DIVISION S-6–SOIL & WATER MANAGEMENT & CONSERVATION

Dynamics of Soil Physical Properties in Amazonian Agroecosystems Inoculated with Earthworms

J. C. Alegre,* B. Pashanasi, and P. Lavelle

ABSTRACT

The combined use of earthworm inoculation and organic inputs is considered an efficient way to improve traditional slash-and-burn agriculture in the humid tropics. This study tests the hypothesis that the resistant macroaggregate structure that results from earthworm activities is likely to promote sustainability by favoring water infiltration and soil aeration. Six successive crops (maize [*Zea mays* L.]-rice [*Oryza sativa* L.]-cowpea [*Vigna unguiculata* (L.) Walp.]-rice-rice-rice) were grown from March 1990 to January 1993 on a fine-sandy, siliceous, isohyperthermic Typic Paleudult previously covered by forest at Yurimaguas (Peruvian Amazonia). The experimental design included a combination of three organic residue treatments (without residues, with crop residues, and with crop residues plus green manure), with or without earthworm (*Pontoscolex corethrurus*) inoculation (36 g fresh weight m^{-2}). Soil physical properties (bulk density, total porosity, infiltration, sorptivity, soil water tension, and aggregate-size distribution) were measured before clearing and after harvesting each crop. The proportion of macroaggregates (>1 cm) increased from 25.1 to 32.7% in inoculated treatments, whereas the proportion of small aggregates (<2 cm) decreased from 33.2 to 26.1%, and no change was observed in the intermediate (2–10 mm) category. In the control treatment, no significant changes were observed. Earthworm activities significantly increased bulk density (from 1.12 to 1.23 Mg m^{-3}), and decreased porosity (from 58 to 53%) and sorptivity (from 0.45 to 0.15 cm $s^{-1/2}$). Soil water tension was also affected by the presence of earthworms through increased water uptake by larger plants and changes in soil structure. Longer term experiments are necessary to confirm that the activity of the earthworm may not eventually have detrimental effects.

FARMERS of the Amazon region of Peru practice shifting agriculture as the principal land use system. They slash and burn a piece of land and grow crops for 1 to 2 yr and the area is then abandoned for 5 to 10 yr with a natural regrowth fallow. In the last few years, due to land pressure, fallows have become shorter. There is insufficient time to recycle soil nutrients and, as a result, crop yields have declined. Any practice that could increase sustainability beyond the short period of cropping would help to decrease the need to clear primary forest and hence contribute to reduced deforestation. Part of the problem can be solved through the use of fertilizers (Sanchez et al., 1983), but suitable soil physical properties need to be maintained. This can be attained by incorporating organic matter, thereby stimulating biological activities that can accelerate the breakdown of this organic matter into the soil and improve soil structure within a short period of time (Swift and Woomer, 1994).

The effect of different types of land use on Macrofaunal communities has been studied at Yurimaguas (Peruvian Amazonia) in 12 different situations (Lavelle and Pashanasi, 1989). Communities were highly depleted in annual cropping systems, compared with the original forest, and pastures had high contents of the peregrine earthworm species *Pontoscolex corethrurus*.

In the experimental situation used for this study, earthworm activities dramatically increased maize (crop no. 1), and rice (crop no. 3, 5, and 6) production by more than 100% in some treatments (Pashanasi et al., 1996). Legumes (crop no. 2) did not respond to earthworm inoculation, and rice cropped out of season (crop no. 4) responded negatively (−43% on average) to earthworm inoculation.

In soils from other regions of the humid tropics, earthworms have been reported to improve soil physical properties by increasing water infiltration and stability of aggregation and reducing the bulk density (Aina, 1984; Barois et al., 1993; Blanchart et al., 1990, 1996; Blanchart, 1992; Lal, 1988; Mulongoy and Bedoret, 1989). The endogeic macrofaunal communities maintain a favorable structure because the casts protect organic matter from decomposition, thereby increasing the stability of macroaggregates (Martin, 1991; Blanchart et al., 1993). On some occasions, however, increased bulk density linked to activities of a specific functional group have also been measured (Gilot, 1994; Rose and Wood, 1980).

The activities of earthworms may be used to regulate the mineralization and humification processes and maintain soil physical structure. It is therefore necessary to identify those species that will survive the conditions of a tropical agroecosystem and significantly influence soil processes through intense activity (Lavelle et al., 1988). The hypothesis is that, under field conditions, the conservation and maintenance of a resistant macroaggregate structure that results from earthworm activities is likely to promote sustainability by preventing erosion and favoring water infiltration and soil aeration.

The main objective of this study was to test this hypothesis by comparing changes in soil physical properties during six successive cropping cycles in a low-input agriculture system affected by the inoculation of the geophagous soil-dwelling (endogeic) earthworm *Pontoscolex corethrurus*.

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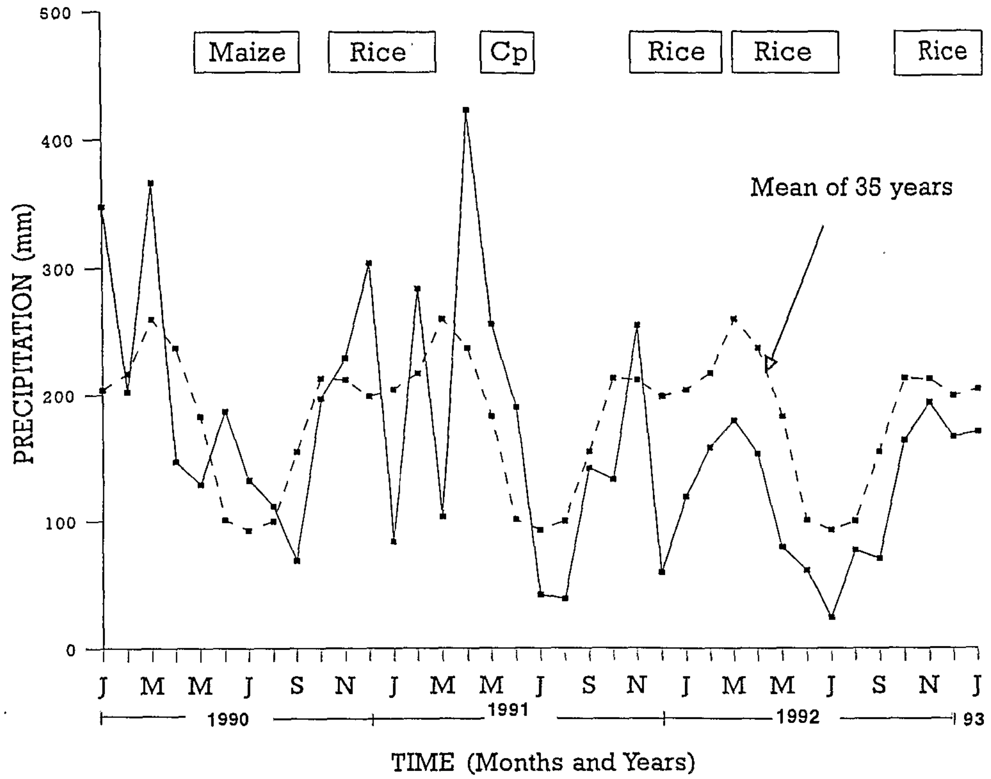

Fig. 1. Crop sequence and monthly rainfall distribution during the study and long-term monthly rainfall distribution (average of 35 yr). Cp indicates cowpea.

MATERIALS AND METHODS

The study was conducted from January 1990 to January 1993 on a 16-yr-old secondary evergreen forest at the Yurimaguas Research Station (5°5′ S, 75°5′ W, 184 m above sea level) in eastern Peru. The soil is a loam, a fine-sandy, siliceous, isohyperthermic Typic Paleudult. Mean annual temperature is 26°C with little monthly or daily variation. Average annual rainfall is 2250 mm, with a relatively dry period in June through August when average monthly precipitation is limited to approximately 100 mm (Fig. 1).

A 0.25-ha plot with slope ranging from 1 to 2% was selected. The total area was slashed by hand, the vegetation burned, and the remaining logs removed. Columnar experimental units (60 cm diameter, 40 cm depth) of undisturbed soil were isolated by digging a circular ditch and placing a 0.5-mm-mesh plastic net down to 40-cm depth. We did not feel it necessary to place the mesh on the bottom of the soil column to prevent colonization from below since *Pontoscolex corethrurus* is rarely, if at all, found below 20-cm depth (Lavelle et al., 1987). After the net had been placed, the circular ditch was refilled with soil. The plastic net allowed free movement of water but prevented earthworms from invading control plots or escaping from inoculated units. Undesired colonization of non-inoculated units was indeed negligible.

Earthworms from the original forest were killed with carbofuran (2,3-dihydro-2,2-dimethyl-7-benzofuranyl methylcarbamate). After 4 wk, the pesticide had been naturally eliminated and *Pontoscolex corethurus* was introduced in the earthworm treatments. The introduced biomass was equivalent to 360 kg of fresh weight ha^{-1} (or 72 kg ash-free dry biomass), slightly below estimates currently reported in surrounding environments (Lavelle and Pashanasi, 1989).

A combination of three treatments, each with different levels of organic inputs (i.e., no inputs, crop residues, and crops residues + legume green manure) was randomly distributed in a completely randomized block design of 108 units. In each treatment, earthworms were inoculated in half of the units. The six treatments are described in Table 1. At each harvest, three blocks of each treatment were destructively sampled to obtain information on earthworm populations, root and microbial biomass, and soil physical and chemical properties (Fig. 2).

The plots were cropped to maize–rice–cowpea–rice–rice–rice from March 1990 to January 1993 (Fig. 1). The soil physical parameters monitored at the end of each cropping cycle were bulk density (D_b), total porosity (P), cumulative infiltration (I), sorptivity (S), soil water tension (SWT), and distribution of aggregates in size classes (AG). Bulk density was measured in 98-mL cylinders (5 cm height) taken at the position shown in Fig. 3.

Table 1. Descripton of treatments in the macrofauna experiment at Yurimaguas, Peru.

Crop no.	Treatment	Earthworm inoculation	Description
1	C	No	Control (C) without crop residues at the soil surface
2	CW	Yes	Same as crop no. 1 with earthworms (W)
3	CR	No	With crop residues (R) at the soil surface without earthworms
4	CRW	Yes	Same as crop no. 3 with earthworms
5	CRG	No	With crop residues and green manure (G) (*Centrosema macrocarpum*) at the rate of 2 Mg ha^{-1} dry matter for the first crop and 2.5 Mg ha^{-1} for following crops
6	CRGW	Yes	Same as crop no. 5 with earthworms

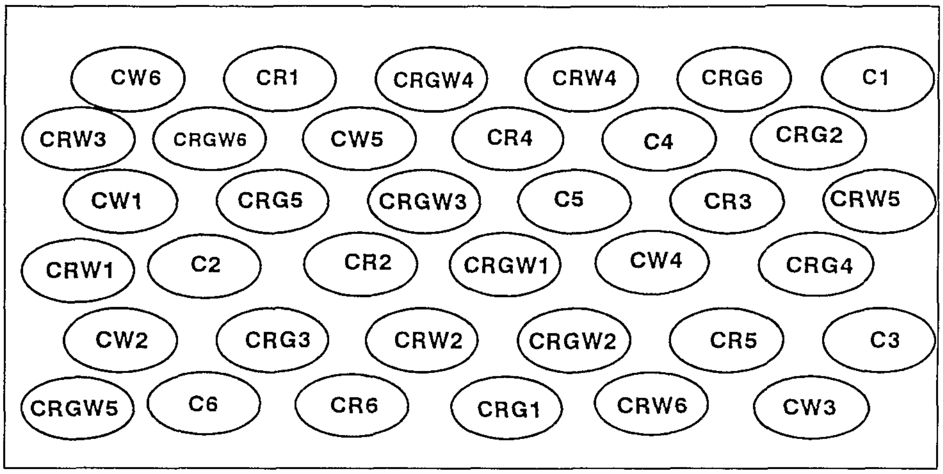

Fig. 2. Distribution of treatments in one block (last number is the crop season).

Total porosity was calculated as a function of D_b and particle density (P_b) (assumed as 2.65 Mg m^{-3}) as follows:

$$P = (1 - D_b/P_b)100$$

Cumulative infiltration was measured in each of the plot units by driving a 110-mm i.d., open-ended steel cylinder into the soil to a depth of 150 mm. Four layers of cheesecloth were placed over the soil surface enclosed by the cylinder. Instantaneous water ponding on the undisturbed soil surface was established by adding the equivalent of a 76-mm-high column of water. Water intake was measured at 5-s time intervals after the onset of ponding until 20 s had elapsed and at 10-s intervals thereafter until 120 s had elapsed. Cumulative infiltration was regressed against the square root of time. The slope of this linear relationship for time to 120 s was used as an estimate of S. A detailed description of the field procedure was presented by Van Es et al. (1988). Gravimetric soil water content at each sampling location was determined on a soil sample collected from the 0- to 100-mm depth.

Soil water tension was measured with tensiometers buried at a 15-cm depth in each microplot unit and read with a digitized tensiometer.

The size distribution of aggregates was measured using the dry sieving method (Blanchart, 1992). Soil samples 10 by 10 by 10 cm were taken from each experimental unit and air dried to a moisture content of 5 to 6% dry weight. Aggregates were separated by dropping the air-dried samples from a constant height of 1.5 m onto a hard surface. They were furthe air dried and sieved on a set of meshes of <250 μm, 250-500 μm, 500-1000 μm, 1-2 mm, 2-5 mm, 5-10 mm, and >10 mm and each fraction was weighed.

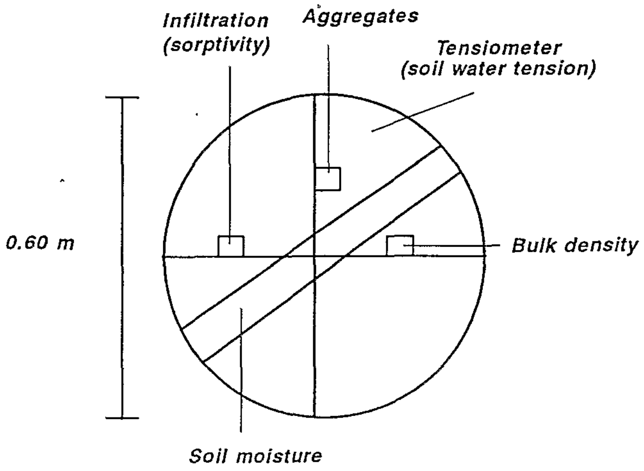

Fig. 3. Sites of soil physical measurements in the microplot, plan view.

RESULTS

Soil Aggregation

Soil ingested by earthworms is expelled as casts after digestion, mostly in the upper 10 cm of the soil. The earthworm *Pontoscolex corethrurus* generally ingests aggregates smaller than the diameter of its mouth (Blanchard et al., 1990). In contrast, casts are large aggregates of several millimeters in diameter. As a consequence of the feeding activity of earthworms, small aggregates are progressively transformed into larger aggregates. These larger aggregates tend to accumulate in the absence of other agencies that break down larger aggregates into smaller ones. Over time, the presence of earthworms led to changes in the distribution of aggregate size classes (Fig. 4). Soil aggregation significantly increased with time for some aggregate size classes in the earthworm treatments (Table 2). Most of the organic treatments alone had no significant effect on this parameter, and the interaction between organic matter and earthworm treatments was generally not significant. In treatments without earthworms, the proportion of small aggregates (<2 mm) increased significantly between the third and fourth crop period (Fig. 4). The proportion of larger aggregates (>10 mm) fluctuated, with no clear trend until the fourth crop; the proportion was greater in the earthworm treatment in the last two crops. In the earthworm treatment, the proportion of small aggregates (<2 mm) decreased from 32.2 to 20.5% (fifth crop) and 26.1% (sixth crop), whereas the proportion of large aggregates (>1 cm) increased from 25.1 to 36.8% (fifth crop) and 32.7% (sixth crop).

Bulk Density and Porosity

There were no significant differences (least significant difference test at 0.05 probability) in D_b among treatments

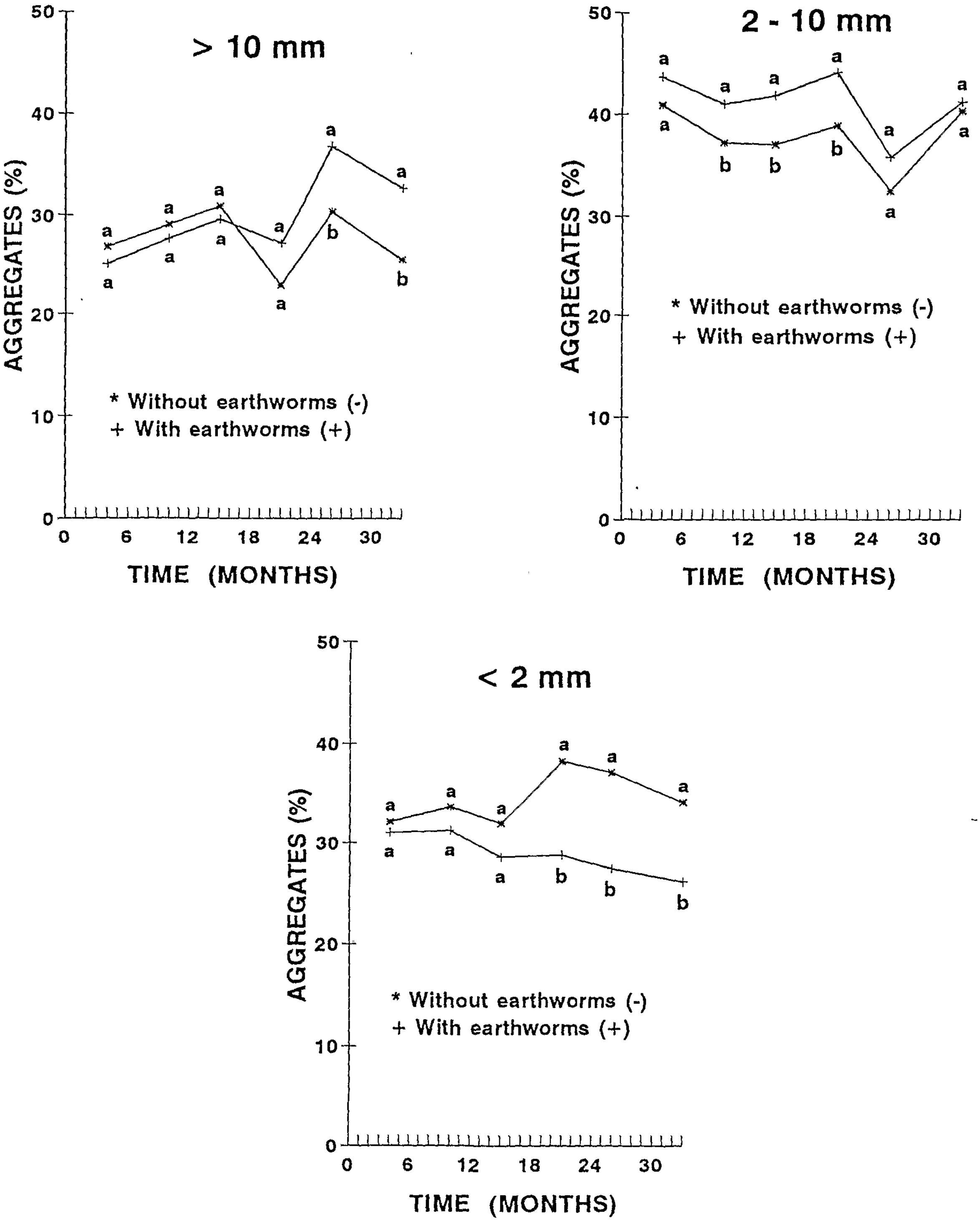

Fig. 4. Dynamics of the proportion of aggregates of different sizes with time for treatments with and without earthworms (values with the same letter are not significantly different).

with different organic inputs. Interaction among the presence or absence of earthworms and organic treatments also did not result in significant differences. In contrast, D_b in the upper 10 cm of soil was significantly higher in treatments with earthworms than in those without earthworms. The apparent contradiction between an increase in aggregation and increase in D_b may be due to the predominance of nonexpandable clay minerals (kaolinitic) (Alegre et al., 1986), since kaolinitic clay has low porosity. In addition, casts of *Pontoscolex corethrurus* with kaolinitic clays have very small pore sizes, and these casts form the bulk of large aggregates (A. Chauvel et al., 1996, unpublished data). Bulk density fluctuated substantially during the experiment (Fig. 5). In the absence of earthworms D_b was variable, probably because the decomposition rate of different residues var-

Table 2. Summary of the levels of significant differences between organic treatments (O), earthworm treatments (E), and the interaction of organic × earthworm treatments (O×E) for aggregates of different size classes.

	>10 mm			2-10 mm			0.5-2 mm			0.2-0.5 mm			<0.2 mm		
Crop no.	O	E	O×E	O	E	O×E	O	E	O×E	O	E	O×E	O	E	O×E
1	ns	ns	ns	ns	ns	ns	ns	ns	*	ns	ns	ns	ns	ns	ns
2	ns	ns	*	ns	*	ns	ns	ns	ns	ns	ns	ns	**	**	ns
3	ns	ns	ns	ns	**	ns	*	ns	ns	ns	ns	ns	ns	ns	ns
4	ns	ns	ns	ns	**	ns	ns	ns	ns	*	**	ns	ns	**	ns
5	ns	**	ns	ns	ns	ns	ns	ns	ns	ns	**	ns	ns	**	ns
6	ns	**	ns	ns	ns	ns	ns	ns	ns	ns	*	ns	ns	**	**

*,** *F* tests significant at 0.05 and 0.01 probability levels, respectively; ns = not significant.

ied, and soil moisture varied during the dry and wet periods. In the earthworm treatments, D_b was less variable. There was a significant increase in D_b up to the third crop.

The activity of earthworms in decomposing the crop residues and green manure reduced the variability of D_b. The maximum value of D_b obtained was 1.23 Mg m^{-3}, which is highly favorable in a continuous cropping system with low inputs. In this kind of soil, with a high percolation rate, this increase in D_b may be very beneficial, since it maintains the available water-holding capacity and hence reduces nutrient loss by leaching and water stress during dry periods. Total soil porosity did not change significantly in treatments without earthworms, whereas a significant decrease from 58.1 to 52.5% was observed in the inoculated treatments (Table 3).

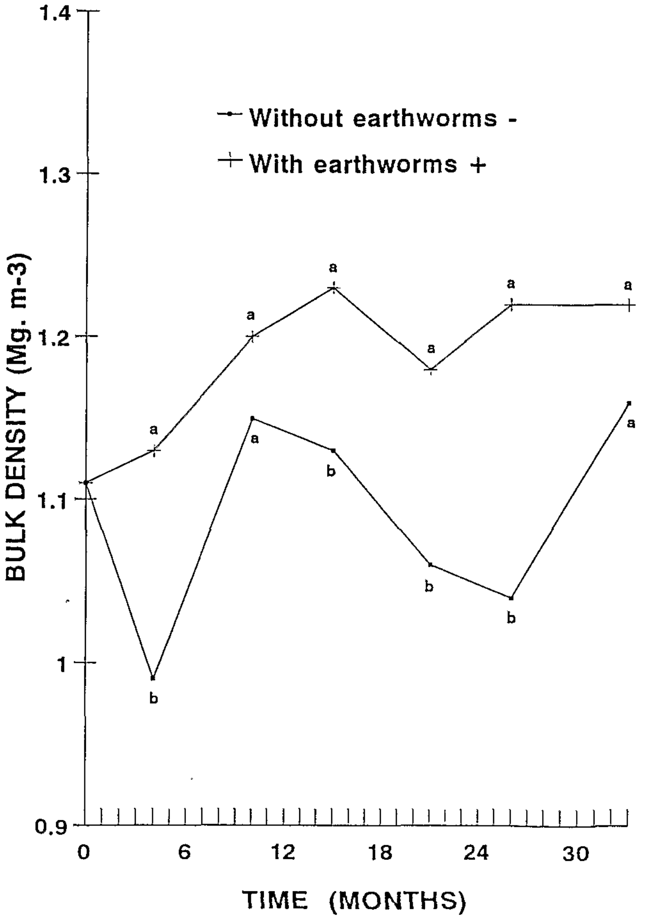

Fig. 5. Dynamics of bulk density for six crop seasons (values with the same letter are not significantly different).

Infiltration

Cumulative infiltration (accumulated during 120 s) for the treatments with and without earthworms significantly differed only for crops 2, 4, and 6 (all with rice; Fig. 6). The initial infiltration or sorptivity (*S*) significantly decreased with time in all treatments, with the greatest reduction in the earthworm treatments (Table 4). In this study, *S* is an empirical parameter that characterizes initial infiltration under the existing physical conditions at the time of measurement. Such *S* values are not equivalent to sorptivity as defined by Philip (1957) because certain assumptions do not strictly hold, i.e., homogeneity of the soil material, uniform antecedent water content, and the second term in the Philip equation being negligible. The *I* and *S* were significantly lower in earthworm treatments, as measured at the end of the sixth cropping sequence. The S for the earthworm treatments at the end of the six crops was 0.150 cm $s^{-1/2}$ while for the no-earthworm treatments it was 0.34 cm $s^{-1/2}$ (Table 4).

Similar to D_b, the variability was lower for the earthworm treatments.

Rainfall Distribution and Soil Moisture Patterns

Rainfall was highly variable with 2450, 2008, and 1452 mm in 1990, 1991, and 1992, respectively (Fig. 1), the last value being well below the long-term average for the area. This variable pattern of rainfall distribution affected crop production, with some differences among treatments depending on the soil moisture content. In general, treatments with earthworms had lower soil moisture contents than non-inoculated treatments. This is probably the result of increased water uptake by larger plants in the inoculated treatments, in spite of the expected increase in water retention due to increased bulk density. The soil moisture regime was significantly

Table 3. Effects of the treatments with and without earthworms on the total soil porosity for six continuous crops.

No.	Crop	Without earthworms	With earthworms
		%	%
	Initial	58.1 (2.2)†	58.1 (2.2)
1	Maize	62.6 (3.6)	57.5 (3.1)
2	Rice	56.8 (3.8)	54.7 (3.8)
3	Cowpea	57.3 (2.9)	53.7 (3.3)
4	Rice	60.0 (4.7)	55.3 (4.9)
5	Rice	60.8 (5.0)	54.0 (3.6)
6	Rice	57.1 (5.2)	52.5 (2.9)

† Values in parentheses are standard deviations.

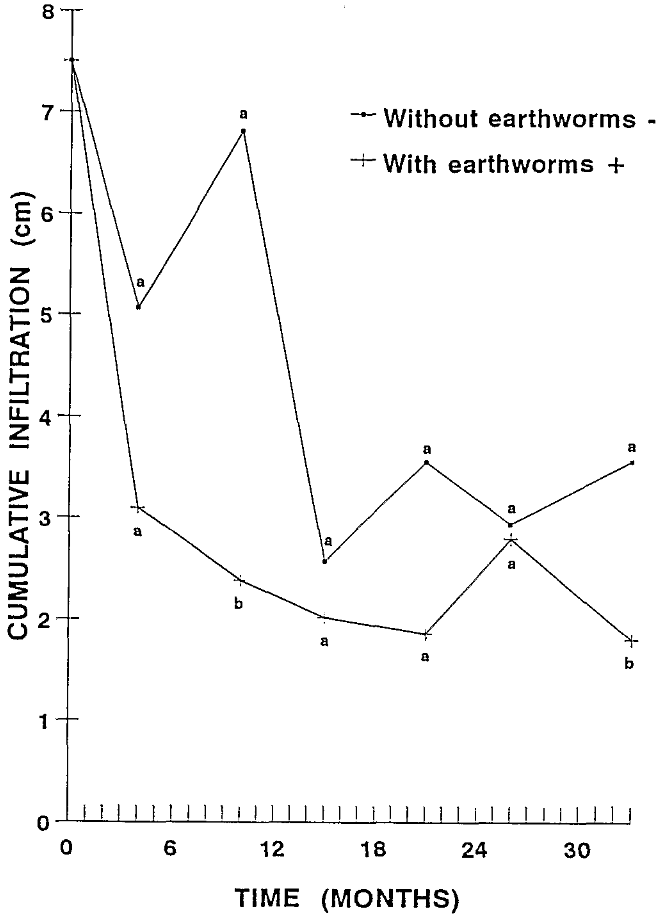

Fig. 6. Dynamics of infiltration during six crop seasons (values with the same letter are not significantly different).

affected by earthworm activities but not by the organic treatment (Fig. 7).

During periods of low precipitation, soil moisture was significantly lower in the earthworm than in no-earthworm treatments. Flowering and earing were affected because plant water requirements are higher during this vegetative stage than at previous stages. During the growing periods of crops no. 1, 3, and 4, with maize, cowpea, and rice, respectively, soil water tension was less than field capacity (i.e., 20 kPa in our experimental conditions) and hence no water stress was observed in any of the treatments (Fig. 7a, 7c, and 7d). During the second and fifth crop with rice, soil tension dramatically increased after the 10th week, and some symptoms of water stress were observed, being more drastic in treatments with earthworms (Fig. 7b and 7e). In the fifth crop, plants were damaged and grain production was significantly decreased in the no-earthworm treatments compared with earthworm treatments (Pashanasi et al., 1996).

Comparable effects have already been observed with *Millsonia anomala*, and African species that produces rounded compact casts, mainly deposited inside the soil (Blanchart et al., 1996; Derouard et al., 1996). These results clearly differ from most observations reported so far (Lee, 1985). It has been, therefore, our hypothesis that at least two groups of earthworms should be separated in view of their effects on soil physical parameters: "compacting" species like *Pontoscolex corethrurus* feed on small aggregates rich in organic matter and transform them into larger aggregates with a compact structure and high content of nutrients in forms that plants can uptake (NH_4 and phosphate) (Brossard et al., 1995; Lavelle et al., 1992; Sharpley and Syers, 1976, 1977; Syers et al., 1979). Earthworm communities also comprise "decompacting" species that break large aggregates into smaller ones with a sometimes fragile structure. A combination of both types of species regulates soil aggregation and all associated physical properties. In soils with high clay contents and low textural porosity, loss of biodiversity leading to an overwhelming dominance of compacting species, may have negative effects on soil structure (Rose and Wood, 1980).

Table 4. Effect of the treaments with and without earthworms on sorptivity for six continuous crops.

No.	Crop	Without earthworms	With earthworms
		cm $s^{-1/2}$	
	Initial	0.45 (0.2)†	0.45 (0.2)
1	Maize	0.47 (0.4)	0.30 (0.2)
2	Rice	0.65 (0.4)	0.22 (0.1)
3	Cowpea	0.26 (0.1)	0.18 (0.1)
4	Rice	0.26 (0.1)	0.18 (0.1)
5	Rice	0.38 (0.2)	0.23 (0.1)
6	Rice	0.34 (0.1)	0.15 (0.1)

† Values in parentheses are standard deviations.

DISCUSSION AND CONCLUSIONS

There were large differences in soil physical properties between treatments with and without inoculation of the earthworm *Pontoscolex corethrurus*.

Earthworms modified soil macroaggregation, which resulted in increased soil bulk density, decreased total soil porosity and water infiltration, and changes in the soil moisture patterns. Such changes in this type of soil (sandy loam texture) may be beneficial for some crops such as rice during the wet season and for cowpea and maize during the drier periods. However, at the larger time scale of 5–10 yr, a continuing process of soil compaction might result in severe problems. Rose and Wood (1980) have already described soil degradation due to an excessive activity of *Pontoscolex corethrurus*. Ongoing research in Central Amazonian pastures (Chauvel et al., 1996, unpublished data) suggests that, at least in some areas, compaction by *Pontoscolex corethrurus* of Oxisols naturally prone to deficient infiltration may be an important factor responsible for the accelerated degradation of pastures. Not all earthworms have the same effects on plants and soils (Lee, 1985; Lavelle et al., 1988; Deoruard et al., 1995) nor do all plants and soils respond in similar ways to their activities. Therefore it seems convenient to maintain some diversity in soil communities, associating "compacting" species that seem to have the most efficient impact on growth of a wide range of plants, with "decompacting" species (of earthworms or any other large invertebrate with similar effects) that prevent soil compaction.

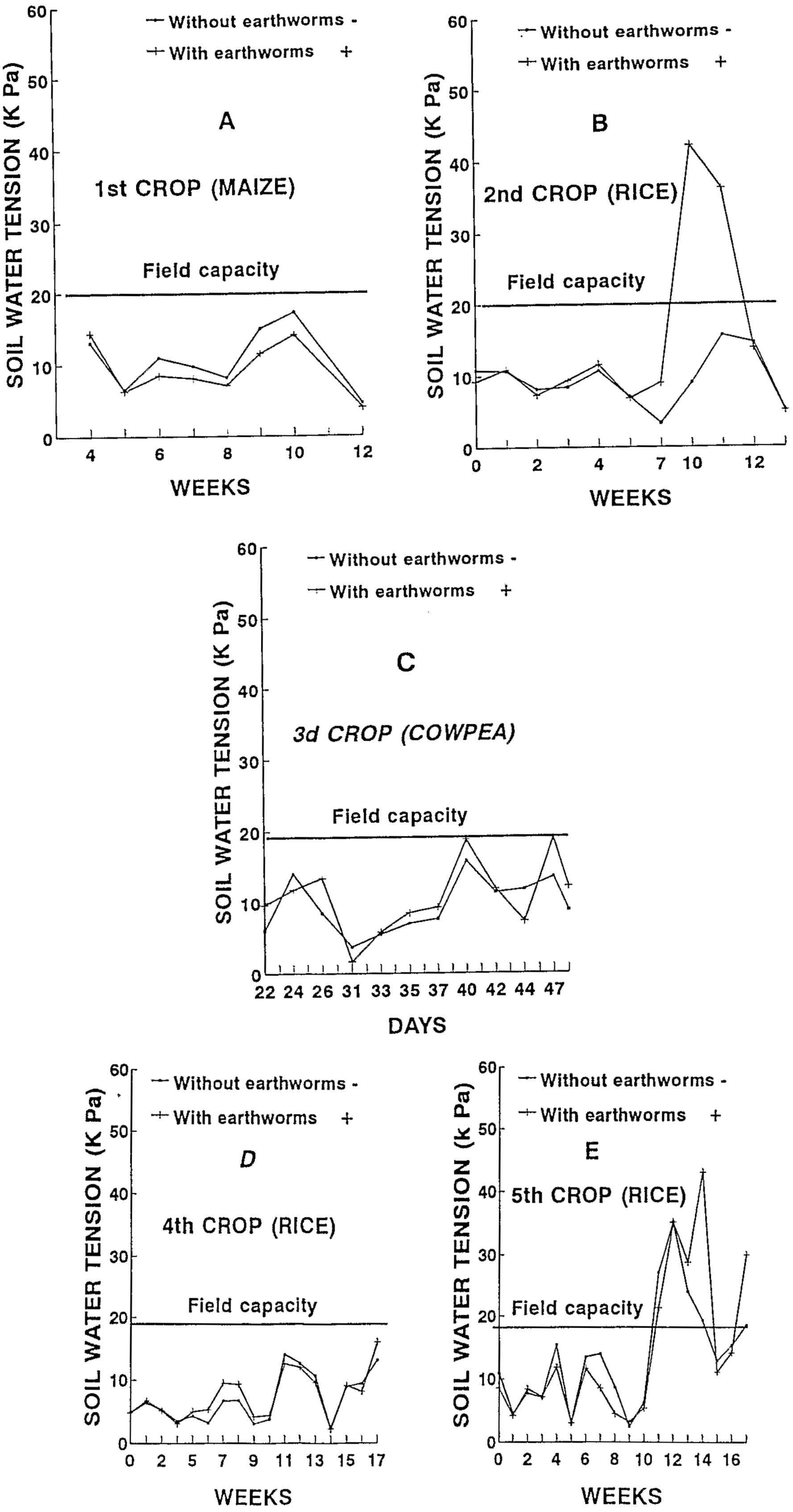

Fig. 7. Changes in soil water tension at 0- to 10-cm depth for crops 1 to 5 (A–E).

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