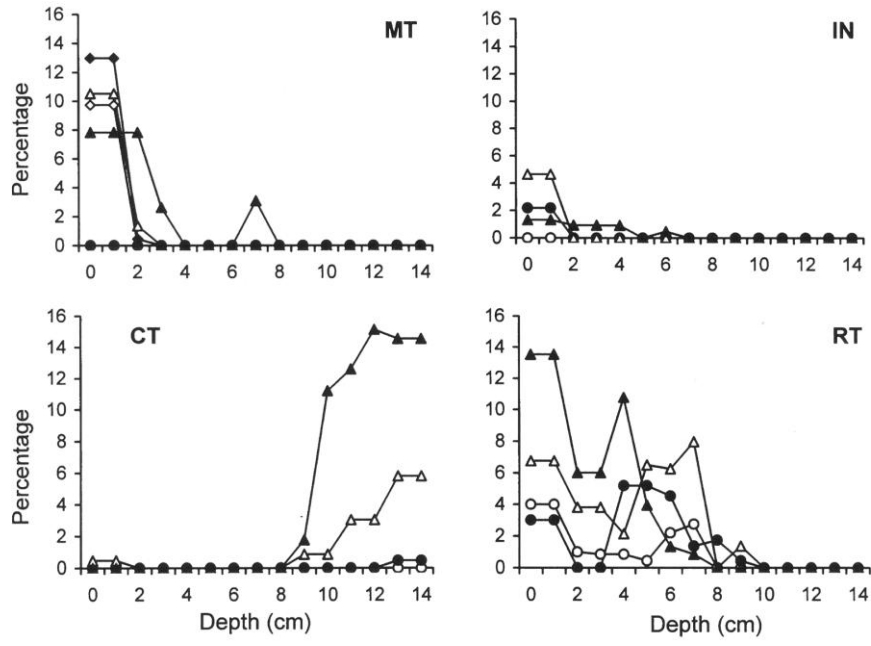


Fig. 9