Restoring soil fertility and enhancing productivity in Indian tea plantations with earthworms and organic fertilizers

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Overview

The long-term exploitation of soil under the tea gardens in Southern India (where many estates are >100 years old) has led to impoverishment of soil fertility and stabilization of yields, despite increasing application of external inputs such as fertilizers and pesticides. Some of the soil degradative processes include:

- decreasing organic matter contents
- lower cation exchange
- reduced water-holding capacity
- loss in important soil biota (reduced up to 70%)
- acidification (pH down to 3.8)
- increases in toxic aluminum concentrations
- compaction of the soil surface
- soil erosion
- leaching of nutrients
- accumulation of toxins (polyphenols) from tea leaves.

On invitation from Parry Agro Industries Pvt. Ltd. (ex- C.W.S. India Ltd.), Prof. Patrick Lavelle from IRD (ex-ORSTOM) and Dr. Bikram K. Senapati from Sambalpur University began several joint projects in 1991 seeking to restore soil fertility and enhance tea production in six private tea estates of the Parry Agro-Industries Ltd., in the state of Tamil Nadu, India. These experiments showed that:

- a mixture of tea prunings, high quality organic matter and earthworms was very effective at raising tea yields (more than application of fertilizers alone) due to its favorable effects on physical and biological soil properties; a bio-organic fertilization technique increased yields from 79.5-276%
- the increase in yields by using a bio-organic fertilization technique ranged from 75.9-282%, representing a profit gain of up to US$5500 per hectare per year compared to conventional techniques
- despite soil faunal depletion in intensive tea plantations, there is a potential for recovering their population and activities by applying various organic materials
- with optimal limitation, there is a significant relationship between the earthworm populations present in the field and total green leaf tea yields
- the termite:earthworm ratio may be a good indicator for assessing soil degradation status.

The combined inter-disciplinary effort of scientists from two research/teaching institutions, and Parry Agro-Industries Ltd., led to the discovery of a practical, economical and conservation-minded solution, that has now been patented and is being spread to other sites in India and to other countries. The bio-organic fertilization technique and the principles of biological management of soil fertility with soil biota and organic matter, have great potential for widespread application, particularly in agro-forestry systems and where soil biological and physical health have been degraded due to intensive or long-term agricultural activities.

The Problem: Soil degradation under intensive tea plantations

Tea is an economically important, high-value plantation crop in India with an old history (*Photo* 1); many estates are more than 100 years old. Tea production levels in India were about 1000 kg ha^{-1} during the 1950's and these increased up to about 1800 kg ha^{-1} in the mid 1980's, due to the introduction of green-revolution technologies such as external chemical inputs (Senapati *et al*., 1994a). Nevertheless, no further yield increases have been obtained in average tea yields, despite increasing application of external inputs such as fertilizers and pesticides (*Photo* 2), and even spraying of plant growth hormones. Reasons for this stabilization are linked to chemical, physical and biological impoverishment of soil fertility under intensive tea production (Panigrahi, 1993).

Photo 1. A privately-owned (Parry Agro Industries Ltd.) intensive tea plantation in the southern Indian state of Tamil Nadu (photo P. Lavelle).

Evidence of this degradation can be seen in the low soil organic matter content, cation exchange and water-holding capacity, poor and little diverse soil fauna populations and highly acidic pH, and in the high soil compaction, erosion, nutrient leaching, accumulation of xenobiotics and toxic aluminum present under high input, intensive teal plantations (Pahigrahi, 1993; Senapati *et al*., 1994a; 1999). All these soil features reduce plant root growth and plant health, limiting any potential benefits of chemically-based recovery of soil fertility (e.g., with high fertilizer applications).

Figure 1. Soil macrofauna biomass (average of three sites; values in g per m^2) in natural forest reserves and nearby intensive tea plantations in Tamil Nadu, India. Trampled areas are zones within tea fields that were compacted by humans in harvesting activities (data from Senapati *et al.*, 1994a).

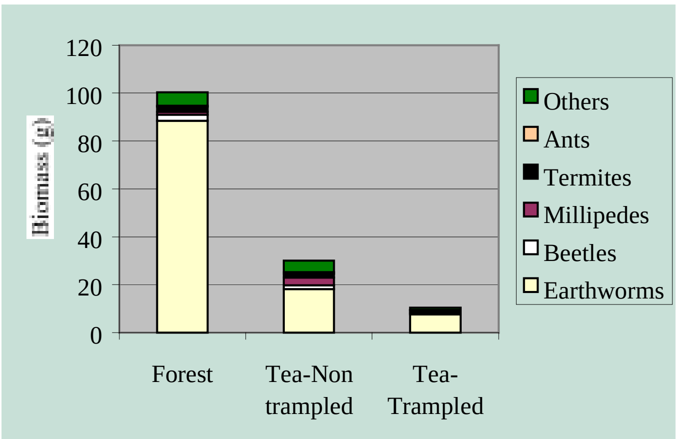


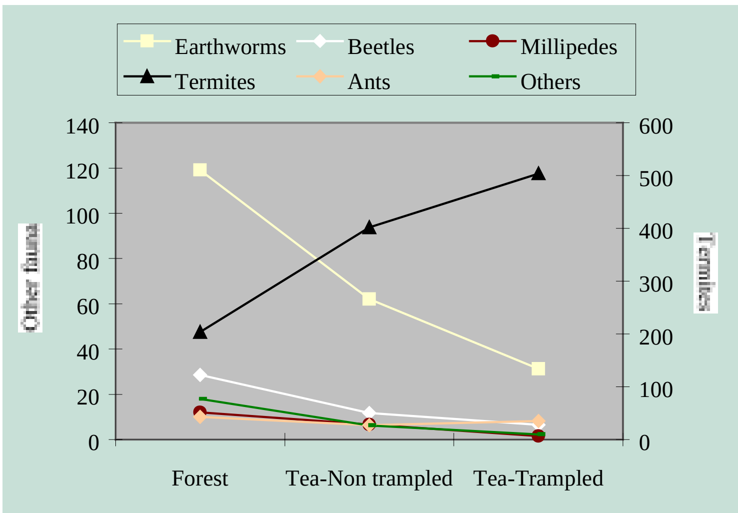
Photo 2. Application of external inputs in intensive tea plantations is very high and has led to considerable soil biological, physical and chemical degradation (photo P. Lavelle).

Intensive tea production and soil biodiversity

The soil conditions under intensive tea plantations are not conducive to high soil fauna populations and activity. Forest reserves dominated by native vegetation near three intensive tea plantations in Tamil Nadu showed a high biomass and density of various soil macro-fauna groups, which contrasted with the low biomass and density of most groups (except termites) in long-term tea plantations (Figures 1 and 2). Human-induced trampling of the soil during tea harvesting further reduced soil macrofauna populations, particularly their biomass (Figure 1). In contrast, abundance of termite pests increased in both trampled and non-trampled areas (Figure 2). The ratio of termite to earthworm populations calculated for several sites showed the potential use as an indicator of soil degradation (Figure 3).

Very few native earthworms were found in tea plantations, and most native species of both earthworms and other faunal groups probably disappeared after original forest was converted to tea plantations decades ago. However, these native animals were responsible for helping to regulate soil structure and organic matter incorporation, and this capacity was lost in conversion to tea.

Figure 2. Soil macrofauna abundance (average of three sites; values in number of individuals per m²) in natural forest reserves and nearby intensive tea plantations (trampled and non-trampled areas) in Tamil Nadu, India (data from Senapati *et al.*, 1994a).



Restoring soil health and tea production using the principles and practices of *Bio-organic fertilization* (FBO)

Because agro-chemicals are unable to sustain production increases and cannot restore soil fertility, solutions must be found to recover the soil's original characteristics (as in the forest), i.e., its biological, physical and chemical properties, before it becomes degraded. The naturally regenerating properties of organic matter are well recognized, such as its ability to increase cation exchange, plant nutrient availability (depending on quality), soil fauna populations and microbial activity, soil structure (aggregation, porosity) and physical processes (infiltration, water holding capacity, erosion).

In a response to this challenge, four separate treatments were installed in 1991 at the Caroline Tea Estate (private tea plantation), in Tamil Nadu, to test the effect of organic matter applications on tea yields and the recovery of soil fauna populations. The four treatments were:

- no fertilization (zero organic and zero inorganic)
- 100% organic fertilization (no inorganic)
- 100% inorganic fertilization (no organic)
- 50% organic, 50% inorganic fertilization.

Figure 3. Termite to earthworm ratios in native forest reserves and tea plantations in Tamil Nadu, southern India (from Senapati *et al*., 1994b).

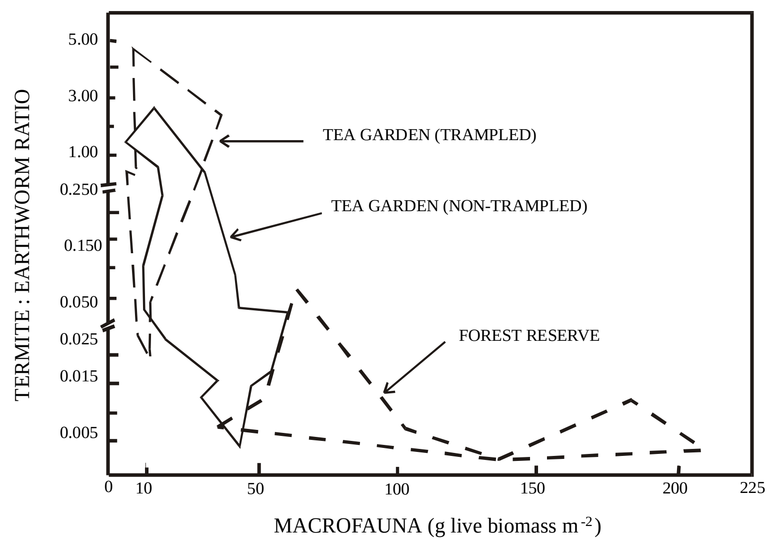
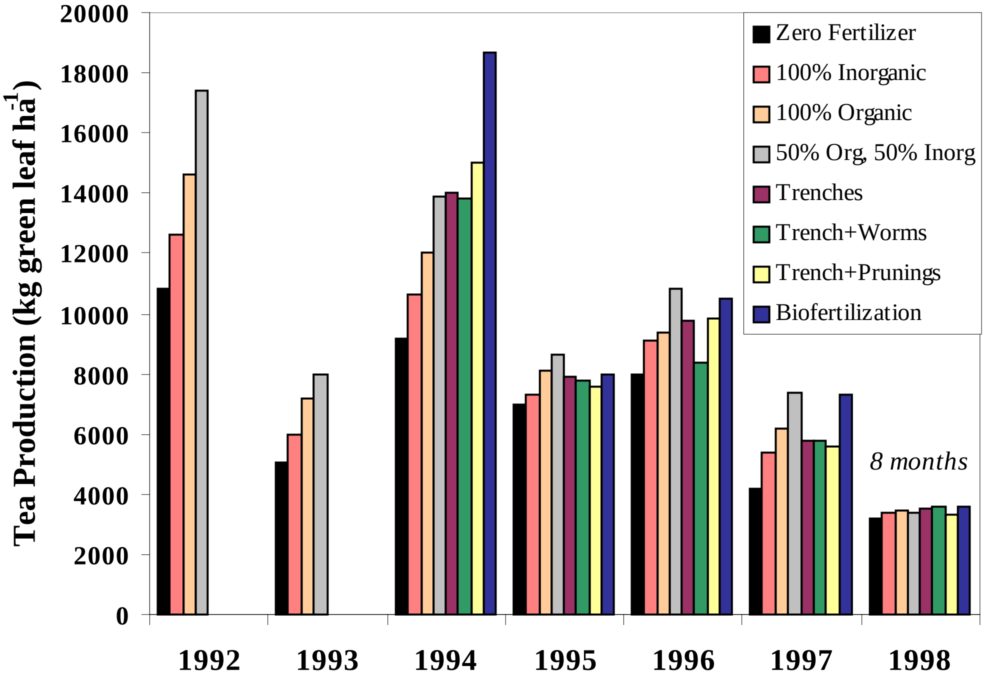


Figure 4. Effect of application of inorganic and/or organic fertilizers and earthworms alone or together with organic materials on annual green tea leaf production (total for year) during the period of 1992-1998, at Caroline Estate, Tamil Nadu (modified from Senapati *et al*., 1999). Data for 1998 represent the total for 8 months only.



The organic fertilizer utilized was a commercial fertilizer derived from composted urban organic wastes, and the amount applied was calculated by its nitrogen fertilizer equivalents, so that the same amount of N was applied with 100% inorganic and 100% organic fertilization. The composition of the commercially available organic fertilizer and the tea residues used is given in Table 1.

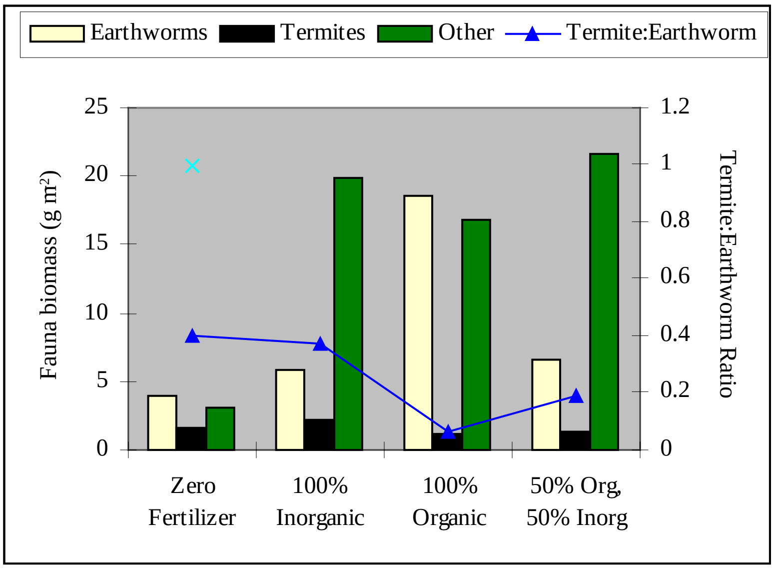
Table 1. Chemical composition of the organic materials applied (commercial organic fertilizer and tea prunings) at Caroline and Lower Sheikalmudi Tea Estates, Tamil Nadu, India (Natesan and Ranganathan, 1990; Senapati *et al.*, 1999).

	Commercial organic fertilizer	Tea leaf	Tea stem	Tea wood
PH	7.6	-	-	-
Electrical conductivity	0.34	-	-	-
%C	8.55	-	-	-
%N	0.67	3.2	1.37	1.04
C:N	12.8	-	-	-
%K	0.53	1.24	1.0	0.55
%P	1.0	0.1	0.07	0.03
%Ca	-	1.1	0.27	0.3
%Mg	-	0.17	0.09	0.06

The results showed that plots with 50% organic and inorganic fertilizers yielded 38, 32 and 31% more green tea leaf biomass in the first three years (1992-1994) compared to the conventional (100% inorganic fertilizer) treatment plots (Figure 4). Over 6 years (1992-1998), the average increase was 23%. The 100% organic fertilized plots also generally out-yielded the 100% inorganic, but to a lesser amount: 16, 17 and 13% in the first 3 years and 9% over the whole experiment (6 years). Cost benefit analyses over 3 years indicated that the 50:50 plots had a profit increase of 27-41% while the 100% organic plots had profits only 10-19% higher.

Furthermore, the application of organic matter also helped raise soil faunal populations, particularly those of earthworms and other arthropods (excluding termites) (Figure 5). The termite:earthworm ratio simultaneously decreased, indicating soil restoration was occurring. In fact, improvements in macroaggregate status and soil available P contents were observed, probably due to an organic matter-induced reduction in Al saturation and higher soil fauna activity.

Figure 5. Soil macrofauna biomass (g m^{-2}) and termite-to-earthworm ratios as affected by organic and/or inorganic fertilization in an intensive long-term tea plantation at Caroline Estate, Tamil Nadu (data from Senapati *et al.*, 1994a).



A second project was undertaken beginning in 1993, with support from the European Economic Community (EEC) and Parry Agro to evaluate the effect of digging trenches into the soil and incorporating or not tea prunings (tea was pruned in 1993), other organic materials and/or earthworms. Trenching is an old practice that has for the most part been abandoned in plantation crops due to the increasing cost of human labor and the substitution for other management techniques (Grice, 1977). Trenches are dug to help minimize soil loss, and improve soil moisture and aeration. Trenches 1.8 m in length, 0.3 m in width and 0.45 m in depth were prepared between the tea rows in 1 hectare blocks at Caroline and Sheikalmudi Estates (*Photo* 3). All trenches were fertilized with both inorganic fertilizers and the commercial organic fertilizer, in a 50:50 proportion.

Earthworms were reproduced by vermicomposting in large covered beds (6 m x 0.9 m x 0.5 m depth) in the field with several earthworm species (*Pontoscolex corethrurus, Megascolex konkanensis, Amynthas corticis* and *Metaphire houlleti*), using a mixture of locally available organic materials and soil (*Photo* 4). This process permitted 1000 adult or sub-adult earthworms to rapidly reproduce and multiply up to 15 times in number, over a period of 90 days. *P. corethrurus* dominated in the beds and therefore represented 80% of the earthworms added to the trenches.

Photo3. The digging of trenches in between tea rows to incorporate various organic materials as a way to restore soil health and tea productivity (photo P. Lavelle).

P. corethrurus is an exotic earthworm species often found in plantation crops in India and in the tea plantations studied, this earthworm species was initially found to be dominant over native earthworms species (Senapati *et al*., 1994a,b). However, inoculation of several species of earthworms and organic matter management at each site, helped rehabilitate native species over *P. corethrurus*. Various greenhouse and field trials have shown important increases in plant production when *P. corethrurus* is inoculated (Brown *et al*., 1999), but its long term impact has also been shown to be detrimental to the system under specific soil and climatic conditions, and in the absence of soil-decompacting earthworm species (Chauvel *et al*., 1999). Promotion of a single earthworm species or single inorganic/organic fertilizer was thus not a component or objective of the experimental conditions to be applied.

Choice of the quality, quantity and placement of organic materials to be used for earthworm production and organic fertilization of tea plantations was also a critical step in the use of these practices. The proper combination to apply was dependent on the status of soil degradation, local availability and its suitability to the ongoing crop culture practices. 'Diversity and dynamism as the key to sustainability and conservation' were followed as the motto during the whole process of development and application of the techniques and experiments here described.

Therefore, the treatments investigated were:

- trenches with (closed) or without (open) soil re-incorporated into the trench
- trenches with earthworms and their substrates (closed)
- trenches with incorporated organic materials varying in quality, quantity and placement
- trenches as above and earthworms (plus their substrates).

Photo 4. Covered vermiculture beds used to produce earthworms 'en masse' for inoculation into trenches (photo P. Lavelle).

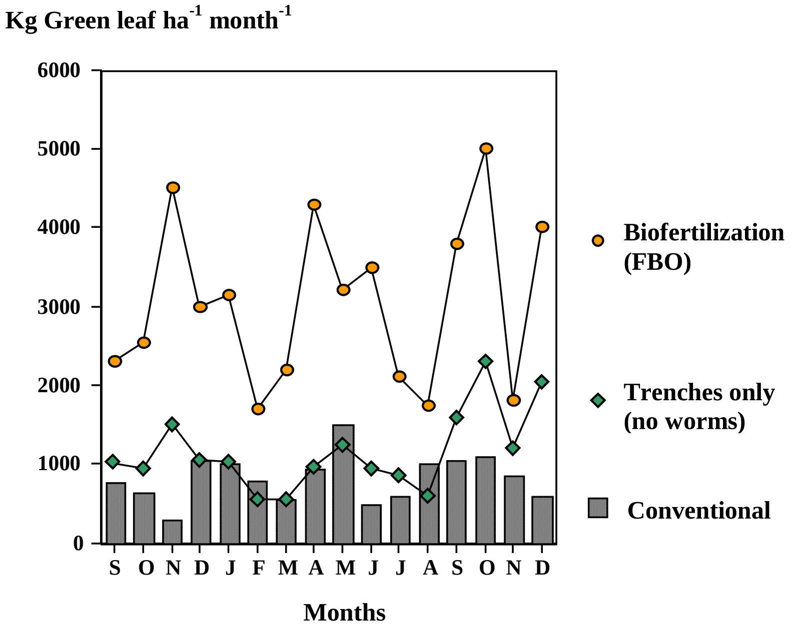
The principles and practices resulting from these experiments have created the technique called Bio-organic fertilization ('FBO' technology for short). FBO is an innovative package which is need-based, location-specific and synchronized as per the management practices of the individual (farmer or producer), institution or body. This innovation includes the following components:

- selection of different functional categories of earthworms
- mass scale production technology for vermiculture and primer
- selection of organic matter quality, quantity and placement
- application of inputs in 'fertilization units'
- adaptable management practices.

At the Caroline Estate, tea yields throughout the experiment (Figure 4) were far above the national average and reached up to 19,000 kg ha^{-1} year^{-1} with FBO the first year (1994). The corresponding profit increase in this treatment was 41% in 1994. The digging of trenches alone and trenches with different organic materials including tea prunings or earthworms by themselves led to significantly higher tea yields compared to the conventional treatment (100% inorganic fertilizers). However, these yields were not significantly higher than tea production levels in the 50% Organic + 50% Inorganic fertilizers treatment during the first year of the experiment. On the other hand, combination of earthworms and organic materials in the trenches, increased yields by 35% the first year compared with the mixed (50% Organic + 50% Inorganic) fertilizer treatment and by 78% compared with the conventional treatment, although in subsequent years the benefits of this technique over the mixed treatment were less evident, with similar yields in most years. Thus, the combination of organic materials with or without earthworms into trenches and their impact on green tea leaf production indicate a particular dynamism of these innovative techniques with time.

At Sheikalmudi Estate, application of earthworms in the trenches with or without organic matter applications led to considerable increases over trenching with or without tea prunings and the conventional treatment (100% inorganic fertilization) (Figure 6, Table 2). Tea pruning is one of the locally available organic resources/materials that were incorporated along with other materials at this site. Application of 'FBO' technology increased yields more than 230%, and profits (Table 2) increased more than 3.5 times the base value (US$2,000 ha^{-1}) in the conventional treatment, reaching up to more than US$7,000 ha^{-1} in the first year of application. The profits obtained using FBO technology were more than three-fold higher despite the costs associated with applying these techniques.

Figure 6. Effect of applying organic materials with or without earthworms into trenches, on green tea leaf production over a 16 month period at Lower Sheikalmudi Estate, Tamil Nadu (modified from Lavelle *et al.*, 1998).



Comparing the results obtained at both sites, it is apparent that the benefits of using earthworms and FBO were much greater at Sheikalmudi than at Caroline during the first year. The results that have been obtained from different experimental situations thus appear to vary in their response to the application of 'FBO' technology between sites as well as with time (at the same site), indicating a dynamism in this technique. This dynamism might be proportional to the recovery mechanisms from the original environmental degradation states, and the degree of response might be dependent on biogeographical regions, management practices and crop history, among other factors.

The 'FBO' technology must therefore be tailored to each specific site, and needs constant intervention of biologists to determine the optimum organic matter quality, quantity, combinations and placement, as well as to monitor the levels of macrofaunal diversity and density and production of biogenic structures (casts, burrows, nests, etc.).

Table 2. Tea production and cost-benefit analysis evaluation of different management techniques implemented in at Sheikalmudi Estate (Parry Agro-Industries, Ltd.) (adapted from Lavelle *et al.*, 1998). Conv = conventional with 100% inorganic fertilization and associated crop culture by Parry Agro; FBO = bio-organic fertilization technique, including earthworm selection, culture, primer preparation and their application along with organic matter quality, quantity and placement in bio-organic fertilization units.

	Management practices adopted				
	Conv.	Trenches alone	Trench+ worms	Trench+ prunings	FBO
Production (kg ha^{-1} yr^{-1})	2306	3104	8377	3132	8667
% increase	0	35	263	36	239
Income (US$ ha^{-1})	**2537**	**3414**	**9215**	**3445**	**9534**
Investment costs (US$ ha^{-1})					
Chemicals and manures	121	162	162	205	205
Manpower	419	573	1541	602	1600
Trench management	-	21	21	21	21
Earthworm management	-	-	114	312	114
Total costs	**540**	**756**	**1837**	**828**	**1940**
Profit (US$ ha^{-1})	**1997**	**2568**	**7378**	**2617**	**7594**
% increase	0	30	249	28	260

Despite the different responses observed, the benefits of FBO technology alternatives, especially over the conventional treatment (100% inorganic), were clearly evident at both sites, providing evidence for a synergistic positive interaction on tea yields, of the presence of both earthworms and high and low quality organic materials in trenches. Extensive root growth observed near and in the trenches may be one of the main mechanisms for the enhanced benefits accrued with FBO (Giri, 1995). Other benefits of FBO come from bioturbating (burrowing, casting, soil loosening), priming (changes in soil microflora communities and activity) and mineralizing activities (nutrient mineralization and organic matter decomposition rates) of earthworms, and the ameliorating properties of organic matter application to soils (e.g., Al detoxification, soil aggregation, cation exchange).

In fact, earthworm biomass and other macrofaunal biomass were linearly related to green leaf production, with an optimal limit that varied with age of plantation, soil quality and degradation status (management practice). It has now been realized that beyond optimal limits, neither the earthworm nor the feeder root biomass continue to maintain linearity. Furthermore, the ratio of termite to earthworm biomass also served as a useful and significant synthetic index value to indicate system degradation and restoration.

Conclusion: The potential for Bio-organic fertilization

The current adoption of FBO techniques in very large scale applications can already assure positive responses of up to 50% enhancement in production. Furthermore, other benefits can accrue, such as land restoration, product quality improvement, soil conservation, landscape and aesthetics values; these have, in many cases not yet even been evaluated (and will certainly greatly amplify the benefits of FBO). This is an indication that in worst case-scenarios, even if production enhancement is insignificant, cumulative values of other components in the system will benefit from the innovation.

Photo 5. Tea is a crop that demands much human labor when machines are not available; the FBO technology currently also has high human labor demands, although these can be reduced with the development of appropriate machinery and technologies (photo P. Lavelle).

Based on the results obtained at Caroline and Sheikalmudi Estates using FBO, a patent was deposited to protect the technique associated with this treatment (selection of earthworms, large-scale vermiculture and primer preparation, selection of organic materials by quality, quantity and placement and their management and application into trenches as a bio-organic fertilization unit). The patent, entitled “Fertilisation Bio-Organique dans les Plantations Arborées” (FBO), was developed by Parry Agro Industries Ltd., in association with the French Institut de Recherche pour le Développement (IRD) and Sambalpur University (Orissa, India). Details of the methodology for its application are described in the patent document (ref. PCT/FR 97/01363).

The holistic system approach of the ‘FBO’ technology has now been extended to about 200 ha in different Estates of Parry Agro-Industries and to other countries and over 20 million earthworms are being produced each year (Senapati *et al*., 1999). The latest development in this technology include the signing of 'LOI' (Letter Of Intent) among three parties (IRD, Parry Agro and Sambalpur University) in Nov. 2000, for technology transfer to China and Australia for large scale implementation. Furthermore, the possible application and benefits of applying the FBO technique and its principles and practices in other tree/bush crops should be explored. This wider applicability could include adoption of FBO to conserve and/or restore soil fertility in degraded or degrading sites planted with crops or bushes and trees such as: coffee, citrus or banana, and even plantations of coconut, oil palm, Eucalyptus or Pine species, etc.

However, FBO techniques are being assimilated at a slower pace than desired, especially because of the deep-rooted tradition of conventional technologies, upheld by agrotechnologists who comprise a large majority of the farm managers in India. Other such impediments for adoption should be investigated and ways of publicizing FBO more widely, and promoting its adoption in other countries experiencing the same difficulties (stagnating or decreasing tea yields and/or degraded or degrading soil conditions), should be found and implemented. Finally, another major constraint presently affecting wide-spread adoption of FBO may be its high human labor demands and the associated availability and cost (*Photo* 5). It was estimated that, in tea plantations, the target sites for application of FBO must be re-inoculated and the trenches re-dug every 3-4 years to ensure that the benefits continue at high levels. Thus, for the technique to lead to highest benefits, an inexpensive and readily available labor source must be present. This is the case for some countries such as India, but not for others, where the cost would become prohibitive unless manual trench digging could be substituted by machine powered diggers (in an economically viable manner), and the cost of producing earthworms (still considerably dependent on human labor) could be minimized. Additionally, as vermiculture techniques modernize and improve, the potential for reducing earthworm production costs for inoculation will increase, making FBO more feasible even in countries where human labor costs are high or few laborers are available.

References:

Brown, G.G., Pashanasi, B., Villenave, C., Patrón, J.C., Senapati, B.K., Giri, S., Barois, I., Lavelle, P., Blanchart, E., Blakemore, R.J., Spain, A.V. and Boyer, J. (1999) Effects of earthworms on plant production in the tropics. In *Earthworm management in tropical agroecosystems*, eds P. Lavelle, L. Brussaard and P.F. Hendrix, pp. 87-147. CAB International, Wallingford.

Chauvel, A., Grimaldi, M., Barros, E., Blanchart, E., Sarrazin, M. and Lavelle, P. (1999) Pasture degradation by an Amazonian earthworm. *Nature* **389**, 32-33.

Giri, S. (1995) *Short term input operational experiment in tea garden with application of organic matter and earthworm*. M.Phil. Thesis, Sambalpur University, Sambalpur.

Grice, W.J. (1977) Catchment planning and contour planting for safe water and soil conservaiton in the plain areas of north-east India. *Tea Research Association Memorandum* **28**, 1-19.

Lavelle, P. (1997) Faunal activities and soil processes: Adaptive strategies that determine ecosystem function. *Advances in Ecological Research* **24**, 93-132.

Lavelle, P., Bignell, D., Lepage, M., Wolters, V., Roger, P., Ineson, P., Heal, O.W. and Ghillion, S. (1997) Soil function in a changing world: The role of invertebrate ecosystem engineers. *European Journal of Soil Biology* **33**, 159-193.

Lavelle, P., Barois, I., Blanchart, E., Brown, G.G., Brussaard, L., Decaëns, T., Fragoso, C., Jiménez, J.J., Ka Kajondo, K., Martínez, M.A., Moreno, A.G., Pashanasi, B., Senapati, B.K. and Villenave, C. (1998) Earthworms as a resource in tropical agroecosystems. *Nature & Resources* **34**, 26-41.

Natesan, S. and Ranganathan, V. (1990) Content of various elements in different parts of the tea plant and in infusion of black tea from South India. *Journal of the Science of Food and Agriculture* **51**, 125-139.

Panigrahi, P.K. (1993) *Biological assessment of soil degradation under high input agroecosystem (tea) from south India*. M.Phil. Thesis, Sambalpur University, Sambalpur.

Senapati, B.K., Panigrahi, P.K. and Lavelle, P. (1994a) Macrofaunal status and restoration strategy in degraded soil under intensive tea cultivation in India. In *Transactions of the 15th World Congress of Soil Science,* Vol. 4A, pp. 64-75. ISSS, Acapulco, Mexico.

Case Study A1: **Restoring soil fertility and enhancing productivity in Indian tea plantations with earthworms and organic fertilizers**

Senapati, B.K., Panigrahi, P.K., Giri, S., Patnaik, A. and Lavelle, P. (1994b) Restoration of degraded soil in intensive tea plantation (India). In: *Conservation of soil fertility in low input agricultural systems of the humid tropics by manipulating earthworm communities*, CCE Macrofauna Project II (STD3) report nº 3, ed. P. Lavelle, pp. 39-51. LEST/IRD, Paris.

Senapati, B.K., Lavelle, P., Giri, S., Pashanasi, B., Alegre, J. Decaëns, T., Jiménez, J.J., Albrecht, A., Blanchart, E., Mahieux, M., Rousseaux, L., Thomas, R., Panigrahi, P.K. and Venkatachalan, M. (1999) In-soil technologies for tropical ecosystems. In *Earthworm management in tropical agroecosystems*, eds P. Lavelle, L. Brussaard and P.F. Hendrix, pp. 199-237. CAB International, Wallingford.