In-soil Earthworm Technologies for Tropical Agroecosystems

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Summary

Collaborative research in the Macrofauna project has enabled development of some techniques that presently are at different stages of advancement, from promising pilot experiments (tomato production and inoculation in plant nursery bags at Yurimaguas and in India) to the fully developed technique of massive worm production and biofertilization of tea gardens in Tamil Nadu (India) (patent deposited). Failures have also helped to gain better insight into the potential and feasibility of techniques that had been considered in the objectives of this project.

Endogeic earthworms (*Pontoscolex corethrurus*) may be produced in large quantities, i.e. about 12,000 worms (1.6–2.8 kg live wt) m^{-2} $year^{-1}$ in specific culture beds using either sawdust (Yurimaguas, Peru) or a mixture of high and low quality materials (Tamil Nadu, India) mixed into the soil as substrates. Cost of production of 1 kg of earthworm biomass through bed culture is about

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3.6 Euro, much lower than the cost of hand collection of worms from pastures/grasslands where these species are abundant (6–125 Euro depending on the cost of labour and earthworm density).

The theoretical value of an active earthworm community with an average biomass of 400 kg live wt has been estimated at 1400 Euro, the price that it would cost to reintroduce an equivalent biomass produced in our culture units, indicating the cost of land restoration.

Direct inoculation of earthworms in the field to improve production may only affect plant growth positively if a large biomass (> 30 g live wt m^{-2}) is inoculated from the beginning. An alternative may be to concentrate the inoculum in small areas regularly distributed across the field.

Due to the high price of earthworm production and inoculation, technologies that involve inoculation should only be applied to high value crops; examples tested in our project are: (i) tree seedling nurseries in Peru and India; (ii) tomato production in Peru; and (iii) tea gardens in India.

In most systems, techniques that maintain locally available earthworm communities should be considered. Experiments at Carimagua (Colombia) showed that: (i) the juxtaposition of plots under different crops with contrasting effects on earthworms did not seem to allow colonization of unfavourable sites from the favourable ones; (ii) some native species may survive, especially if tillage is done early in the rainy seasons when populations are in diapause deep in the soil out of reach of the plough; (iii) reconstitution of populations in a plot that has been replanted to a crop that is favourable to earthworms (e.g. an improved pasture at Carimagua) may be significant after a few years (2–4).

Recolonization patterns have been studied particularly at the SECI station of St Anne (Martinique) in a pasture planted on a degraded Vertisol. Recolonization originated from a few individuals that managed to adapt to conditions of the degraded soil by a combination of genetic selection, concentration in better suitable micro-environments and better growth and reproduction efficiencies. Massive reintroduction of earthworms significantly accelerated the establishment of populations, which otherwise were rather slow to develop in this system. There was no evidence that earthworm activities would accelerate the reconstitution of organic stocks. The only visible effect after 3 years was a difference in the vertical distribution of soil organic matter (SOM) with depth in the presence of earthworms.

Of the three techniques that have been developed successfully, two are promising, although further research is still needed before they can be widely used. They are: (i) inoculation of worms in nursery pots enhanced the growth of three out of the four species that were tested, and mycorrhizal infections were improved. Further experiments are needed to test for further survival and growth of these trees when planted in the field; (ii) tomatoes and other market gardening products were produced at Yurimaguas, Peru on a mixture of soil and sawdust. Supplementation of this substrate with essential nutrients (phosphorus and, to a lesser extent, nitrogen contained in chicken manure slurry) and improved disease control should increase production to satisfactory levels.

A great advantage of this technique is that it makes use of sawdust, a by-product of the timber industry that accumulates in suburban areas and may create environmental problems.

A third technique has been developed fully in India, in association with Parry Agro Industries Ltd, to stimulate growth of tea plants and enhance soil quality. This technique uses a combination of mechanical intervention (digging trenches in contour lines), input of organic matter of different qualities in a specific spatiotemporal design and the inoculation of earthworms produced locally using a special technology. Enhancement of production was 79.5–276%, and profit was increased in similar proportions, while soil quality was restored by large organic inputs and earthworm activities. This technique and the associated system for massive production of earthworms has been protected by a patent 'Fertilisation Bio-organique dans les Plantations Arborées' deposited in Sri Lanka (4/9/96 at Colombo, Ref. No. 11034) and internationally (ref. PCT/FR 97/01363). This technique has been extended currently to about 200 ha located at different sites of Parry Agro's plantations.

Introduction

Earthworms are a resource that may be used in agriculture because their effects on nutrient dynamics and the physical structure of soil may significantly enhance plant growth and conserve soil quality [see Chapters 1–6), reviewed by Lee (1985), and, more recently, by Lavelle *et al.* (1998)]. It has, therefore, been hypothesized that management options that stimulate the activities of these organisms could promote sustainable production in tropical agroecosystems (Swift, 1987; Myers *et al.*, 1994). Results from previous chapters suggest that the success of techniques of earthworm management may depend upon the choice of suitable species, the provision of adequate organic supplies to feed the worms and the maintenance of a minimum diversity in whole invertebrate communities. All these biological resources, therefore, need to be managed at the same time.

In the humid tropics, 'in-soil' technologies that incorporate organic residues into the soil to stimulate the activities of local or inoculated populations of soil-dwelling earthworms should be preferred in most cases to 'off-soil' techniques (vermicomposting) that simply use earthworms to prepare compost (Fig. 7.1). Vermicomposting of residues allows the quick transformation of fresh residues into a compost that can be used readily in the field (see Chapter 9). However, a large amount of C is lost that might have been used to sustain mechanical activities of earthworms and other invertebrates in the soil. Endogeic earthworms indeed participate in the humification of organic matter, but they also contribute to macro-aggregation of soil particles, maintenance of macroporosity and the intimate mixing of organic compounds, with expected effects on long-term sustainability of soil fertility (Blanchart *et al.*,

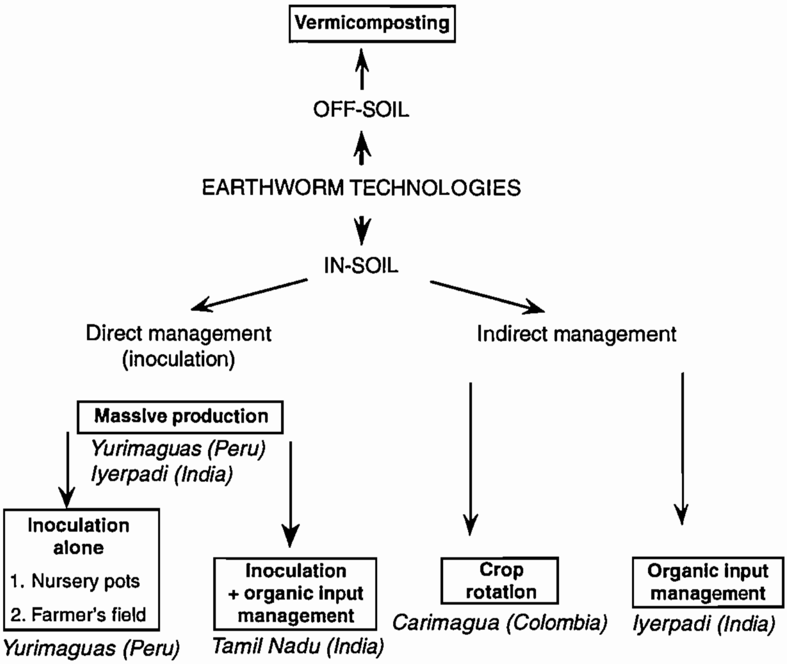

Fig. 7.1. Management alternatives for earthworm technology.

1997). Vermicomposting should only be recommended when either the quality, the amount or the location of organic residues make them unsuitable for local use in agriculture. In such conditions, vermicomposting generally produces a better compost with higher C and N contents and lower concentrations of aromatic C than a compost produced without worms (Vinceslas, 1998; Aranda *et al.*, Chapter 9).

In-soil technologies are based on the use of endogeic and anecic earthworms that significantly influence soil physical properties (see Chapter 5) and regulate the dynamics of soil organic matter on different scales of time and space (Chapter 6). These technologies manipulate earthworm communities, either directly through the massive inoculation of suitable populations, or indirectly by promoting suitable conditions for the activity of already existing populations through the manipulation of plant communities and/or organic inputs. Optimal levels of biomass to enhance soil fertility and crop yield significantly must be established through these technologies.

Different techniques have been developed in this project. They include the intensive production of the endogeic earthworm *Pontoscolex corethrurus* on different substrates to allow large-scale inoculations, enhancement of growth of tree seedlings in nursery pots and a new market gardening technique based on the joint use of earthworms and sawdust at Yurimaguas, Peru. Intensive production of endogeic and anecic earthworms in vermiculture units, growth stimulation of tea seedlings in nursery bags and biofertilization of tea plantations using diverse organic materials have been developed in Tamil Nadu (India). Indirect management techniques have been also investigated at St Anne (Martinique) and Carimagua (Colombia).

Earthworm Collection

In-soil technologies require mostly endogeic, endo-anecic to anecic earthworms with specific ecological characteristics (Chapter 3). These types of earthworms are not available commercially. Therefore, they can be collected from the field, which is labour intensive and may damage the natural system, or produced in intensive cultures made close to the inoculated fields or experimental units.

Costs of earthworm collection from natural environments has been calculated at St Anne (Martinique, French West Indies), Yurimaguas (Amazonia, Peru) and Pandalur (Tamil Nadu, India) (Table 7.1). Due to the high costs of labour at St Anne, the price for collecting 1 kg of fresh mass of the endogeic earthworm *Polypheretima elongata* was 125 Euro. This actually is a prohibitive price considering that a minimum inoculation of 300–400 kg of fresh biomass is necessary to produce significant effects on plant growth (Brown *et al.*, Chapter 4); intensive cultures are to be preferred.

Table 7.1. Cost of earthworm collection from natural environments at three sites.

	St Anne (Martinique)	Yurimaguas (Peru)	Pandalur (India)
Time to collect 1 kg of earthworms from the field (in days)*	2.25	4.2	4.5
Average weight (g live wt worm^{-1})	1.5**	0.5***	0.45***
Age classes	Mixed	Adults	Adults + late immatures
Cost of daily wage labourer (in Euro)	56	4.3	1.4
Cost of 1 kg of live earthworms (in Euro)	125	18	6.2

*Eight hours work, day^{-1}; ***Polypheretima elongata;* *** *Pontoscolex corethrurus.*

Earthworm Culture

The proportion of soil used in endogeic and anecic earthworm cultures is more than 50% of the substrate (Senapati, 1994). The most commonly used earthworms so far have been the endogeics *P. corethrurus* and *P. elongata*. Details regarding the biology and ecological strategies of these worms are given in Fragoso *et al.* (Chapters 1 and 2) and Barois *et al.* (Chapter 3). Small- and large-scale earthworm culture technologies have been developed in Yurimaguas (Peru) and Tamil Nadu (India) to provide the earthworms necessary for inoculation.

Culture of *P. corethrurus* at Yurimaguas (Peru) in the greenhouse

Pashanasi *et al.* (1992a) observed fast growth of *P. corethrurus* in the mixture of soil and sawdust used to grow seedlings of tropical fruit trees. This experiment indicated that the composted sawdust, a waste of the timber industry, might be used in the context of low-input agriculture as a food resource to produce large quantities of earthworms, and possibly sustain their activity in otherwise unsuitable soils (i.e. with C% = 1.5; N% = 0.11; Al saturation = 70%). Experiments have been done first in the laboratory to identify relative proportions of soil and sawdust that would optimize earthworm growth and reproduction. The following treatments were applied to identify the most efficient mixture:

- control soil;
- 75% soil; 25% sawdust by volume;
- 50 : 50 mixture;
- 100% sawdust;
- 25% soil; 75% sawdust;
- 75% soil; 25% sawdust + 20 p.p.m. inorganic P;
- 75% soil; 25% sawdust + 40 p.p.m. inorganic P;
- 75% soil; 25% sawdust + 60 p.p.m. inorganic P.

Inorganic P was added to some treatments to prevent phosphorus deficiency, a problem that may occur in earthworm cultures. Soil was taken from the upper 10 cm of a 20 year secondary forest. Sawdust was taken from a large pile outside the main sawmill at Yurimaguas. The residue had been deposited outside for at least 1 year and its dark colour revealed an advanced stage of composting. Sawdust is relatively rich in Ca, K and Mg, but is highly deficient in P and N.

Results indicated that *P. corethrurus* may grow and reproduce well in a mixture of soil and sawdust. Earthworms matured between 16 weeks (3 : 1 soil/sawdust) and 25 weeks (all other treatments except for pure sawdust and the 3 : 1 mixture with 60 p.p.m. P where the adult stage was never reached).

Maximum weights were observed in the 3 : 1 mixture with 40 p.p.m. P after 75 weeks. Minimum growth occurred in pure sawdust. Relatively high proportions of sawdust (1 : 1 mixture) seemed to be favourable to reproduction (206 cocoons produced within 75 weeks using an initial inoculum of 15 worms). The maximum mortality of worms (93.3%) occurred in pure sawdust, whereas the minimum of 27% mortality occurred in the 3 : 1 mixture with 60 p.p.m. P in 75 weeks. A 1 : 1 mixture by volume of soil and sawdust appeared to provide a low mortality (33.3% in 75 weeks), high cocoon production (206) and rapid growth (1204 mg on average at week 75). Addition of inorganic P improved the performance of earthworms, although differences were not significant.

On the basis of the above laboratory experiments, two types of earthworm cultures have been developed at Yurimaguas, i.e. (i) a small-scale nursery culture in wooden frames; and (ii) a large-scale culture in field bed culture.

Small-scale wooden frame earthworm culture technology developed at Yurimaguas (Peru)

Wooden frames 50 cm in length, 50 cm in width and 20 cm in height, closed at the bottom with a mosquito net wire mesh, have been used for laboratory cultures. Soil was taken from the upper 10 cm of a pasture soil. Sawdust was brought from a sawmill in the city of Yurimaguas where two species (i.e. the Melicaceae *Cedrela odorata* and *Swietenia macrophyla*) comprise most of the timber and boards that are produced. Soil and sawdust mixtures of 1 : 3, 1 : 1 and 3 : 1 have been tried. All the mixtures of soil and sawdust improved the growth of *P. corethrurus*, and the best result was obtained with a 3 : 1 soil : sawdust mixture. A moisture content of 36% equivalent to water content at field capacity was maintained in all sets. The wooden frames were kept in a cool and shady area. Forty earthworms weighing 20 g were introduced into each unit. The population reproduced rapidly and, after 1 month, more than 200 cocoons had been deposited (Fig. 7.2). One month later, an average population of 514.5 earthworms weighing 67.2 g fresh was found, which represents respective multiplication rates of 13.0 and 3.4 for numbers and biomass. Most individuals, however, were still immature and of a relatively small size (Table 7.2).

Large-scale bed earthworm culture technology developed at Yurimaguas (Peru)

To produce earthworms on a large scale, culture beds of 5 m × 1 m × 20 cm were installed in the field (Fig. 7.3) and filled with a 3 : 1 mixture of soil and partly composted sawdust, as was done for the wooden frame cultures. The beds were surrounded with nylon net to prevent escape of earthworms. No

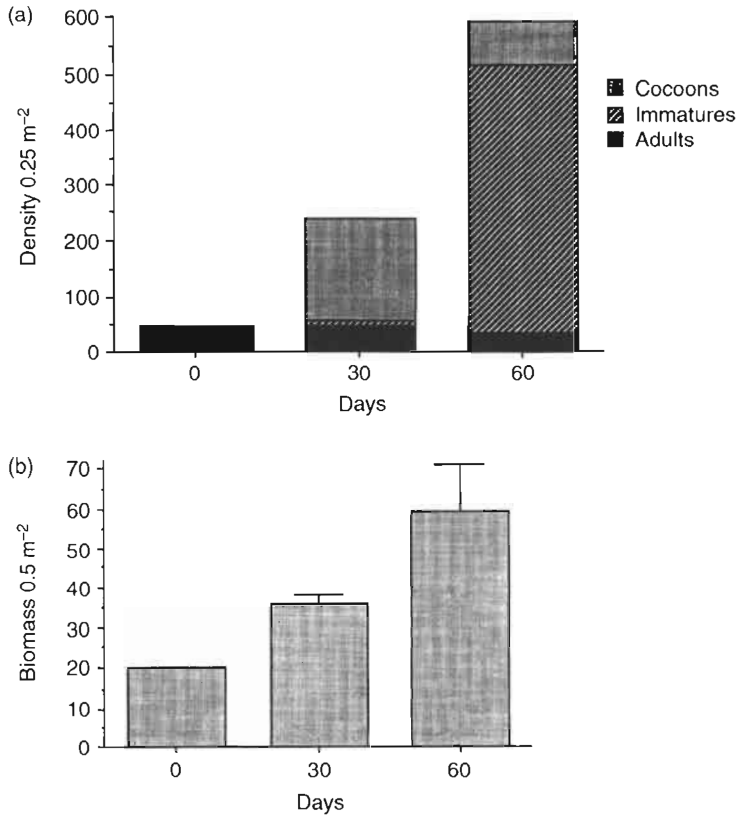

Fig. 7.2. Production of *Pontoscolex corethrurus* in wooden frames 50 × 50 × 15 cm in a 3 : 1 mixture of soil and sawdust (average of two replicates for each date). (a) Worm density; (b) production rate (estimated at 12,400 individuals (1.6 kg) m^{-2} $year^{-1}$ and cost estimated as 7.8 Euro kg^{-1}; Table 7.1).

significant difference was observed between the sets with and without a net, indicating that when conditions are suitable earthworms do not tend to migrate. Initially, 20 *P. corethrurus* m^{-2} were inoculated in the bed culture. Another inoculation of 20 individuals m^{-2} was made after 40 days when it became evident that the initial inoculation was not sufficient (Fig. 7.4) (Pashanasi *et al.*, 1994). Thus, a total of 200 adult *P. corethrurus* weighing about 100 g live wt was later inoculated into all new units (Table 7.2). The cultures were maintained for 120 days. A total of 3355 worms weighing about 839 g live wt was harvested from each culture unit. Most earthworms were immature and still rather small.

Table 7.2. Technologies for production of soil-dwelling earthworms at Yurimaguas (Peru), and Carolyn and Sheikalmudi at Tamil Nadu (India).

	Yurimaguas (Peru)		Tamil Nadu (India)
	Wooden frames	Wooden log-lined bed	Vermiculture beds
Earthworm species	*Pontoscolex corethrurus*	*Pontoscolex corethrurus*	80% *P. corethrurus*, 20% *A. corticis* + native anecics
Size of units	50 cm × 50 cm × 20 cm	5 m × 1 m × 20 cm	6 m × 0.9 m × 55 cm
No. and biomass (g fresh mass) of adults inoculated	*40* 20	*200* 100	*1000* 450
Culture time (months)	2	4	3
Worm harvest per unit (*n* and g fresh mass)	*514. 5* 67. 2	*3355* 839	*15,000* 3750
Annual production (m^{-2}) *n* and kg fresh mass	*12,400* 1.6	*2000* 0.5	*11,100* 2. 8

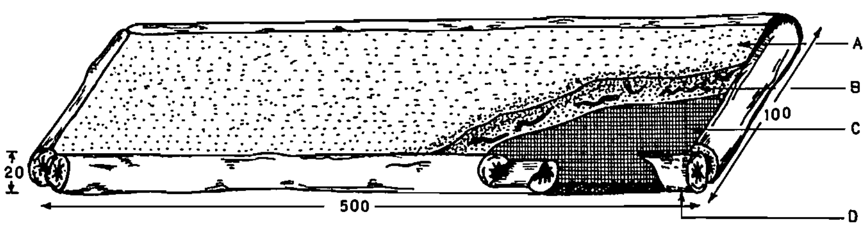

Fig. 7.3. A field unit for massive production of *Pontoscolex corethrurus* at Yurimaguas (Peru) . A, Soil and sawdust mixture (3 : 1 ratio); B, earthworm; C, mosquito net; D, wooden log. Dimensions are in centimetres.

Large-scale earthworm bed culture technology developed at Carolyn and Sheikalmudi (Tamil Nadu State, India)

Large-scale bed cultures have been developed close to field sites. Individual vermiculture units 6 m × 0.9 m × 55 cm depth were grouped into larger units of 26 beds at Carolyn and 20 beds at Sheikalmudi site of Tamil Nadu. Each bed was surrounded by a 2 foot pathway to allow access, and was surrounded by a side drain which ultimately led to the main drain to release excess water, especially in the monsoon period. The boundary of the vermiculture site was surrounded by shade trees. The culture site was covered by a galvanized wire frame supported by stone pillars. A layer of old sack cover/live creeper plant was provided to protect the cultures from high intensity solar radiation and rainfall (Fig. 7.5). Details of organic matter and the soil layout plan for preparation of the vermiculture bed and their justification have been given in the patent paper.

Soil moisture was maintained close to field capacity (15–20%) and soil temperature varied between 22 and 25°C at 30 cm of soil depth in the

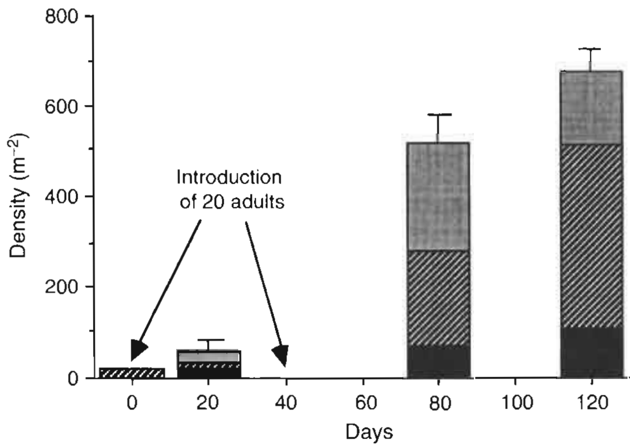

Fig. 7.4. Production of *Pontoscolex corethrurus* in a large-scale field culture in Yurimaguas (Peru).

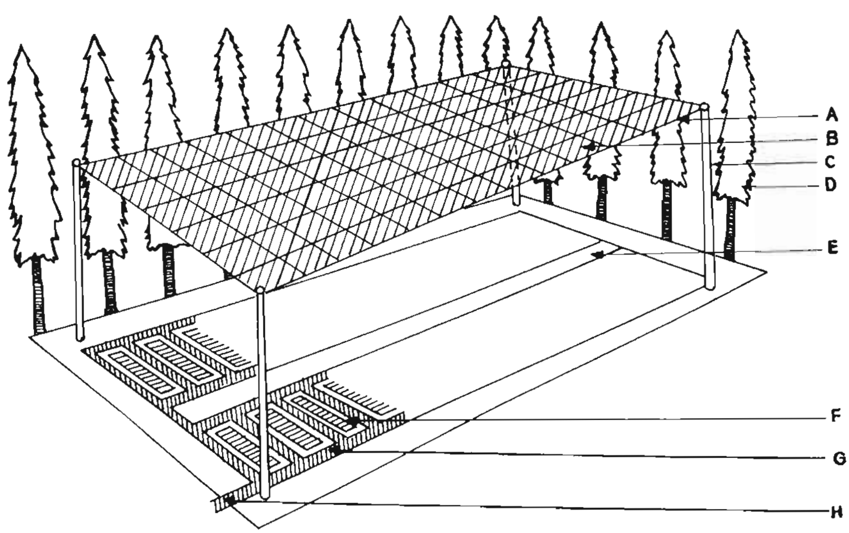

Fig. 7.5. Vermiculture plan layout to produce inoculum for in-soil technology. A, Galvanized iron wire; B, old sack cover; C, wooden/stone/iron pillar; D, shade tree; E, road; F, vermiculture bed; G, boundary drain; H, drain outlet.

vermiculture beds. *P. corethrurus* constituted approximately 80% of the culture, while other earthworms, e.g. *Megascolex konkanensis*, *Amynthas corticis* and *Metaphire houlleti*, constituted the rest of the population. This combination was determined by the initial proportions of earthworms existing in the field where there is need of earthworm application. Initial inoculation of 1000 adult and late immature worms to each vermiculture bed has resulted in production of about 15,000 assorted worms (Table 7.2, Fig. 7.6).

This amounts to about 185 individuals and 83.25 g live wt inoculated m^{-2} area of the vermiculture bed. The resulting cost of 1 kg of live *P. corethrurus* worms was 3.6 Euro when produced through large-scale bed culture (Table 7.3). Different levels of maintenance of on-farm bed culture in Tamil Nadu have shown that poor maintenance may result in about an 82% reduction in population density and biomass in comparison with properly maintained sites.

A comparison of wooden frame and bed culture has been made with respect to technology (Table 7.2) and cost of worm production (Table 7.3). Populations increased their density very rapidly in all situations, with multiplication rates of inoculum of 12.8, 15 and 16.5 after 2, 3 and 4 months, respectively, in small wooden frames and bed cultures in India and Peru. The multiplication rate of biomass calculated on a 1 year basis was 3.1 in wooden frames and 8.3 and 8.4, respectively, in bed cultures in Peru and India. These results indicate that although density increased very significantly in 2 months,

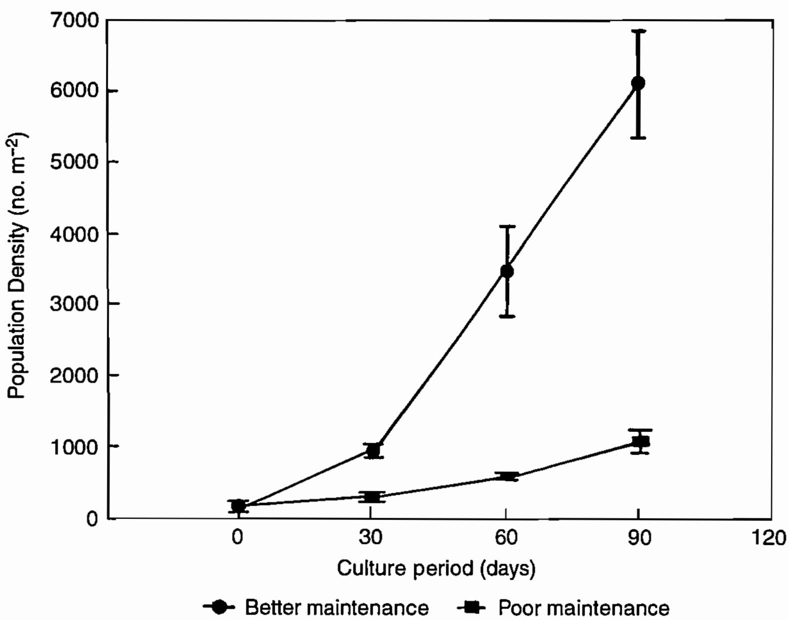

Fig. 7.6. Production of *Pontoscolex corethrurus* in a large-scale field culture in Tamil Nadu (India) at different levels of maintenance.

Table 7.3. Cost of production of endogeic earthworms at Yurimaguas (Peru) and at Tamil Nadu (India) sites.

	Yurimaguas (Peru)		Tamil Nadu (India)
	Wooden frames	Wooden log-lined bed	Vermiculture beds
Materials % (organic inputs + wooden frames)	16	9	44
Labour + maintenance%	31	34	37
Cost of inoculum%	53	57	19
Cost of production of 1 kg of live worms (Euro)	9.2	3.4	3.6

1 Euro = 1.1 US$.

it took 1 or 2 months more to obtain the subadult and adult worms that perform best in inoculations. Production in wooden frames had a 2.5-fold higher cost than the field method but had the advantage of occupying less space and being easier to control.

The cost of worm culture through different technology is comparatively less expensive by about 36% at Tamil Nadu and 79% at Yurimaguas for large-scale bed culture than collection from the field.

Development of Indirect Technologies

Effect of spatio-temporal management of crop rotations on earthworm communities at Carimagua (Colombia)

Soil macro-invertebrate communities

Savannas at Carimagua traditionally have been used for extensive cattle grazing. A long-term research project was conducted by Centro Internacional de Agricultura Tropical (CIAT) to find suitable and productive alternatives for sustainable land use based on rotations of annual crops with improved pastures (Thomas and Kevan, 1993). The aim of our specific research was to assess the impact on earthworm communities of experimented practices and identify spatio-temporal designs of rotation that would best sustain earthworm activities. Immediate objectives were: (i) to evaluate the diversity and ecological functions of earthworm species present in the area (see Chapters 1–3) and (ii) to describe the dynamics of the communities in time and space. Implementation of the latter objective has led to the design of new sampling techniques that allow collection of data sets that are suitable for geostatistical treatments (Rossi *et al.*, 1995, 1997). The total earthworm and macrofaunal biomasses at Carimagua show distinct variations with respect to land-use patterns (Decaëns *et al.*, 1994) (Fig. 7.7). The native savanna had the highest species richness (seven species). In the pasture–legume system, the same seven species were present and biomass had increased ten times, largely due to the response of *Martiodrilus carimaguensis*, a large anecic species (Jimenez *et al.*, 1998). Similar results had been observed already in a number of other tropical sites (Dash and Patra, 1977; Senapati, 1980; Senapati and Dash, 1981; Lavelle *et al.*, 1981). Improved pastures had the highest earthworm biomass, with a maximum value (41.2 g live wt m^{-2}), in a pasture consisting of the African grass *Brachiaria decumbens* and the herbaceous legume *Pueraria phaseoloides* ten times greater than in the original savanna.

In the rice monoculture, earthworm biomass was drastically reduced (1.86 g live weight m^{-2}) as in many tropical soils cropped to annual cultures (e.g. Lavelle and Pashanasi, 1989; Lavelle *et al.*, 1993; Panigrati, 1993; Senapati and Sahu, 1993; Senapati *et al.*, 1995; Mboukou-Kimbasta, 1997). This is largely due to soil tillage, reduction in soil organic matter returned to the soil and the application of pesticides (Domsch, 1970; Eijsackers and van de Bund, 1980; Austin, 1987; Austin and Smith, 1989; Woomer and Swift, 1994; Senapati *et al.*, 1994b; Giller *et al.*, 1997). There was an inverse relationship between termite and earthworm abundance, termites being more abundant in the native savanna and in cultivated plots where earthworm communities were reduced.

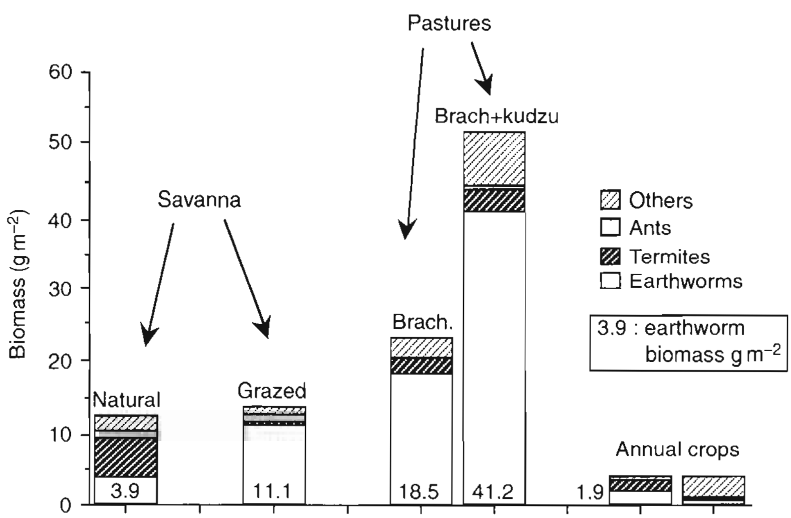

Fig. 7.7. Effect of land use on macrofaunal communities at Carimagua (Colombia).

Changes in earthworm spatial distribution

An experiment was started at Carimagua to test the effect of different crop and pasture rotations and their relative spatial layout on parameters of soil fertility and sustainability. The culticore experiment comprises ten different land-use systems organized in adjacent bands 20 or 40 m wide and 100 m long in a split plot design replicated four times (Fig. 7.8). Cropping systems under study were: (i) rice monoculture; (ii) rice–cowpea rotation; (iii) rice–green manure rotation; (iv) native savanna; (v) rice–pasture rotation; (vi) maize monoculture; (vii) maize–soya rotation; (viii) maize–green manure rotation; (ix) natural savanna; and (x) maize–rice–pasture rotation. In this design, it is possible to follow the spatial (i.e. local and across parcels) and temporal (i.e. across seasons and alternating type of land use) patterns of community dynamics.

A sampling was done using an experimental design consisting of 60–120 samples of 25 cm × 25 cm × 30 cm size, taken at every 5 m interval on regular square grids. Sampling done in 1995–1997 showed that populations of the main two species are distributed in subcircular patches about 20 m in diameter. This sampling showed that *M. carimaguansis* was able to build abundant populations in pastures and had low population densities in all cropped systems, although patches might be observed temporarily in cropped plots located close to a pasture. Avoiding tillage when populations are fully active seems to be an efficient way to prevent destruction of populations (Fig. 7.9).

Glossodrilus sikuani, a smaller size endogeic species (see Chapter 3), developed abundant populations in the 2-year pasture. In other systems, populations remained at a low level of abundance (Fig. 7.10). At the boundary between two different land-use systems with contrasting effects, patches did not seem to expand from the favourable to unfavourable systems.

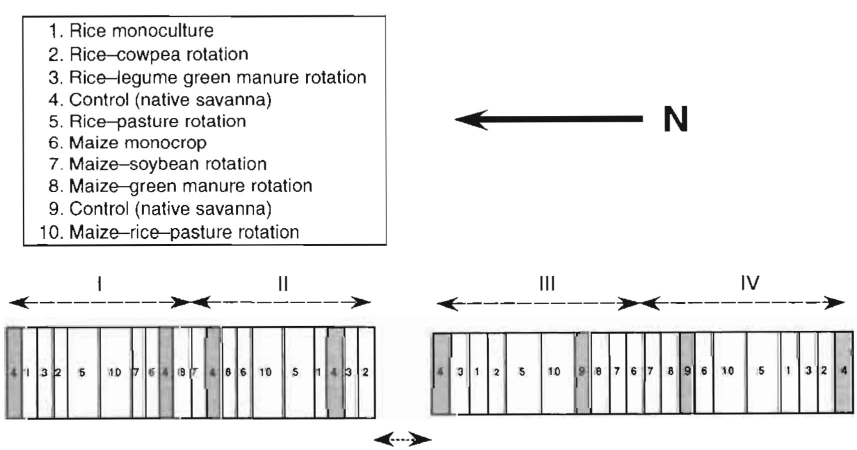

Fig. 7.8. Allocation of replicates and treatments into the Culticore experimental design at Carimagua (Colombia) (Thomas and Keiran, 1993).

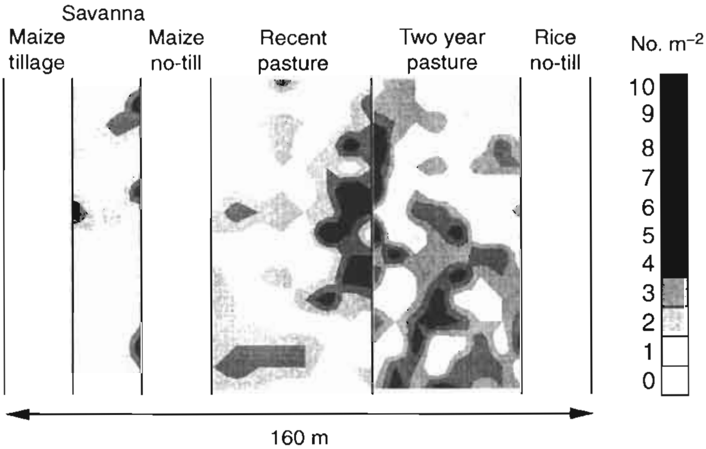

Fig. 7.9. Spatial distribution of *Martiodrilus carimaguensis* in the rainy season in the different plots of the CULTICORE experiment.

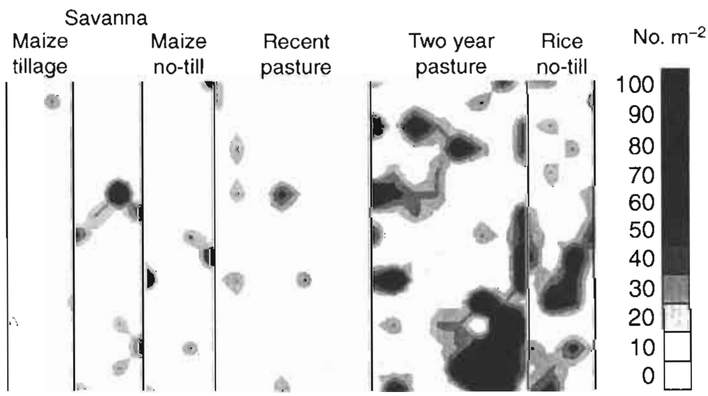

Fig. 7.10. Spatial distribution of *Glossodrilus sikuani* in the rainy season in the different plots of the CULTICORE experiment.

Therefore, the hypothesis of a colonization of earthworms from rich to poor systems is not supported. On the other hand, when two favourable systems were adjacent, there seemed to exist some continuity in the distribution of patches (see, for example, transition between rice and 2 year pasture for distribution of *M. carimaguensis*, Fig. 7.9). These observations showed that a proper management of soils may sustain and even increase earthworm activities when a natural ecosystem is converted to crops or pastures.

Direct In-soil Earthworm Technologies

Different techniques based on the inoculation of earthworms have been tested in our project. They comprise small-scale manipulations in nursery pots for tree seedlings, intensive horticulture plots of a few square metres and 0.5 ha plots of slash-and-burn agriculture at Yurimaguas (Peruvian Amazonia), 1 ha blocks in tea gardens of Southern India and restoration areas of Vertisols degraded by 15 years of intensive market gardening in Martinique. Earthworms (*P. corethrurus* and, occasionally, native species) were produced on site at Yurimaguas and at the two Indian locations; at St Anne (Martinique), *P. elongata* were collected manually from neighbouring pastures.

Development of direct technologies at Yurimaguas (Peru)

Experiments at Yurimaguas started in December 1989. Small-scale experiments were conducted to look into the effects of earthworms (*P. corethrurus*), crop residues (upland rice stubble) and legume green manure (*Centrosema macrocarpum*) on yield of various crops and soil fertility. Physico-chemical and biological parameters including plant production and decomposition kinetics of organic residues have been quantified and reported (Pashanasi *et al.*, 1992b, 1994; and Chapters 3–5). Crop production was sustained at the highest levels in the best treatments with high organic inputs and earthworm inoculation. The effect of earthworm inoculation was still observed at the fourth crop with a 50% higher grain production over no earthworm treatments. The incorporation of crop residue in the absence of earthworm inoculation resulted in a 38% increase in crop production in comparison with the control plot. Synergistic interaction of crop residue, legume green manure and earthworms resulted in enhancement of crop production by about 79.5% over the control (Pashanasi *et al.*, 1992b).

Enhancement of growth of tree seedlings by inoculation of earthworms in nursery bags at Yurimaguas (Peru)

Tree seedlings are highly responsive to the inoculation of *P. corethrurus* in nursery bags (see Chapter 4). At Yurimaguas, plastic bags were filled with a 1 : 3 mixture of composted sawdust and soil. Inoculation of ten young *P. corethrurus* in soil where tree seedlings were grown resulted in a significant increase in growth, especially with *Bixa orellana*, which grew 16 times better in 120 days and *Eugenia stipitata* (+150% growth), while *Bactris gasipaes* did not respond (Pashanasi *et al.*, 1992a). In the second phase of the Macrofauna programme, a similar technique was applied successfully to tea cutting culture resulting in a 220% increase in plant growth over a period of 6 months (Giri, 1995; see Chapter 4). An experiment was designed at Yurimaguas to test the hypothesis that such improvements were due to a higher rate of mycorrhizal infection (Ydrogo, 1994). Earthworm activities actually significantly increased this parameter in all cases. The highest rates of infection were observed with the highest levels of earthworm biomass, and with *B. orellana*, the tree species that was most responsive to earthworm effects. *B. gasipaes*, which is much less responsive, showed the lowest increase in mycorrhizal infection (Fig. 7.11). These results demonstrate that earthworms may have rather diverse effects on plants, which explains the variable responses that sometimes were observed. At Yurimaguas, *P. corethrurus* is now being inoculated systematically into nursery pots to stimulate growth of seedlings and mycorrhization in the field.

Development of horticulture techniques based on the joint use of composted sawdust and earthworms at Yurimaguas (Peru)

At Yurimaguas, in Peruvian Amazonia, 95% of vegetables consumed come from the Pacific Coast and San Martin region. Due to poor soil conditions, only native varieties can be produced locally, with low production rates and low prices, whereas the prices of good quality tomatoes vary between 0.6 and 1.8 Euro kg^{-1}. Local demand at Yurimaguas was 1300 kg per month in the market conditions of 1995. Limitations for market gardening production at Yurimaguas are mainly the low quality and acidity of soils close to the town, and scarcity of organic and mineral fertilizers. Experimentation has been implemented to try and establish a new technique based on the common use of sawdust as an organic resource and earthworms to stimulate nutrient release from sawdust and enhance plant growth.

At Yurimaguas, massive production of *P. corethrurus* was made on a 1 : 3 ratio mixture of composted sawdust : soil. Sawdust has high contents of nitrogen (3–4.7 g kg^{-1}), calcium (4.2–9.4 g kg^{-1}), magnesium

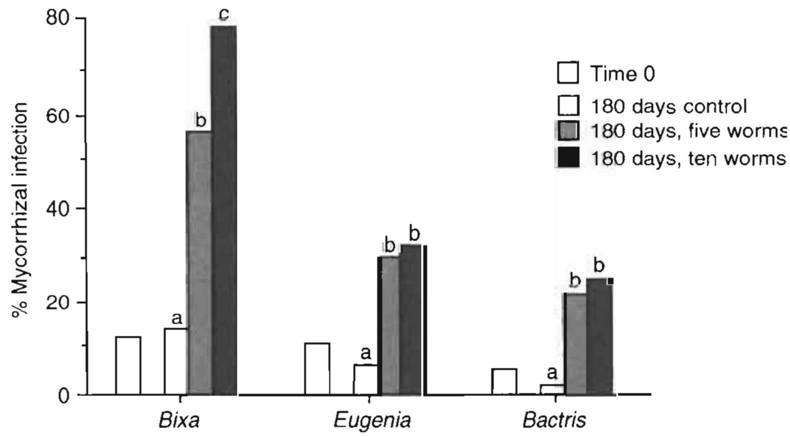

Fig. 7.11. Effect of inoculation of earthworms on mycorrhizal infection of three tree seedlings in the greenhouse at Yurimaguas.

(0.4–0.5 g kg^{-1}) and potassium (0.35–0.60 g kg^{-1}), but very low levels of phosphorus (0–0.29 g kg^{-1}). High proportions of lignin and polyphenols are considered limiting factors to nutrient mineralization. Analyses of the mixture after worms had been produced showed that aluminium toxicity was significantly decreased whereas concentrations of a few other essential nutrients such as calcium, magnesium and potassium were increased (Table 7.4). Preliminary experiments allowed the identification of tomato varieties that could grow in these conditions; a large tomato with high acceptance on the local market and, Perle, a very small tomato highly appreciated in developed countries as a snack, but rejected in Yurimaguas.

The first set of experiments was carried out with five treatments, two replicates of each treatment and 14 plants in each replicate. Production was low in most treatments. Production in a 1 : 3 mixture of sawdust and soil was twice as high as in the control soil, similar to a culture with a purely inorganic fertilization, but much lower than a conventional treatment with organic fertilization, and a treatment with organic and inorganic fertilization (Table 7.5). Differences in production may be attributed partly to the availability of nutrients in the diverse systems. Mortality of plants was high in all treatments due to unsolved problems of pests and diseases and to nutrient deficiencies.

Table 7.4. Chemical analysis of control soil and 1 : 3 by volume sawdust and soil mixture in vermiculture beds at Yurimaguas (mean of 12 different culture beds after 6 and 10 months of earthworm activity).

Time	pH	C (g kg^{-1} soil)	P (mg l^{-1})	Ca (cmol (+) l^{-1})	K (cmol (+) l^{-1})	Al (%)
Control soil	4.5	21.3	17.9	1.5	0.26	62.5
Six months	4.6	21.7	12.6	1.9	0.29	53.9
Ten months	4.2	25.4	15.5	2.9	0.28	47.3

Table 7.5. Production of tomatoes at Yurimaguas using different conventional treatments and an experimental earthworm technology.

Treatment	Yield (kg m^{-2})	% Mortality
Organic fertilizer 25 t ha^{-1}	1.43	25
Inorganic fertilizer NPK: 100–140–60	0.69	46
Organic fertilizer + NPK 50–70–30	2.77	11
Sawdust-soil 1:3 mixture + earthworms (200 m^{-2})	0.57	57
Control (soil)	0.29	57

Treatments with sawdust and worms had a relatively high mortality compared with other systems. New experiments have been started in which the system with sawdust and worms is supplemented with nutrients in organic (chicken slurry) and inorganic (inorganic fertilizer) forms to prevent any nutrient deficiency. The system that uses a mixture of organic and inorganic fertilizer is taken as control.

Large-scale on-farm experiments at Yurimaguas (Peru)

Most of the farmers at Yurimaguas practise traditional slash-and-burn cultivation systems. They clear and burn portions of the forest and then crop them to upland rice, maize or beans. After a brief period of two or three cropping cycles, fertility decreases and weeds invade the area. These portions are then abandoned as fallow land. Any practice that would increase sustainability beyond that short period of two cropping cycles and/or increase production would help to decrease the need to clear primary forest and significantly alleviate the task of farmers. Research at the experimental station 'San Ramon' at Yurimaguas had shown that application of fertilizers may partly solve the problem, but local constraints reduce the possibility to implement this technique effectively. Alternative methods are required that make better use of locally available resources (Sanchez *et al.*, 1982).

The experiment consisted of 12 plots with two treatments and three replicates in each plot (Fig. 7.12). In the middle of the plot, a strip of 0.4 m

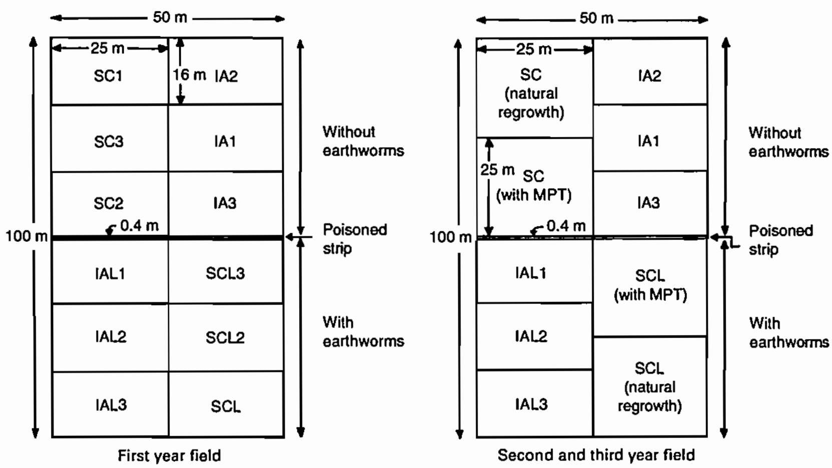

Fig. 7.12. Layout treatments for a first, second and third year field at Yurimaguas (Peru). L, earthworm (*P. corethrurus);* IA, improved agriculture with (L) and without earthworms; SC, shifting agriculture with (L) and without earthworms; MPT, multipurpose trees, replicates 1,2, and 3.

width and 50 m length was isolated by plastic sheets set vertically into the soil to 60 cm depth and treated with Furadan 4F (Carbofuradan 0.9 ml, l^{-1} of water) before each crop. This buffer strip was designed to prevent the movement of earthworms from the inoculated to the non-inoculated area. The secondary forest was slashed and burned manually, planted with rice as a first crop and interplanted with cassava after 2 months. After harvest, this area (shifting cultivation; SC) was abandoned to fallow. In half of the abandoned area, fallow was improved by planting some multipurpose trees (*Shaina* sp., *Inga edulis*) and the other half was left for natural regrowth. The improved agriculture treatment (IA) involved manual slash-and-burn preparation, and a yearly plant rotation of rice, cowpea and green manure (*Mucuna cochinensis*) sustained for 3 years. The major earthworm populations found in the plot were the three native species *Martiodrilus pano*, *Rhinodrilus lavellei* and *Rhinodrilus pashanasii*, together with *P. corethrurus*. Earthworm populations were sampled before and after the vegetation was burned. *P. corethrurus* obtained from large-scale bed culture (details given in this chapter) developed at Yurimaguas, Peru, were inoculated 15 days after planting the first crop in order to avoid death of earthworms due to high soil surface temperature. Inoculation of two *P. corethrurus* worms was made in the same hole where each seed had been planted 15 days before. A total of 17,500 worms was thus inoculated, i.e. 3300 in the SC and 14,200 in the IA plots at the onset of the experiment (Table 7.6). Inoculations were repeated twice in each treatment, and 62,000 worms were inoculated, presenting a biomass of 63.5 and 60.3 kg fresh mass, respectively, in the improved and traditional system.

Earthworm communities in the secondary forest had highly variable densities, with a minimum of 3 m^{-2} in SCL2 and a maximum of 62 in IAL1 and SC2. In the IA system, the parcels to inoculate already had a much higher biomass than the non-inoculated plot; the reverse situation was observed in the SC system. At the first harvest, populations of *M. pano* had totally

Table 7.6. Dates and amounts of earthworm inoculation (*Pontoscolex corethrurus)* on the two 1260 m^2 experimental plots at Yurimaguas.

Date	Improved agriculture	Traditional system
Jul 1993	12, 600 (10 m^{-2})	3,278 (2.6 m^{-2})
Dec 1993–Jan 1994	9,600 (7.7 m^{-2})	2,400 (1.9 m^{-2})
Jan 1995	9,600 (7.7 m^{-2})	
May 1995		24,600 (19.7 m^{-2})
Total	31,800 ~8 kg (63.5 kg ha^{-1})	30,278 ~7.6 kg (60.3 kg ha^{-1})
Cost of inoculation ha^{-1} (US$)	254	241

disappeared, but other forest species, especially *R. lavellei*, were still present. *Rhinodrilus pashanasii* populations increased in all situations (Fig. 7.13). This might have occurred due to high rainfall during the growing period and the use of surface residues after the slash-and-burn process. Introduction of *P. corethrurus* had no important effects on the overall density because juveniles of this worm need 3–4 months to become adults. Crop production was very uneven (Pashanasi *et al.*, 1992b, 1994). Earthworm biomass never reached 40–50 g fresh wt and the inoculum was probably insufficient to allow a rapid development of the earthworm population when the soil would have been still

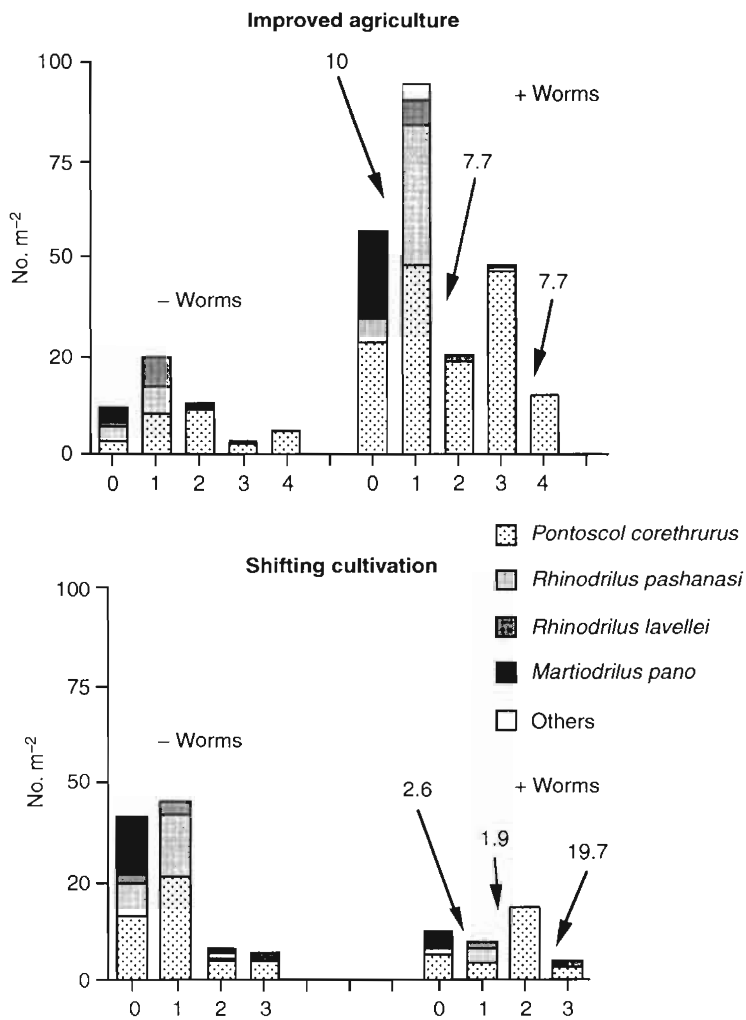

Fig. 7.13. Changes in the composition of earthworm communities in the two cropping systems during 3 years of experimentation (arrows indicate numbers of inoculated individuals).

favourable for their growth. The mode of inoculation (earthworms alone, with no soil) and the high proportion of juveniles in the inoculum (that would need at least 2–3 months before they would reproduce, and suffer mortality during this time) were factors responsible for this situation. Finally, the texture and fertility of soil appeared to be highly heterogeneous in the experimental plot; as a result, earthworm biomass was significantly greater in the non-inoculated control of the SC treatment than in the inoculated plot at all sampling dates.

There was no correlation between earthworm biomass at harvest and grain production. However, inside the SC treatments, correlation between crop yield and earthworm abundance at each sampling point was highly significant ($r = 0.78$, $P < 0.01$). Economic evaluation has been made on the first crop, and the costs of labour were 55 and 62.7% higher, respectively, in inoculated plots of SC and IA. As a result, the financial budget was negative in all treatments with earthworms (Pashanasi *et al.*, 1992b, 1994) (Table 7.7). No significant difference in any of the parameters monitored in this experiment was observed between inoculated and non-inoculated treatments.

The experiment failed because the initial inoculated biomass was too low and dispersed. In the unfavourable conditions of a slash-and-burn plot, populations could not multiply and their abundance remained at the initial level of inoculation. Another reason for the failure was that inoculated worms were mainly juveniles. Therefore, an initial inoculum of more than 300 kg ha^{-1} of adult worms seems to be necessary to provide efficient worm activity; as the cost of 1 kg fresh wt of worms is 3.4 Euro, inoculation of 1 ha would cost about 1000 Euro, a totally unrealistic investment in the economic context of these crops. An alternative may be to concentrate the inoculum in a small proportion of the area, within the reach of the roots, or to use techniques that stimulate the activity of local populations indirectly.

Table 7.7. Cost–benefit analysis of traditional slash-and-burn and improved agriculture with and without earthworm inoculation at Yurimaguas (Peru).

	Shifting culture		Improved agriculture	
	Non-inoculated	Inoculated	Non-inoculated	Inoculated
Incomes	3086	2137	1434	1222
Costs	923	2796	1289	4355
Benefits	2164	–479	145	–3134
Crops	Maize–cassava–fallow 12 months		Maize–rice–cowpea–rice 14 months	

Effect of earthworm inoculation in the restoration of a degraded vertisol by a pasture fallow at St Anne (Martinique)

In the south-east of Martinique, vertisols are usually cropped either to pastures (planted with *Digitaria decumbens*) or long-term intensive market gardening production. The latter practice has resulted in severe degradation through loss of organic matter, soil organisms and soil aggregate stability inducing soil erosion (Feller *et al.*, 1983) (Table 7.8).

In this degraded situation, the density of the existing dominant earthworm *P. elongata* is very low (2 m^{-2}) compared with the native pasture (90 m^{-2}) in Martinique. Pasture fallows may restore soil conditions in 5–10 years (Albrecht *et al.*, 1986). An experiment was conducted to evaluate the relative contribution of roots and earthworms to regeneration of degraded soils under pasture fallow. The aims of the study were: (i) to identify patterns of reconstitution of carbon stocks and recolonization by earthworms, and (ii) to test the effect on these processes of an early massive reinoculation of earthworms at the density of adjacent pastures.

A pasture was established at St Anne to restore the stocks of organic matter and, hence, the stability of the physical structure. This plot had been planted with *D. decumbens* 1 year before the onset of the experiment. Soil aggregate, carbon content, root biomass and earthworm abundance had been quantified for 3 years on a 0.5 ha plot at 178 sampling points randomly distributed on a regular square grid at 1 m intervals. This allowed the choice of three experimental plots 5 m × 10 m in size, located at places with equivalent carbon contents inside the 1 ha study field. Replicates were not possible due to the large amount of disturbance and elevated associated costs.

Table 7.8. Soil and biological properties of a Vertisol of south-east Martinique under long-term market gardening cultivation and long-term pastures.

		Market gardening	Pasture
Soil organic matter (t C ha^{-1})	0–20 cm stock	39	82
Soil loss under simulated rainfall (t ha^{-1})	150 mm h, 30 mn, ploughed surface	20.1	2.1
Root biomass (mg C g^{-1} soil)	> 500 μm (0–10 cm)	0.12	10
Microbial biomass (μg C g^{-1} soil)	0–10 cm	600	1200
Earthworm biomass (g m^{-2})	30 × 30 × 30 cm samples	3.1	336.4
Earthworm density (ind m^{-2})	30 × 30 × 30 cm samples	2	93.4

The three treatments were: (i) bare soil, no earthworms; (ii) plants only (*D. decumbens*); and (iii) a plot with both plants and earthworms (*P. elongata*, at a density of 90 m^{-2}). Vermicide carbofuran (1 kg 50 m^{-2}) was used under the trade mark name of Furadan 5G (5% active ingredient) to kill earthworms (Edwards, 1974; Thompson, 1974; Brown, 1978). In the experimental plot with earthworm inoculation, a trench of 30 cm width and 30 m length was dug out around the plot down to the bed rock. After excavating the soil, a thick plastic film was placed in the trench in a 'U' shape and soil was put back into this trench to prevent the escape of earthworms. A wire netting fence was installed around the experimental plots to prevent cattle from entering the field. Earthworms were collected from irrigated pastures where the population biomass may be as high as 4 t live wt ha^{-1} (Barois *et al.*, 1988). About 4500 live *P. elongata* worms were needed for the inoculation. To ensure a safe inoculation, earthworms were put in containers filled with soil, turned upside down and covered with mulch to avoid heating during introduction. A hundred such containers were evenly distributed at the surface of the plot. After 1 week, containers were removed and the contents were hand sorted for the presence of earthworms.

In the large plot, the carbon content in the 0–30 cm stratum averaged 14.1 mg g^{-1} soil at time zero but increased significantly to 16.6 mg g^{-1} soil after 4 years (Table 7.9). In the fourth year, the spatial distribution of carbon across the plot had regained the initial pattern of distribution (Fig. 7.14a). Low density of earthworms in Vertisols under intense market gardening (Barois *et al.*, 1988) had increased during the first year but decreased in the second

Table 7.9. Abundance of earthworms in the regeneration plot (density m^{-2}) and soil organic carbon content (mg C g^{-1} soil) (0–30 cm).

Time (years)	*Polypheretima elongata*	Cocoons *P. elongata*	Polyhumic endogeic sp1	Epiendogeic sp2	Total m^{-2}	C (mg g^{-1})
0	3.5	0.6	6.0	—	10.1	14.2
	(1.0)	(0.5)	(2.7)	—	(2.9)	(0.2)
1	5.6	3.7	20.1	—	29.3	14.3
	(1.6)	(1.2)	(7.2)	—	(7.5)	(0.2)
2	3.3	1.9	6.8	3.1	15.0	14.2
	(1.1)	(0.8)	(2.2)	(1.4)	(3.1)	(0.2)
3	8.6	4.8	43.0	19.7	76.1	16.7
	(1.9)	(1.4)	(11.1)	(4.7)	(14.0)	(0.3)
4	40.2	9.1	6.1	8.0	50.6	16.6
	(6.0)	(2.1)	(3.4)	(3.5)	(10.0)	(0.4)

sp1 small polyhumic endogeic species + newly hatched *P. elongata*; sp2 small epiendogeic species. Confidence limits are shown in parentheses.

year due to unfavourable moisture conditions during the sampling period, and increased again in the third year (Table 7.9).

Populations concentrated in patches about 20 m in diameter that developed from the edges of the plot and seemed to be interconnected (Fig. 7.14b). This pattern was apparent after 1 year. In the third year, a significant increase in carbon content and earthworm density was observed. However, a large part of the increase in density was represented by two small-sized species, one a small filiform polyhumic endogeic linked to the rhizosphere, and the other a small and slightly pigmented epi-endogeic. No spatial correspondence between increases in carbon and earthworm population were observed at that stage.

In the small experimental plots, the distribution in depth of carbon was different in treatments with earthworms: more carbon was found in the upper 10 cm and less below 30 cm (Fig. 7.15). The introduced population was maintained at a density and biomass much higher than in the non-inoculated plot, but still lower than in the adjacent permanent pasture (~90 m^{-2}) (Table 7.10). Part of the difference, however, may have been due to the relative inefficiency of the sampling method, since collection of individuals was limited to the upper 30 cm of soil. The experiment showed that in these soils, inoculation of an earthworm population equivalent to that of an old pasture is feasible. The carbon content in the soil was sufficient to sustain the biomass at a relatively high level, and reproduction occurred. There was no apparent effect of earthworm activities on overall accumulation of carbon, although depth distribution was modified in the third year. Regarding the impact on soil erodibility, plants clearly improved resistance to erosion. Earthworm-inoculated plots gave variable results, close to controls with no plants at the beginning (months 6 and 12), and similar to treatments with plants only after 18 months (Fig. 7.15). After 1 year, the root biomass sampled from a depth of 40 cm showed a maximum value of 15.4 g kg^{-1} dry soil) in the earthworm introduction plot, an intermediate value of 11.2 g kg^{-1} dry soil in the plot with only plants but no earthworms, and the lowest value of 3.3 g kg^{-1} dry soil in the plot where both worms and plants were eliminated. Only the differences between treatments with and without plants were significant.

Indirect and direct technologies in tea gardens at Carolyn and Sheikalmudi, Tamil Nadu (India)

Tea is a high value plantation crop in India. From an ecological viewpoint, it can be seen as one of the most important agroforestry systems maintained for more than 100 years (Banerjee, 1993). Production of tea was around 1000 kg ha^{-1} $year^{-1}$ during the 1950s and increased up to approximately 1800 kg ha^{-1} $year^{-1}$ between 1970 and 1985 due to the introduction of agrochemicals, after which production has almost stabilized. In the Anamallai and the Nilgiris tea gardens, Parry Agro Industries Ltd produce 3000 and 3500 kg ha^{-1} $year^{-1}$ respectively, but production is stabilized in spite of

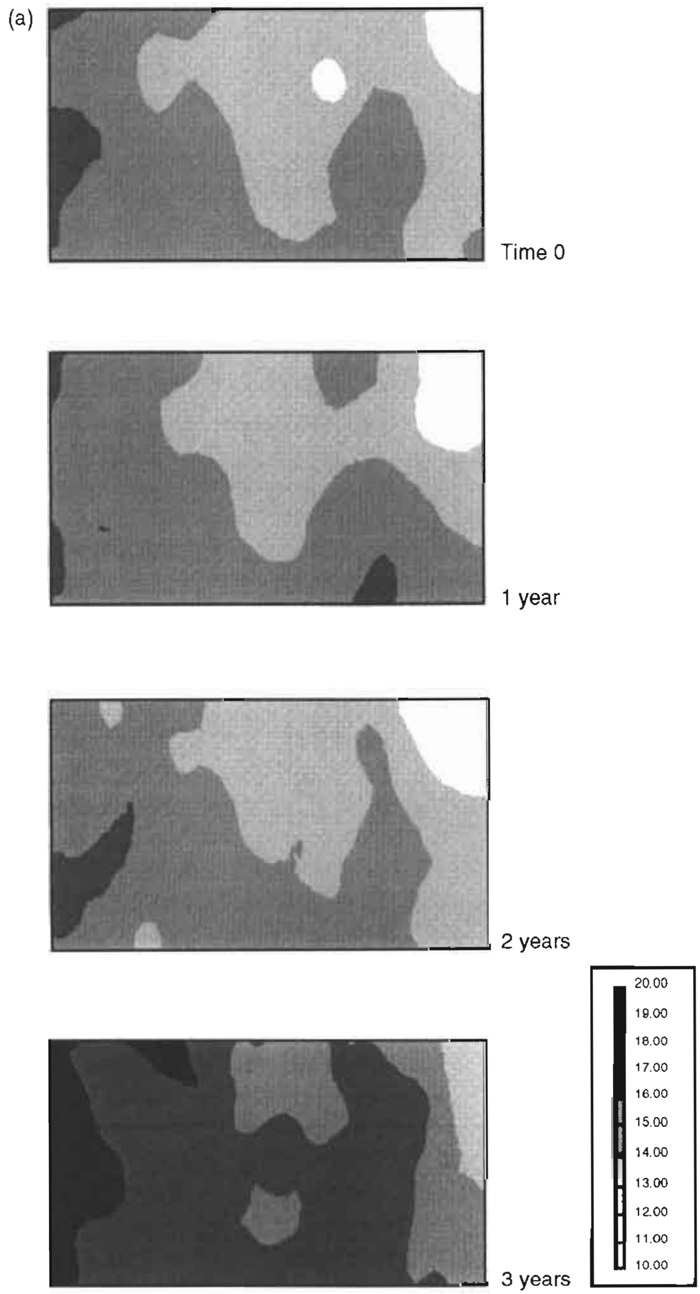

Fig. 7.14. Spatial distribution of (a) carbon content (% in upper 10 cm) and (b) earthworm density (m^{-2}) in the upper 30 cm of a 60 m × 140 m plot planted to *Digitaria decumbens* for 0, 1, 2 and 3 years after 15 years of continuous market gardening production.

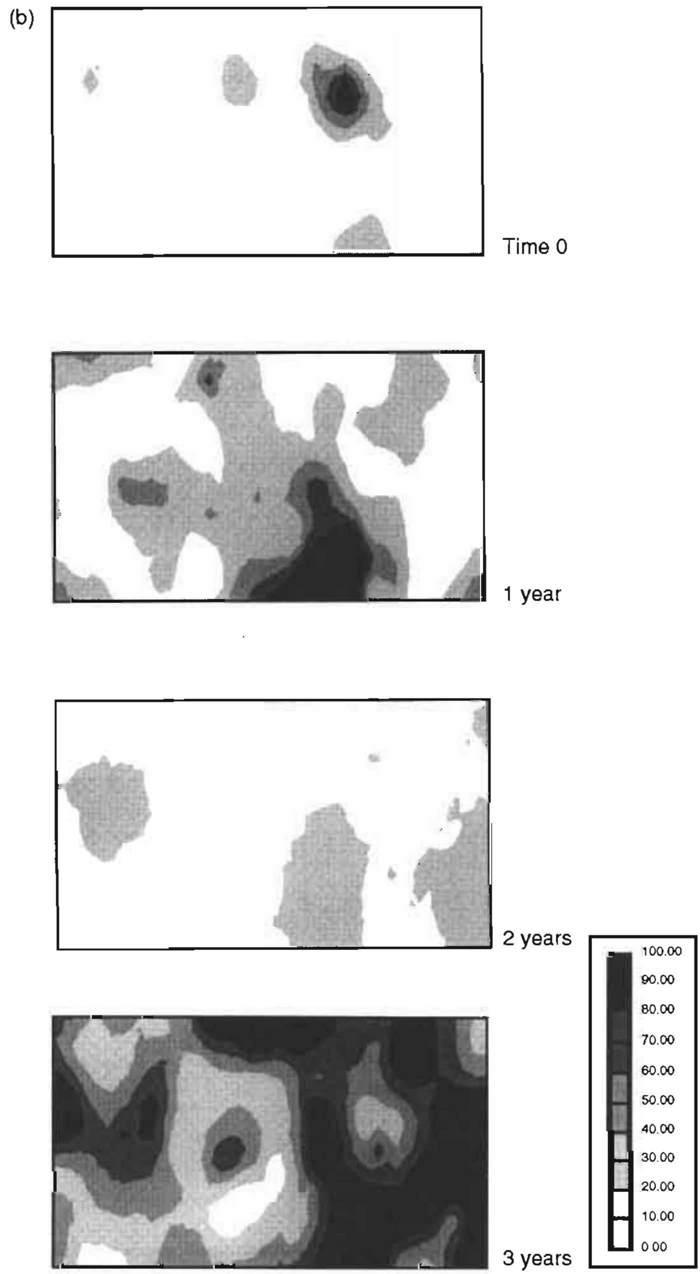

Fig. 7.14. *Continued.*

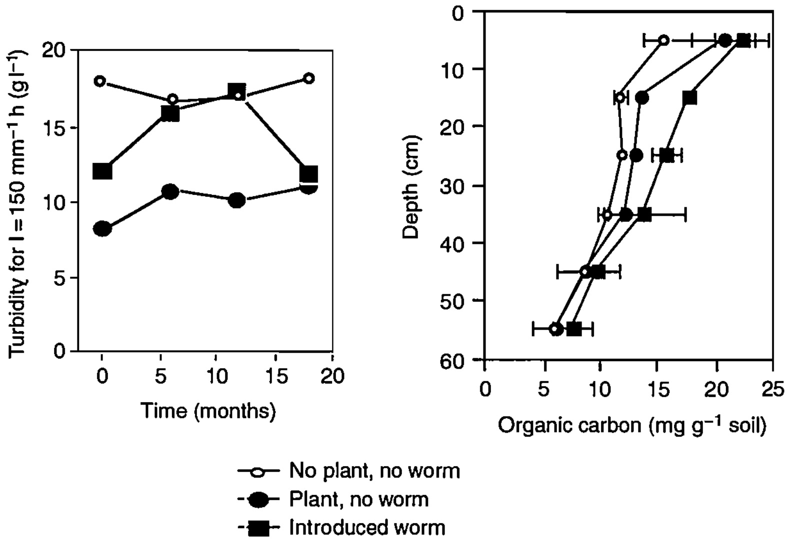

Fig. 7.15. Turbidity of runoff water after a 150 mm rainfall in 1 hour and distribution of carbon stock in the upper 60 cm of soil in the three treatments at St Anne (Martinique) after 2 years of experiment.

Table 7.10. Earthworm abundance in enclosures submitted to three specific treatments, and the large plot in process of natural regeneration.

	Control (bare soil)	Plants only	Plants + worms*	Natural regeneration
December 1994 (13 m)				
Biomass (g m^{-2})	0.05	0.07	35.7	6
s	0.08	0.13	38.4	10.4
Density (ind m^{-2})	4	4	48	43
s	6	6	34	74
June 1995 (19 m)				
Biomass (g m^{-2})	0.19	0.15	46.6	10.5
s	0.08	0.21	34.5	17.5
Density (ind m^{-2})	40	18	44	25
s	6	17	11	25

*Earthworms inoculated in November 1993, 90 ind m^{-2}; estimated biomass; 90 g m^{-2}.

continuously increased inputs of fertilizers and pesticides (Swaminathan, 1983; Beare *et al.*, 1997).

Preliminary studies indicated a significant depletion of soil faunal communities, especially litter-feeding epigeic and anecic earthworms of tea garden soil in comparison with the nearby forest. The excessive use of agrochemicals associated with problems such as compaction, leaching and soil erosion have actually eliminated 60–70% of the non-target organisms (Senapati *et al.*, 1994a, b). In tea gardens, native earthworm populations are most affected whereas proliferation of termites has been observed in some cases. As a result, the termite:earthworm ratio tends to increase in degraded soils and a negative correlation has been observed between this ratio and total yield ($r = -0.84$, $P < 0.01$). The long-term exploitation of soil has significantly affected some basic parameters of soil fertility such as water-holding capacity (WHC) (–11% compared with a nearby forest site), cation exchange capacity (CEC) (–29%) and organic matter content (–33%) in tea garden soil in comparison with the original forest soil (Senapati *et al.*, 1994b). Soil pH has decreased from 5.0 to 3.8, and aluminium saturation of the CEC subsequently increased from 10 to 60%. Soil of the tea garden also has a low calcium content and a high content of sesquioxides of aluminium and iron. Soil organic matter contents are correlated negatively ($r = -0.98$, $P < 0.001$) with the amount of agrochemical input.

Experiments have been conducted at Carolyn Estate (East division), Field No. 15 of Parry Agro Industries Ltd to test technologies that would indirectly, or directly, stimulate earthworm activities. Eight blocks, each of 1 ha containing 5000 tea bushes, located in the same field facing west were demarcated. Each block was isolated from the next by four rows of tea bushes serving as a buffer zone. Experimental units of 1 ha blocks were preferred by Parry Agro Industries Ltd to a classical split plot experimental design because: (i) technology developed on at least a 1 ha block could be adopted directly, and (ii) estimates of production of finished tea and qualitative assesment are usually done on areas of 1 ha. Special attention was paid to chosing blocks with similar soil and exposure conditions in order to produce significant results. The same design as repeated at another site (Sheikalmudi) with different soil conditions.

Treatments consisted of a control maintained under conventional technology (100% inorganic fertilizer inputs), four with different amounts, qualities and placement of organic inputs but no earthworm inoculation [i.e. 'organic' with 100% organic fertilization, mixed fertilization (50% organic), mixed fertilization with specific mechanical interventions ('trenching') and the same with incorporation of pruning material ('trench + inputs')] and two with earthworm inoculation, mixed organic and chemical fertilization, with or without incorporation of tree prunings ('trench + worms' and 'bio-organic fertilization'). The last treatment has been protected by a patent and all the experimental designs and technical layouts are detailed in the patent description. The effect of the first three treatments on tea production were assessed during nearly 7 years at Carolyn Estates; technologies involving mechanical operations and earthworm inoculations were tested during 5 years at two different sites (Fig. 7.16). Another experiment was established at another site for comparison.

Impact of high quality organic matter quantity

This experiment was designed to look into the impact on green leaf production and soil physico-chemical and biological components of replacement of respectively 50 or 100% of inorganic fertilizer with organic fertilizers providing an equivalent amount of mineral nitrogen. The inorganic fertilizer full dose was equivalent to 300 g N ha^{-1} as practised by Parry Agro Industries Ltd. High quality organic manure used in the experiment for 50 or 100% replacement of inorganic fertilizer was a commercially available brand prepared from processed city waste (Table 7.11).

Production in blocks fertilized with 50% organic inputs was respectively 37.6, 31.5 and 30.8% higher than in the block conventionally maintained during the first 3 years. In the following years, the difference decreased, due partly to the discontinuation of organic inputs for some time in 1995 and 1996 (Fig. 7.16). The average increase from 1992 to 1998 was 23%. Respective increases of 15.7, 17.1 and 12.6% (9% for the whole period) were observed during the same years in the block that received 100% organic inputs. ANOVA tests showed significant differences with respect to land

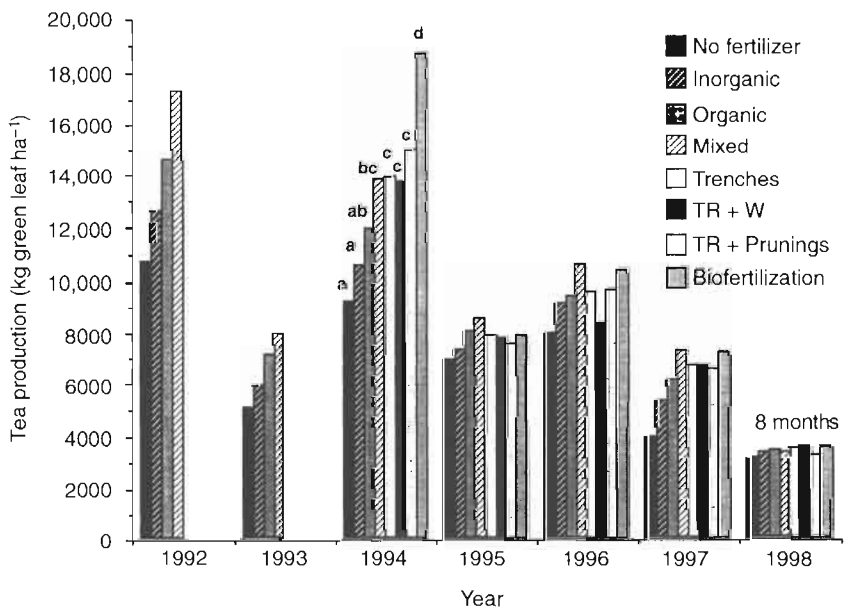

Fig. 7.16. Tea production at Carolyn Estate (Tamil Nadu, India) in plots submitted to different treatments (pruning occurred in 1993 and 1997).

Table 7.11. Chemical composition of Humigold.

pH	7.6
EC	0.34
C%	8.55
N%	0.67
$P(P_2O_5)$%	2.36
K_2O%	0.65
C : N	12.8

* Humigold is the commercial name of an organic manure prepared from city waste. Constituents are as per UPASI Tea Research Institute, Valparai , Tamil Nadu (India) analysis.

management alternatives (blocks). In the following years, differences were less marked. Cost–benefit analyses for 1992–1994 indicate 27.3–41.3% improvement in profit in the 50 : 50 inorganic : organic block and 10.3–18.9% improvement in the 100% organic block over the control block. The decrease in production observed in 1993 was due to pruning of the tea bushes, an event that occurs every 4 years.

Impact of trench incorporation

Trenching is an old practice that has been abandoned in plantation crops because of the increasing cost of human labour during conventional farming (Grice, 1977). Contour trenches with a 'lock and spill' quincuncial regular arrangement help to minimize soil loss and enhance production by about 12% in comparison with plots with no trenches (Padmanaban, 1975). This result is attributed to improved conditions of moisture and aeration. Trenches 1.2 m in length, 0.3 m in width and 0.45 m in depth were prepared between tea bushes in the experimental block in a lock and spill arrangement. About 3000 trenches were prepared in each 1 ha block and the impact of trench construction was studied. Of these 3000 trenches, 2000 were kept open with the excavated soil heaped on the lower edge to help in water harvesting, and the rest were filled with the excavated soil. This experiment served as a control for the next treatment where organic materials were incorporated into part of the trenches.

Trenching alone did not significantly enhance tea production in treatments that had received 50% of their N in an organic form (Fig. 7.16).

Impact of crop residue placement

Tea prunings, a low quality organic matter (Table 7.12), were buried in 1000 of the 3000 trenches made in experimental blocks where trenching had been done. The layout of different organic materials and other details have been

Table 7.12. Chemical composition of tea prunings (Natesan and Ranganathan, 1990).

	Mature leaf	Small stem	Thick wood
N%	3.20	1.37	1.04
P%	0.10	0.07	0.03
K%	1.24	1.00	0.55
Ca%	1.10	0.27	0.30
Mg%	0.17	0.09	0.06
Zn	1.75	2.05	2.25
Mn	48.9	17.7	12.8
Fe	13.8	30.2	16.4
Cu	6.6	13.6	4.2
Bo	1.8	1.2	0.6

described in patent papers. The total weight of the applied pruning material was about 12.5 kg m^{-2}. During the first year, results showed respective increases in production in comparison with conventional treatment, of +30.8 for treatment with 50% organic fertilization and surface application of prunings, and +42.3% when prunings were buried in trenches, although differences with plots receiving mixed fertilization were not significant. Corresponding increases in profit of 30.2 and 41.1% respectively were measured during the first year in comparison with conventional treatments.

The bio-organic fertilization technique

The bio-organic fertilization technique involves the use of organic fertilizers of low and high quality and earthworm inoculation following rather specific spatio-temporal patterns. This technique has proved very successful at Carolyn Estate, where tea production increased by 79.5% in comparison with a control plot receiving 50% fertilization as organic material. During the first year of application (1994), the bio-organic fertilization technique was significantly more productive than all the other techniques. For the period 1994–1998 (Table 7.13), differences in production between the biofertilization, and mixed fertilization techniques were not significant. Significant differences were observed with the unfertilized control plots receiving purely organic, or inorganic fertilization, and plots that had been submitted to trenching and earthworm inoculation, with no addition of prunings. This probably means that the biofertilization technique only stimulates production for some time and that organic materials and earthworms should be reinoculated at every pruning event. These two techniques, however, had significantly higher productions than the no fertilization, 100% inorganic and 100% organic

Table 7.13. Comparison of monthly values of tea production using different treatments from 1994 to 1998 at Carolyn Estate (Fisher's PLSD test).

	No fertilizer	Inorganic	Organic	Mixed	Trenches	Trenches + prunings	Trenches + worms	Bio-organic fertilization
No fertilizer		0.35	0.09	0.04*	0.02*	0.009*	0.06	0.0001*
Inorganic			0.44	0.05*	0.16	0.09	0.35	0.001*
Organic				0.24	0.52	0.36	0.88	0.01*
Mixed					0.59	0.79	0.30	0.20
Trenches						0.78	0.63	0.07
Trenches + prunings							0.44	0.12
Trenches + worms								0.02*

*Difference significant at $P < 0.05$.

fertilization techniques, respectively. Encouraged by these first experimental results, Parry Agro tested the technology at Lower Sheikalmudi, another site with different soil and climate conditions, where management of tea plantation is identical. Production was enhanced by 276% during the first year, and profit increased by 282% (Fig. 7.17). Large areas have been managed since then using the technology, and results confirm the trend observed during the first year following installation. At present, 80 ha $year^{-1}$ are being treated with the technique, and over 20 million worms are produced yearly (Panigrahi, personal communication).

A patent was deposited in 1996 in Sri Lanka ('Fertilisation Bio-organique dans les Plantations Arborées' 4/9/96 at Colombo, Ref. No. 11034) and internationally (ref. PCT/FR 97/01363) to protect the technology. It has been extended since to several countries. All the technical details and procedures for operation are described in the patent document.

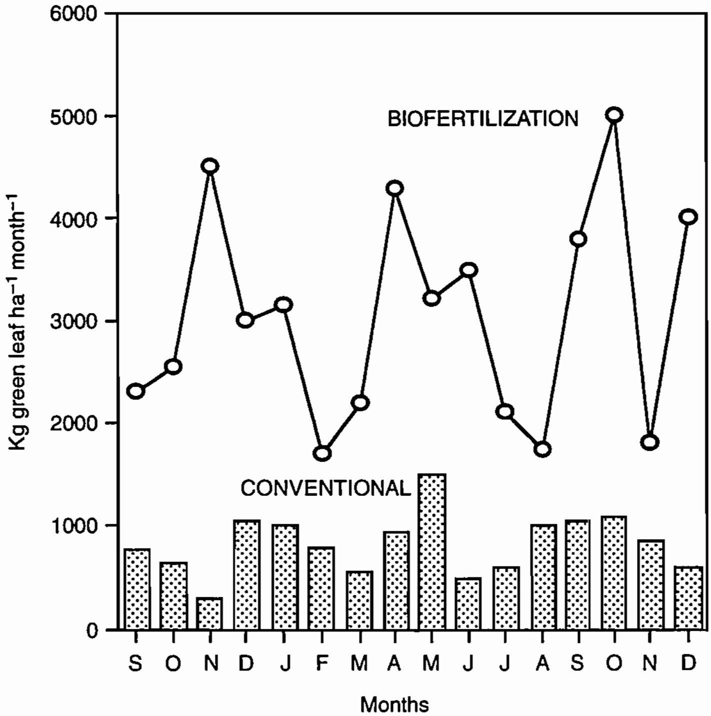

Fig. 7.17. Tea production at Sheikalmudi Estate (Tamil Nadu, India) in 1995, in plots managed with three different technologies.

Conclusions

Soil faunal communities and especially earthworms are negatively affected in most annual and some perennial cropping systems. Short-term and long-term earthworm inoculation experiments in different countries have indicated that management of organic matter and earthworms may significantly enhance plant production and profit (see Chapter 4). The bio-organic fertilization technique that allowed increases in tea production of 79.5–276% and of profit from 75.9–282%, respectively, in the first year following installation is a good example of the success of this approach in wealthy agricultural systems. This technique should be applied every time the high value of crops justifies it; this involves tree crop plantations in the tropics, and suburban horticulture where the shortage of land makes intensification of production necessary, and earthworm activities allow the use of low quality organic wastes as fertilizer. Remediation of degraded ecosystems might also benefit from these techniques, where earthworm activities may considerably accelerate soil formation and enhance production of pioneer trees used to recreate an ecosystem. More research is needed to consolidate and expand the technical knowledge elaborated in this project and in others.

However, the cost of earthworm production and inoculation (e.g. 5.5 Euro kg^{-1} fresh wt, i.e. at least 1500–2000 Euro to have a significant inoculum on a 1 ha base) is such that, in many cases, indirect stimulation of earthworm communities will be the only way to take advantage of their beneficial activities. This consists mainly of improving organic inputs through the use of suitable perennial plants when possible, or via organic inputs. Yet, it is still impossible to relate the amount of organic inputs of determined quality(ies) and the diversity and abundance of the soil macrofauna that will be sustained with these inputs.

Experiments at Carimagua suggest that the spatial and temporal array of parcels allocated to different crops may favour the conservation of locally high earthworm population density and diversity; these spots may serve as reservoirs and refuges for colonization of depopulated areas. However, much research is still necessary to produce simulation models and technical procedures that conceptualize these issues and result in applicable techniques.

Among the other important questions still not answered are the level of biomass that is required, the value of maintaining biodiversity in the managed communities, and the ways to achieve this purpose. Our results have shown that only a few earthworm species, mainly peregrine 'exotics', are susceptible to direct management. It has been proved recently that, under specific conditions of mismanagement of pastures in Central Amazonia, *P. corethrurus*, an exotic species that enhances the growth of most of the plants that have been tested, may behave like an 'invasive species', occupying niches made empty by deforestation and severely compacting the soil, with immediate negative effects on plant production and soil properties (Chauvel *et al.*, 1999).

The use of direct technologies such as the bio-organic fertilization technique, when it becomes widely used, will raise problems linked to the shift from the local to regional scale. Conflicts of interests possibly will occur due to the use of organic resources of different qualities, and space necessary for the production of the large amounts of earthworms required, at least in the early stages of the technical shift. As a result, while technical progress gradually improves techniques that favour earthworm activities, socioeconomic research will be needed to prepare the ground for their wide acceptance and optimal use.

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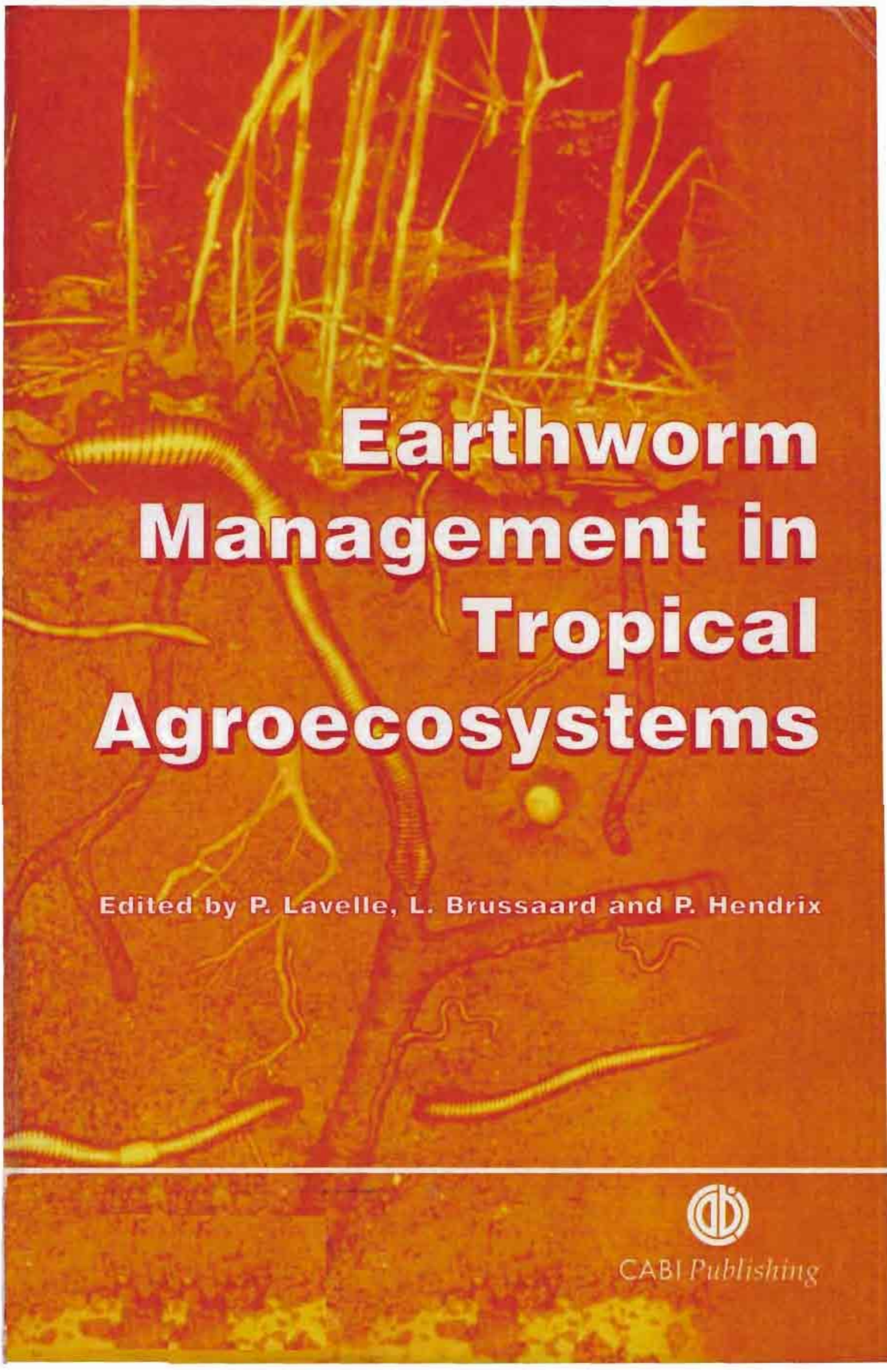

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