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EFFECT OF THE ENDOGEIC EARTHWORM *PONTOSCOLEX CORETHRURUS* ON SOIL CHEMICAL CHARACTERISTICS AND PLANT GROWTH IN A LOW-INPUT TROPICAL AGROECOSYSTEM

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Summary—Low densities of *Pontoscolex corethrurus* have been introduced into low-input cropping systems at Yurimaguas (Peru) to test their effects on soil fertility under field conditions for six successive cropping cycles. Earthworm biomass was sustained at 40g m^{-2} fw (ca. 3 g ash-free dry mass) on the average with peak values of 80 g at harvests 2 and 3 in treatments receiving an application of legume green manure. At the 6th harvest, earthworm biomass was significantly lower in the treatment with no organic input than in treatments with crop residues and legume green manure. Earthworm activities did not prevent C and nutrient stocks from being significantly depleted although P, K and Ca concentrations tended to be higher than in non-inoculated treatments at the 6th harvest. Plant production was significantly increased by 36% due to earthworm inoculation in a traditional low-input rotation (maize, rice, cowpea, rice, rice, rice) with variation between − 43 and + 78%, depending on the crop and climatic conditions. In a continuous maize culture that received fertilizers for the last three crops, grain production was increased by 2.45-fold on average, due to earthworm inoculation. These results demonstrate that the maintenance of active earthworm populations was favourable to crop production during the time scale of our experiments (3 y). Longer term experiments are required to test the sustainability of the positive effects observed. Copyright © 1996 Published by Elsevier Science Ltd

INTRODUCTION

In Amazonia, demographic pressure and inefficient agricultural practices are the major causes for accelerated deforestation (Fearnside, 1987). Farmers burn the forest and crop the soil to annual plants once the soil has been fertilized by nutrients from plant biomass that has been mineralised by burning. Such practices produce low crop yields and they are by no means sustainable since soils rapidly loose their organic reserves and physical structure (Brown *et al.*, 1994). As a result, they are abandoned after a few crops and left to fallow for 10–20 years or more before they can be used again. The use of fertilizer and pesticide inputs, improved seeds and mechanisation, may significantly improve the efficiency and economic value of agriculture. Nonetheless, these practices are often limited by socio-economic and ecological drawbacks. In that context, a significant improvement of productivity and sustainability of agriculture is expected from methods that favour and manipulate the biological processes that sustain soil fertility in natural ecosystems (Woomer and Swift, 1994). Special attention is paid to the production and management of organic inputs that allow an efficient use of nutrients released from decomposing residues by plants, and stimulation of faunal activities.

Endogeic earthworms are a major component of soil fauna communities in most natural ecosystems of the humid tropics (Lavelle *et al.*, 1992); they comprise a large proportion of macrofaunal biomass, and in artificial pastures that receive high amounts of rainfall, their biomass may be as high as 1–3 mg fresh mass ha^{-1} (ca. 80–240 kg ash-free dry mass). In most annual crops, earthworm populations are severely depleted since native species from the original forest rarely adapt to the difficult conditions of cropped soils and exotic species that might develop under these conditions are not able to colonise (Lavelle *et al.*, 1994). We have tested the hypothesis that an early introduction of adapted earthworms in low-input agricultural systems would prevent the rapid loss of fertility generally observed in these systems. This effect would result from a regulation of soil organic matter (Martin, 1991), increased rates of release of mineral N and P in synchrony with plant demand (Lavelle *et al.*, 1992; Lopez-Hernandez *et al.*, 1993; Brossard *et al.*, in press), the conservation of soil physical structure (Blanchart, 1992) and a subsequent enhancement of plant production (Spain *et al.*, 1992; Pashanasi *et al.*, 1992). An experiment has been conducted for six successive cropping cycles; the effect of earthworm introduction on a wide range

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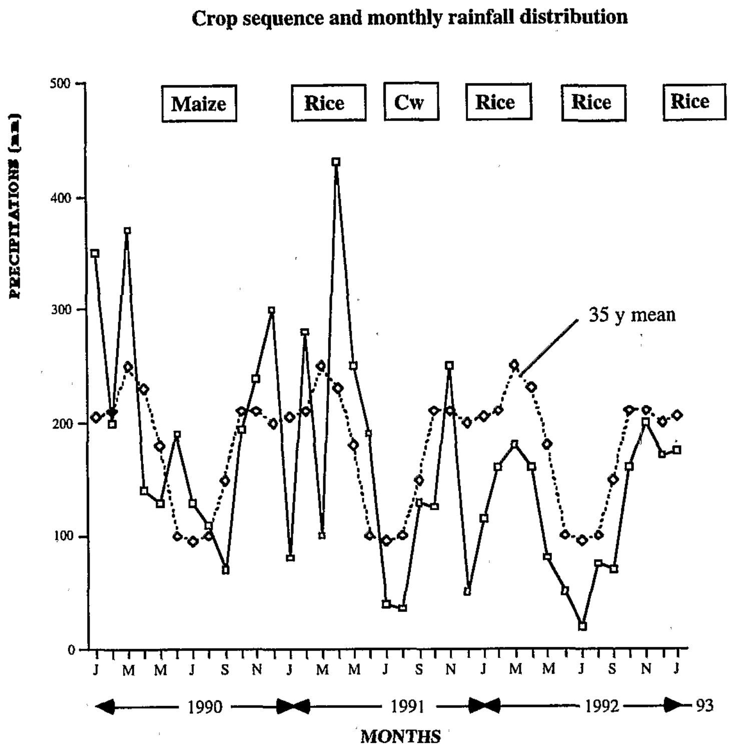

Fig. 1. Distribution of cropping cycles and rainfall pattern during the field experiment.

of factors relevant to soil fertility has been assessed in small experimental units, with three different rates of organic inputs and three different crops in alternation.

MATERIALS AND METHODS

Site characteristics

Experiments were carried out at the Experimental Station 'San Ramon' of Instituto Nacional de Investigaciones Agricolas y Agropecuarias (INIAA) at Yurimaguas, located at 5°56'N, 76°5'W and 184 m elevation. Climate is humid tropical. Mean annual temperature is 26°C with little daily and monthly variation. Rainfall is 2250 mm, with a relatively dry period from June through to August. Soil is an Isohyperthermic typical siliceous Paleudult with a fine sandy loam texture (23% kaolinitic clay, 55% sand and 22% loam). pH is 4.0, aluminum saturation is 94%, and nutrient contents are low, especially assimilable P (0.0029 cmol 100 g^{-1}); K (0.07 cmol 100 g^{-1}) and Mg (0.10 cmol 100 g^{-1}). Soil macrofauna was abundant with an average density of 1719 individuals m^{-2} (SE = 75.8) and a fresh biomass of 30.8 g m^{-2} (SE = 10.9), or ca. 2.5 g ash-free dry weight, in the 20-y secondary forest that was used for the experiments. Earthworms comprised 60% of the biomass whereas termites were dominant in terms of density (42%)(Lavelle and Pashanasi, 1989).

Experimental design

A 0.25 ha plot with slope ranging from 1 to 2% was selected in a 20-y secondary forest and prepared following the traditional slash-and-burn technique (Benites *et al.*, 1987). Burning was done outside of the plot. Ashes were then collected and weighed. A mass equivalent to 1.6 t ha^{-1} was then evenly distributed over the experimental area and watered to facilitate incorporation in soil.

Circular experimental units of undisturbed soil (60 cm dia) were isolated by introducing into the soil plastic net (0.5 mm mesh) down to 45 cm depth. This would prevent undesired movements of earthworms while allowing free movement of water and nutrients. One hundred and eight such units were isolated and regularly distributed on a 30 × 26 m plot. Earthworms from the original forest were successfully eliminated using a 0.9 ml l^{-1} solution of Furadan 4F (Carbofuradan). Two months after this application, pesticide had been eliminated and *Pontoscolex corethrurus*, an exotic species with a wide tolerance for human disturbances and active demography (Lavelle *et al.*, 1987) could be reintroduced. After the third cropping cycle, Furadan was applied to treatments without earthworms since half of the units had been invaded by *Pontoscolex corethrurus* in spite of the nylon net. The worms had probably escaped from the sampled inoculated units. In spite of the low persistance of this pesticide, some secondary effects

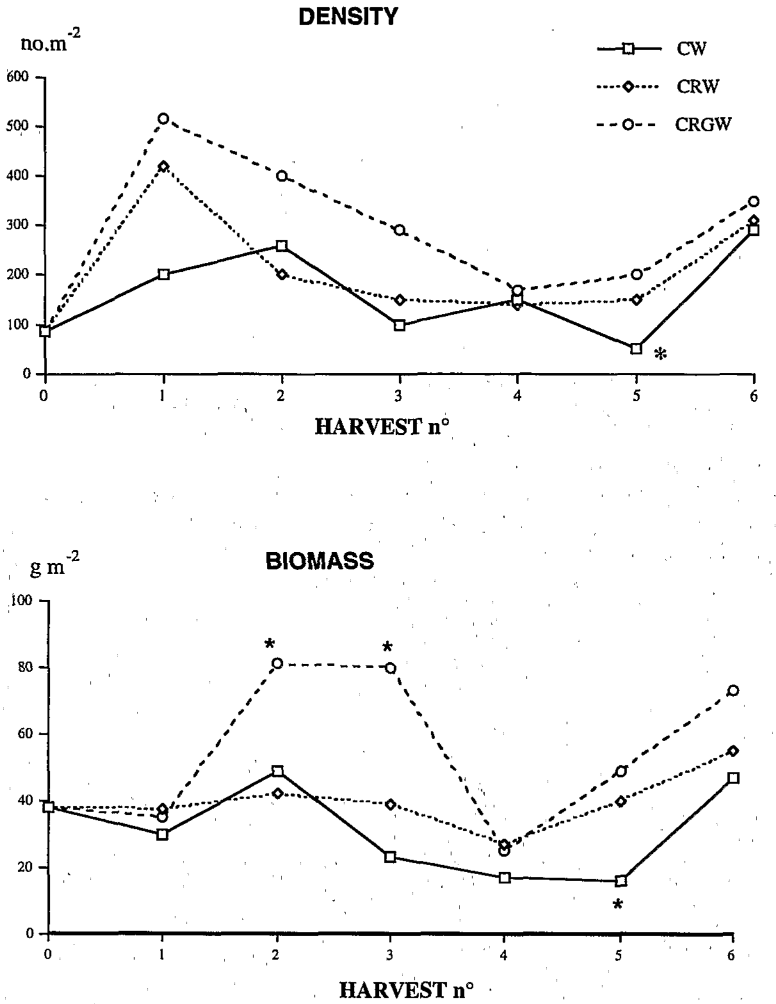

Fig. 2. Changes of density and biomass of populations of *Pontoscolex corethrurus* in three different treatments (CW, control; CRW, surface application of stubble; CRGW; stubble + 2.51 legume green manure).

may have interfered in our treatments after the third cropping cycle. Secondary effects of Furadan reported in the literature include reduction of nematode and bacterial populations (Wright and Coleman, 1988; Parmelee *et al.*, 1990), no influence on protozoa and micro-arthropods (Parmelee *et al.*, 1990) and acceleration of growth of Graminea (Brown, 1978). Some stimulation of plant growth may have occurred in treatments without earthworms.

Inoculated biomass was equivalent to 360 kg fresh weight ha^{-1} (ca. 28 kg ash-free dry weight) in half of the units (labelled W). This biomass is moderate in comparison with figures obtained locally in pastures (800–1200 kg fw ha^{-1}), primary forest (450 kg) or legume fallows (800 kg) (Lavelle and Pashanasi, 1989). Thirty to forty worms (ca. 13g fw) of different size classes, collected manually in an adjacent pasture, were inoculated in the evening of a rainy day in each of the units. They were placed beneath a plastic box driven a few centimeters into the soil, to force them to enter the soil readily. Earthworms that had remained on the soil surface were replaced. During the experiment, no other inoculation took place. The initial population reproduced and probaby died within a few months, being replaced by individuals born inside the experimental units.

Three organic treatments were imposed, i.e. no organic input (C), application of crop residues produced in the unit (CR), application of crop residues plus legume green manure (*Centrosema macrocarpum*)(CRG).

Experimental units were separated into three blocks and six repetitions of each treatment were randomly distributed into each block. They were cropped using a traditional system, with no tillage and respective distances of 40 and 25 cm between rows and plants. Experimental units had two plants each and they were separated from each other by two non-experimental plants. During the three years of the experiment, six crops were done starting with maize, upland rice and cow-pea and ending with three successive crops of rice (Fig. 1).

A small plot that comprised two rows of 6 units surrounded with non-experimental plants was installed on the upper side of block I and allocated to continuous maize production. After the third crop, inorganic fertilizers were applied to sustain the productivity. In this plot, only plant above ground production was measured. Results of the first five crops are reported in this paper.

Measurement of the main variables

At each harvest three units of each treatment were destructively sampled to measure all the variables relevant to soil fertility. Crop yield and above-ground production were measured in all the units. Earthworm density and biomass, and root biomass were measured by handsorting half of the units. Soil chemical variables (C, N and nutrient contents) and microbial biomass (ninhydrin extraction method) were measured on soil taken from a 5 cm wide diametrical section, respectively at 0–10 and 10–20 cm depth. Methods proposed by the TSBF programme were used (Anderson and Ingram, 1993)

Soil physical properties (aggregation, water infiltration, porosity and water tension) were measured in the remaining two quadrants. Results are detailed by Alegre *et al.* (in press). Statistical treatments (ANOVA and LSD tests) were done using the SPSS software for PC.

RESULTS

Earthworm populations

P. corethrurus adapted well to the conditions of the crops. They reproduced actively and no further inoculation was necessary. Density increased sharply from ca. 90 m^{-2} at inoculation to a maximum of 530 m^{-2} at the first harvest, and then fluctuated from 75 (treatment with no organic inputs) to 300–400 m^{-2}

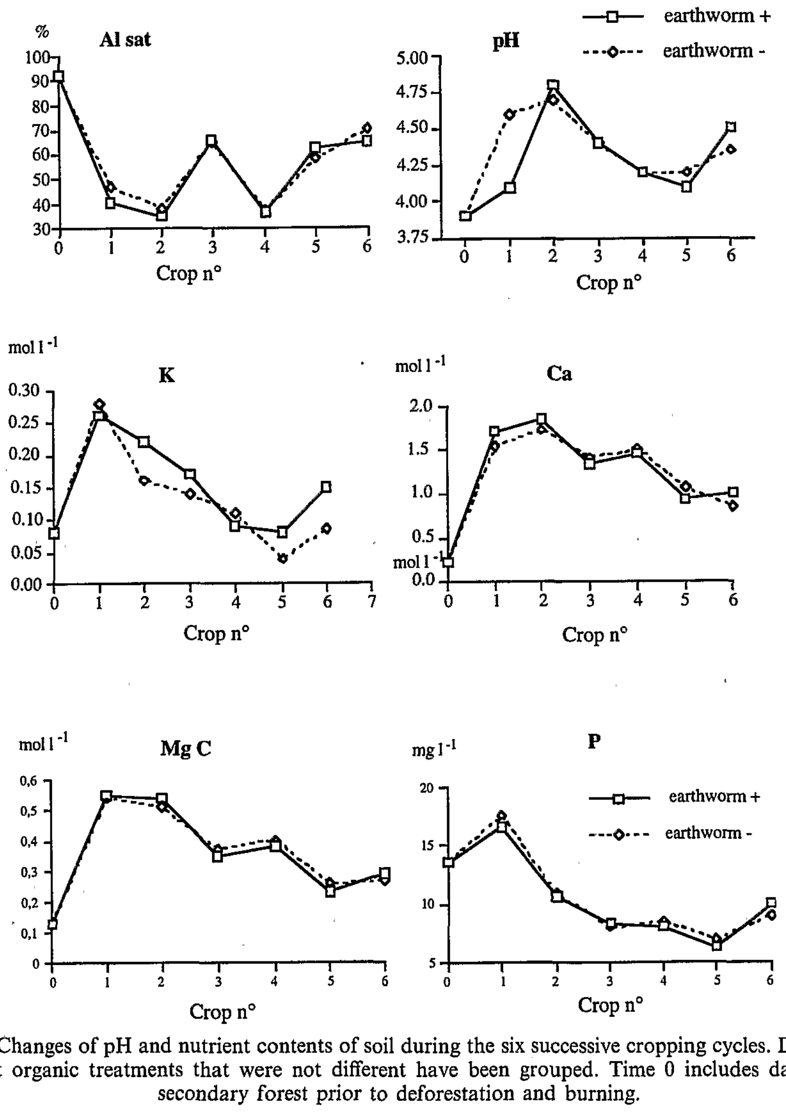

Fig. 3. Changes of pH and nutrient contents of soil during the six successive cropping cycles. Data from different organic treatments that were not different have been grouped. Time 0 includes data in the secondary forest prior to deforestation and burning.

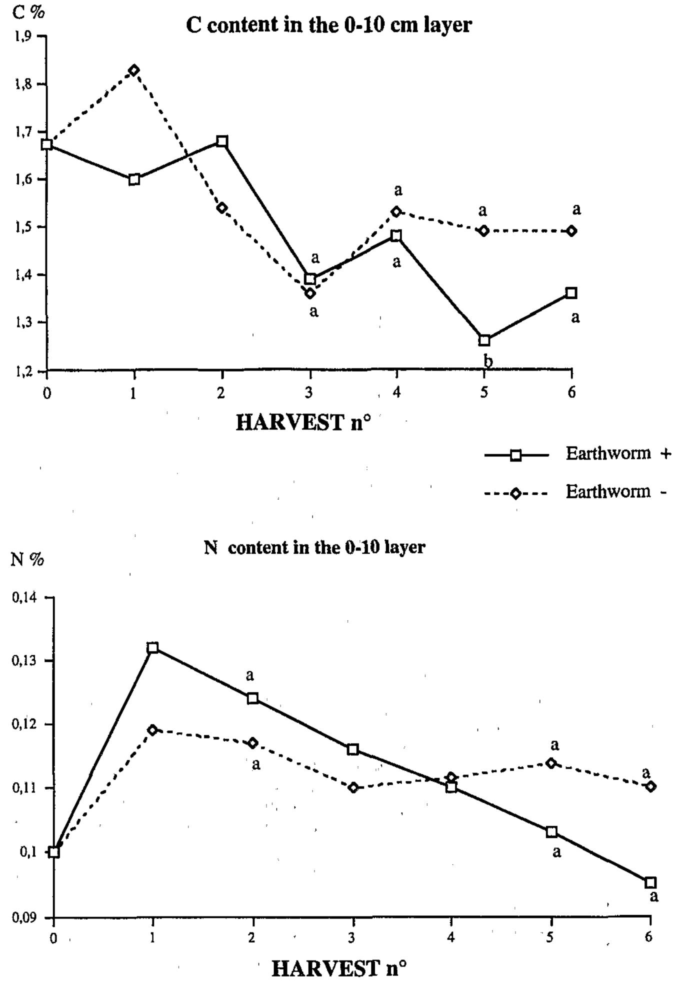

Fig. 4. Changes of total C and N contents of soil during six successive cropping cycles.

(all treatments at harvest 6). Treatment with no organic input tended to have less earthworms, especially at the 5th harvest when the difference was significant (Fig. 2). Biomass was sustained at different weights depending on the organic treatment, with a maximum value of 80 g fresh weight m^{-2} at the 2nd and 3rd harvest and the usual 75 g at the 6th harvest in treatment with full organic inputs, and minimum values of 18 g in treatments with no organic inputs at the 4th and 5th harvests. Fluctuations of biomass seem to be largely influenced by climatic variations although the nature and abundance of organic inputs had some influence.

Nutrients and soil organic matter

Application of ashes at the soil surface resulted in significant increases of pH, nitrogen and nutrient contents and subsequent decreases of acidity and aluminum saturation (Figs 3 and 4). There was no significant effect of the presence of earthworms on fluctuations of these variables. Nonetheless, at the 6th harvest, there was a trend for all nutrient concentrations, except N, to slightly increase in inoculated treatments, although the difference was only significant for K. pH increased to 4.7 at the 2nd harvest as a result of the incorporation of ashes to the soil, and remained higher than in the original forest (pH 4.0) during the six cropping cycles. Aluminum saturation decreased from 88% to 35% at the 2nd harvest and then tended to increase. All nutrients significantly decreased after the 2nd harvest. At the 6th harvest, P content had decreased to values largely inferior to the initial values, contrary to Mg and Ca contents that were still higher than in the original forest and K content that was in the same range.

Earthworm activities did not prevent C and N stocks from being significantly depleted. There was no effect of the organic input. C contents decreased from 1.68% to 1.42% in the treatment with earthworms and 1.56% in treatments without earthworms (Fig. 4). The difference between treatments was only significant at the 5th harvest. N contents tended to be higher in the presence of earthworms during the first three crops and then an opposite pattern was observed that could lead to a significant decrease of N contents in the longer term.

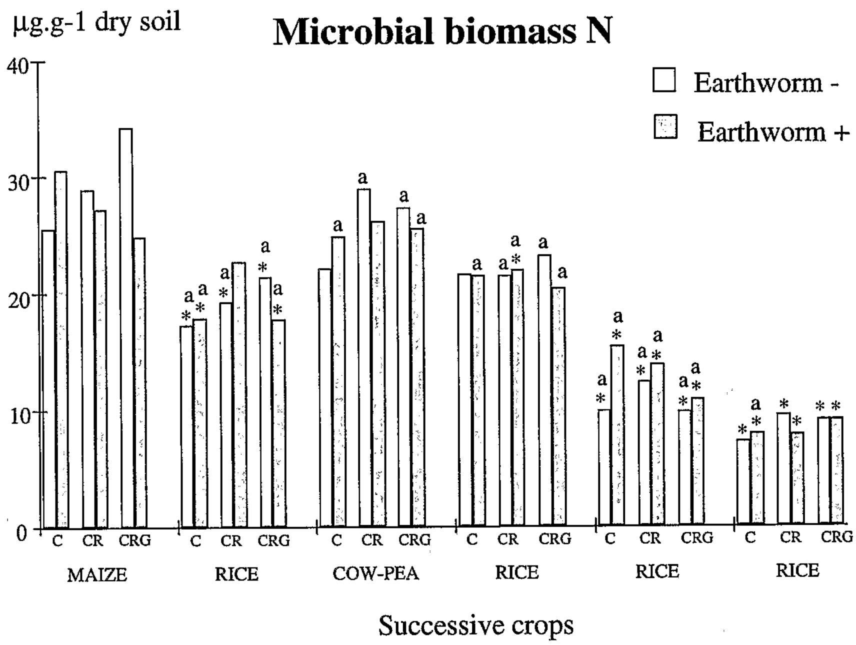

Fig. 5. Changes of microbial biomass N extracted by ninhydrin during the five successive cropping cycles in the 0–10 cm layer. C: control; CR: surface application of stubble; CRG stubble + 2.5 t legume green manure ha^{-1}.

However, N stocks may have changed less than concentrations would indicate since soil had suffered compaction and intense mixing in the presence of earthworms (Alegre *et al.*, 1996): N-concentrations expressed as mg cm^{-3} dry soil, remain greater in inoculated treatments untill the 5th harvest.

Metabolic activity

Microbial biomass decreased sharply during the experiment, except for a transitory increase following the legume cropping (Fig. 5). After the 6th cropping cycle N in microbial biomass had been reduced to ca. one-third of the initial value. There was no significant effect either of the organic treatment or of the presence of earthworms on this variable.

Plant production in the main plot

Plant production was significantly affected by the introduction of earthworms and by the quality and quantity of organic inputs. Increases of grain production due to earthworm activities and application of organic residues were generally greater than corresponding increases of shoot and root production (Tables 1 and 2).

In the main experimental plot, grain production was sustained at relatively high values according to local standards. In treatments with application of legume green manure and earthworm inoculation, the average production was 1.62 t ha^{-1} for five successive crops, i.e. 2.12-fold greater than in the control with no earthworms nor organic application (0.77 t ha^{-1}).

At the first harvest, maize production varied from 1.09 to 2.13 t ha^{-1}. Production increased along with the quantity and quality of organic treatments, and earthworm activities resulted in significant increases of production by 40%, 39% and 32% respectively, in treatments C, CR and CRG. Production of shoots and roots showed similar trends.

During the second cropping period, production of rice was in the range 0.77–1.49 t ha^{-1}. No effect of organic treatments was observed whereas, the effect of earthworm inoculation resulted in respective increases of 2.04, 2.08 and 1.57-fold in treatments C, CR and CRG. This cropping cycle was characterised by the occurrence of heavy rainfalls. Occasional flooding, favourable to rice, was observed in treatments with earthworms since they tended to compact soil in the upper 10 cm and reduce water infiltration (Alegre *et al.*, 1996). Contrary to the first two crops, the third crop, cow-pea, did not respond positively to the inoculation of earthworms. Crop yield varied from 0.84 to 1.22 t ha^{-1} and highest values were observed in treatments with application of crop residues and legume green manure as opposed to the other two organic treatments. At the 4th harvest, yields of upland rice were in the range 0.73–2.00 t ha^{-1}. There was a significant positive

Table 1. Production of grain, shoots and roots (dry mass t ha^{-1}) for six crops, with or without earthworm inoculation

	C	CW	CR	CRW	CRG	CRGW
1st crop MAIZE						
grains	1.09	1.53	1.22	1.70	1.62	2.13
stalks	1.89	2.55	2.05	2.52	2.64	3.12
roots	0.20	0.40	0.22	0.44	0.33	0.34
2nd crop RICE						
grains	0.77	1.57	0.78	1.62	0.95	1.49
stalks	1.28	2.09	1.31	2.13	1.80	2.71
roots	0.29	0.29	0.16	0.54	0.37	0.47
3rd crop COW-PEA						
grains	0.84	0.85	0.91	0.78	1.24	1.22
stalks	1.23	1.28	1.52	1.16	1.86	1.69
roots	0.05	0.04	0.07	0.05	0.04	0.04
4th crop RICE						
grains	0.73	1.12	1.02	1.53	1.39	2.00
stalks	1.56	2.35	2.32	2.71	2.60	3.14
roots	0.28	0.33	0.37	0.50	0.47	0.53
5th crop RICE						
grains	0.86	0.71	1.16	0.66	1.59	0.95
stalks	1.39	1.09	1.88	0.98	1.92	1.23
roots	0.32	0.16	0.29	0.15	0.25	0.28
6th crop RICE						
grains	0.30	0.94	1.10	1.21	1.70	1.95
stalks	0.98	1.82	2.64	2.82	3.22	4.08
roots	0.22	0.45	0.39	0.54	0.77	0.89

Table 2. Treatments with similar letters in a series are not significantly different ($P = 0.05$)(C : no surface mulch, no worms; CW : no surface mulch, worms; CR : application of crop residues, no worms; CRW : same with worms; CRG : crop residues + legume green manure (2.5 t ha^{-1}), no worms; CRGW : same with worms)

		Effect of organic treatments			Effect of earthworm inoculation	
		C	CR	CRG	+	–
1st crop MAIZE	grains	a	ab	b	a	b
	stalks	a	a	b	a	b
	roots	a	a	a	a	a
2nd crop RICE	grains	a	a	a	a	b
	stalks	a	a	b	a	b
	roots	a	a	a	a	b
3rd crop COWPEA	grains	a	a	b	a	b
	stalks	a	a	b	a	b
	roots	a	a	a	a	a
4th crop RICE	grains	a	b	c	a	b
	stalks	a	ab	b	a	b
	roots	a	ab	b	a	a
5th crop RICE	grains	a	a	b	a	b
	stalks	a	ab	b	a	b
	roots	a	a	a	a	b
6th crop RICE	grains	a	b	c	a	b
	stalks	a	b	c	a	b
	roots	b	b	ab	a	b

effect of organic inputs on production. Earthworm activities also had significant effects on production of roots, shoots and grains with respective increases of 1.53-, 1.50- and 1.44-fold of grain production in treatments C, CR and CRG.

During the 5th cropping period, rice was cropped out of season and grain yield varied from 0.86 to 1.61 t ha^{-1}. Treatments with crop residues and legume green manure were significantly more productive than treatments with no organic inputs. Furthermore, earthworms had significant negative effects with respective decreases of 17.4%, 59.0% and 40.3% in treatments C, CR and CRG. There was a marked shortage of rainfall at the end of the cropping cycle, earthworm activities increased rates of soil drying probably through changes in the soil porosity (Alegre *et al.*, 1996). At the 6th harvest, crop yield was again positively influenced by organic inputs and earthworm activities. Grain production was extremely low in the control treatment with no organic inputs or earthworm activities (0.30 t ha^{-1}) and maximum in the CRGW treatment with earthworms, crop residues and green manure (1.55 t ha^{-1}). Earthworm activities resulted in respective increases of 3.1-, 1.1- and 1.5-fold in C, CR and CRG treatments.

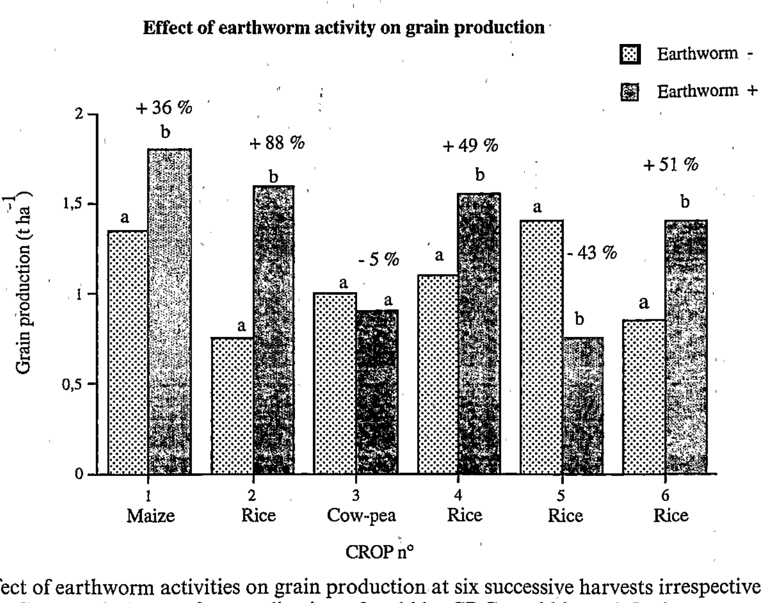

Fig. 6. Effect of earthworm activities on grain production at six successive harvests irrespective of organic treatments. C: control; CR: surface application of stubble; CRG: stubble + 2.5 t legume green manure ha^{-1}.

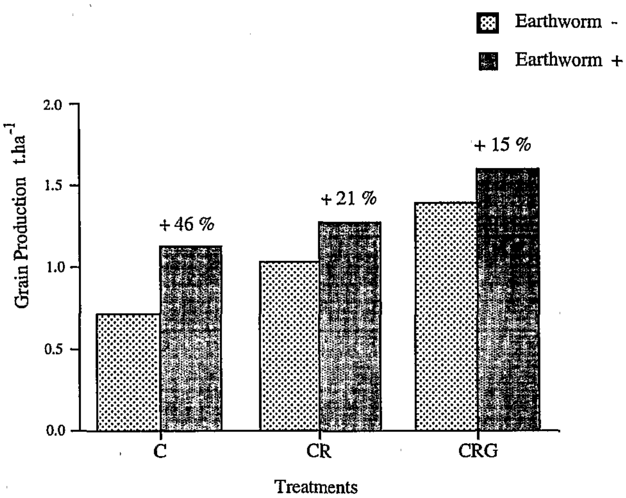

Fig. 7. Effect of organic treatments and earthworm inoculation in different treatments for six successive cropping cycles. C: no mulch; CR: surface application of stubble produced on the experimental unit; CRG: stubble + 2.5 t dry weight legume green manure ha^{-1}.

Earthworm inoculation thus had significant positive effects on grain production at crops 1 (maize, + 41% on average), 2 (rice, + 78% on average) 4 (rice, + 50%) and 6 (rice, + 51%); there was no effect at crop 3 (cow-pea, − 3% non significant) and a negative effect at crop 5 (rice, − 43%) (Fig. 6). Growth was also faster in the presence of earthworms and complete maturity was often attained 2 weeks earlier in the inoculated treatments.

The effect of earthworms was significantly different depending on the organic treatment: the average increase of grain production was respectively 46% in the control, 21% in CRG (stubble + legume green manure) treatments and 15% only in the CR (stubble) treatment (Fig. 7). These results show that complex interactions between the quality and quantity of organic residues and earthworm activities may eventually result in different effects on plant growth.

As expected, organic treatments alone also had

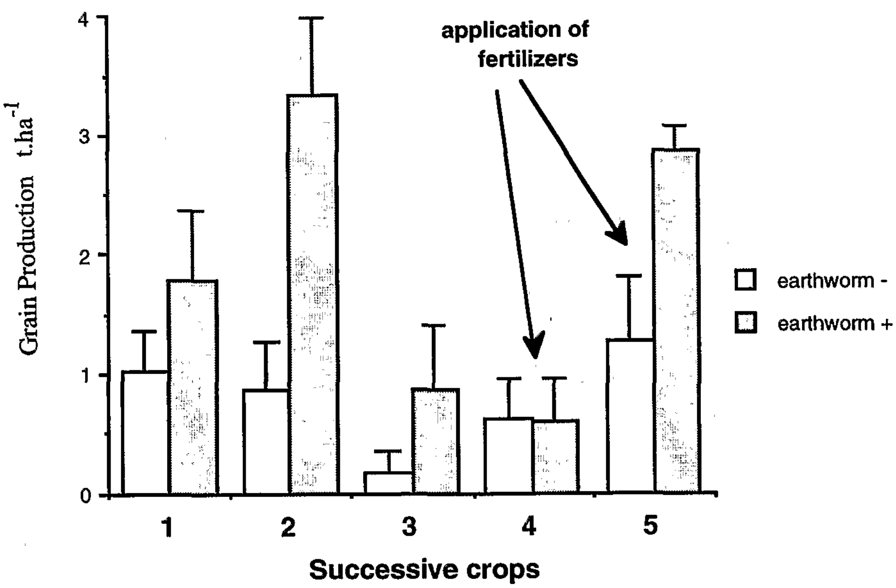

Fig. 8. Effect of earthworm activities on grain production at five successive harvests in a continuous maize crop with application of stubble mulch produced in the unit, and fertilizers after the third harvest. (Bars indicate S.E.)

significant effects on plant growth with respective average increases of 26 and 62% of grain production in treatments receiving stubble or stubble + legume green manure as compared to the control situation (Tables 1 and 2).

Grain production in the continuous maize plot

In the small plot allocated to continuous maize cropping, the effect of earthworms on shoot and grain production was greater than in the traditional rotation (Fig. 8). The increase of grain production due to earthworm activities was 2.45-fold on average and, at the second cropping period, production in inoculated treatments was 3.3 t i.e. 4 times the amount of production in non-inoculated treatments. At the third crop, production had declined in all treatments; although earthworm activities had not impeded this decline, production in inoculated treatments had been sustained at a much higher level than in non-inoculated treatment. When fertilizers were applied, there was a better response of the system especially at the 5th crop where grain production was 1.2 t ha^{-1} in the absence and 2.8 t ha^{-1} in the presence of earthworms.

DISCUSSION

At Yurimaguas, inoculation of earthworms had significant effects on soil properties and plant production. Although the depletion of soil organic and nutrient reserves were not impeded, the physical structure of soil was greatly modified. Earthworms increased the proportion of macroaggregates in soil whereas, in their absence, the general trend was disaggregation (Alegre *et al.*, 1996). Unexpectedly, this increased macroaggregation resulted in increased bulk density; nonetheless, the increase, although significant, was not greater than 10%. In the presence of earthworms, infiltration rates were lower during the first four cropping cycles; at the 5th harvest, there was no difference since the earthworm had probably opened macropores at the soil surface in response to compaction (Lavelle, 1988).

Plant production was significantly enhanced although this positive effect varied depending on rainfall, plants and organic inputs. Maize seemed to respond better than rice to earthworm effects with respective changes of grain production from 0.95- to 4.50-fold (2.48-fold on the average) and 0.57- to 1.78-fold (1.28-fold on the average) for rice; cowpea did not respond at all. Such variations of the response of plants to earthworm activities had already been observed with tree seedlings at Yurimaguas (Pashanasi *et al.*, 1992), peanuts (*Arachis hypogea*), maize (*Zea mais*), grass (*Panicum maximum*) and rice (*Oryza sativa*) at Lamto (Côte d'Ivoire)(Spain *et al.*, 1992; Derouard *et al.*, 1996). In these situations, legumes and a palm-tree (*Bactris gasipaes*) were not responsive to earthworm activities, whereas production of *Panicum maximum* and maize was greatly increased. The effect of earthworms was greater when no organic residues, or a mixture of organic residues and legume green manure were applied (+46% grain production on the average in the traditional rotation) than when stubble only was applied (+13%).

CONCLUSION

We draw three major conclusions from these experiments:

1. A low input cropping system that associates incorporation of stubble + legume green manure as surface mulches and the inoculation by *Pontoscolex corethrurus* may sustain high productions by local standards for longer periods than the traditional system with no earthworms and no specific organic application.
2. Earthworm activities did not impede the decline of soil organic matter and nutrient contents during the time of our experiments (3 years). Nonetheless, at the end of our experiment, production was still acceptable by local standards. N and C soil contents were lower after 3 years in earthworm treatments although differences were not significant, especially when concentrations were transformed into stocks by taking in account changes to soil bulk density. Longer-term experiments are necessary to determine the effect of the observed modifications of soil aggregation, soil water regime and plant production on the composition and dynamics of soil organic matter. There is at least one reported case of soil degradation caused by excessive activity of *Pontoscolex corethrurus* for several years in a clayey soil cropped to sweet potato (Rose and Wood, 1980).
3. When fertilizers were applied to the maize plot, there was still a significant response to the presence of earthworms in the plot. This indicates that modifications of the soil physical structure by earthworm activities may, at least partly, explain the effect of earthworms on plant production, irrespective of their effects on nutrient cycling. Another hypothesis may be that under conditions of enhanced plant production following the application of fertilizers more organic resources were available to earthworms and their activity was favoured.

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