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Earthworm Populations, Microbial Biomass and Coffee Production in Different Experimental Agroforestry Management Systems in Costa Rica

YANIRIA SÁNCHEZ-DE LEÓN[1]*, ELIAS DE MELO[2], GABRIELA SOTO[2], JODI JOHNSON-MAYNARD[1], AND JAVIER LUGO-PÉREZ[1]

[1]*Plant, Soil and Entomological Sciences, Room 242, University of Idaho, Moscow ID 83844-2339, USA*
[2]*Centro Agronómico Tropical de Investigación y Enseñanza (CATIE), Escuela de Posgrado, Sede Central, CATIE 7170, Turrialba, Costa Rica.*
**Corresponding author: sanc0745@uidaho.edu*

ABSTRACT.—**Coffee management systems are diverse and can have significant impacts on soil biota. Earthworms are important members of the soil biotic community and may enhance soil fertility in agricultural soils. The impact of coffee management on earthworms and other factors related to productivity are not well known. Our main objective was to determine the impact of coffee management on earthworm populations, microbial biomass, and coffee production in Turrialba, Costa Rica. Three experimental coffee (*Coffea arabica* 'Caturra') management systems were studied: full sun, shade with *Erythrina poepiggiana* and shade with *Terminalia amazonia*. Within these systems there were three sub-treatments with different levels of inputs: high conventional or medium conventional sub-treatments with chemical fertilizer, herbicide and fungicide additions, and organic inputs in the shade systems. We found the earthworms *Pontoscolex corethrurus* and *Metaphire californica* in shade treatments, but *M. californica* was absent from sun systems and *Terminalia* high conventional systems. Mean earthworm density was lowest in the sun high conventional treatment (63 ind. m^{-2}), higher in medium conventional treatments (from 108 ind. m^{-2} to 225 ind. m^{-2}), and highest in *Terminalia* organic systems (334 ind. m^{-2}). In 2003, coffee production was highest in sun high conventional treatments (17.6 Mg ha^{-1}), but in 2004 it was highest in the *Terminalia* organic treatments (9.2 Mg ha^{-1}). Microbial biomass was not different among treatments, but was correlated with total earthworm density and biomass. Results indicate that shade organic management favors high earthworm density and biomass and that coffee yields under organic management can equal those of conventional systems.**

KEYWORDS.—**sun and shade coffee, organic, exotic earthworms, agroforestry, Costa Rica**

INTRODUCTION

Coffee is one of the most important agricultural commodities worldwide occupying 10,095,276 hectares of land (FAOSTAT data 2004), and providing economic support for 20 to 25 million people (Aguilar and Klocker 2000; Somarriba et al. 2004). In Costa Rica and other tropical countries, coffee exportation is considered a critical component of the country's economy (Aguilar and Klocker 2000; Somarriba et al. 2004). Because of its extensive cultivation and economic importance, there is considerable interest in improving the sustainability of coffee production in Costa Rica (Aguilar and Klocker 2000).

Management of coffee-producing lands in Costa Rica varies widely; with specific techniques depending on site conditions and socioeconomic pressures (Beer et al. 1998; Aguilar and Klocker 2000; Somarriba et al. 2004). Coffee management systems occur as a continuum from open-sun monocultures to multistrata coffee polycultures with different levels of agrochemical inputs (Somarriba et al. 2004). Sun coffee management is recommended in cloudy areas of elevation higher than 1000 m and in areas where agrochemical inputs are available (Beer et al. 1998; Aguilar and Klocker 2000). In areas that receive more intense radiation, the use of shade trees is considered

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beneficial because they decrease exposure of coffee plants to extreme heat or cold. Shade trees will also reduce wind speed, control erosion, and help maintain soil fertility (Beer et al. 1998; Aguilar and Klocker 2000; Somarriba et al. 2004). Within shade coffee systems, organic production represents a new market for farmers and an opportunity to increase income from coffee farms (Beer et al. 1998; Lyngbæk et al. 2001; Somarriba et al. 2004). Factors such as biological conservation, low environmental impact, valuation of environmental services (e.g., water and soil conservation, carbon sequestration) and the fall of international prices have placed organic coffee in a preferential place in the market over coffee produced with conventional practices (Beer et al. 1998; Lyngbæk et al. 2001; Somarriba et al. 2004).

Agricultural management in tropical agroecosystems has a significant impact on soil macrofauna communities, microbial biomass and soil organic matter (SOM) content (Woomer et al. 1994; Edwards and Bohlen 1996; Lavelle et al. 2001). These soil properties are essential for the maintenance of soil fertility and sustainable agricultural production in tropical regions through their influence on soil biological, physical and chemical properties (Scholes et al. 1994; Woomer et al. 1994; Lavelle et al. 2001). Agricultural management practices that minimize negative impacts on soil macrofauna and SOM are critical for maintaining the sustainability of agroecosystems (Woomer et al. 1994; Brown et al. 1994; Lavelle et al. 2001).

Soil macrofaunal populations play an important role in the degradation of organic matter, nutrient cycling, carbon sequestration, and soil aggregation and macropore formation through their behavioral activities (Edwards and Bohlen 1996; Sollins et al. 1996; Groffman and Bohlen 1999; De Goede and Brussaard 2002). Earthworms may have a positive or negative impact of variable magnitude on agricultural production through a variety of biological, chemical, and physical mechanisms (Brown et al. 1999; Senapati et al. 1999; Lavelle et al. 2001). As discussed by Brown et al. (1999), biological mechanisms include competition between earthworms and plants for water, increase in microbial biomass and microbial activity, alteration of carbon and nitrogen status, reduced damage from parasitic nematodes, and increased plant nutrient uptake. Chemical mechanisms include increased nutrient availability, recycling of nutrients from dead worm tissues and excretions, and accelerated nutrient release from decomposing plant residues. Physical mechanisms include changes in soil aggregation, porosity, aeration, water infiltration and bulk density.

Maintenance of SOM is of critical importance within tropical agroecosystems, because it is the principal source of energy for the soil ecosystem, and a nutrient source for plants (Woomer et al. 1994; Carter 1996; Schroth et al. 2001; Coleman et al. 2004). In addition, SOM improves soil physical and chemical properties important for plant productivity through increasing aeration, cation exchange capacity and water holding capacity while reducing erosion (Woomer et al. 1994; Carter 1996). Conceptually, SOM is described as separate pools that include the microbial biomass, macroorganic matter or coarse fraction, and mineral associated organic matter or fine fraction (Carter 1996). Changes in soil microbial biomass and SOM fractions in different agricultural management systems have been proposed as early indicators of change in SOM content (Powlson 1994; Woomer et al. 1994; Alvarez and Alvarez 2000).

Few studies of coffee management systems have focused on measuring and comparing the soil biological properties mentioned above in relation to coffee yields. Furthermore, Schroth et al. (2001) identified relationships among SOM dynamics, soil microorganisms and soil fauna in tropical agroforestry systems as a topic that deserves more research attention. The objectives of this study were to describe and compare earthworm populations, microbial biomass and coffee production among sun coffee plantations and shade coffee systems with *Erythrina poepiggiana*, a nitrogen fixer, and with *Terminalia amazonia*, a timber species in Turrialba, Costa Rica. These coffee plantations had different levels of agrochemical inputs (high conventional, medium conventional and intensive organic). In addition, we wanted to describe the relationship among the soil biological properties under these different management systems. We hypothesized that earthworm species composition, density and biomass, microbial biomass and SOM fractions would be higher under shade-organic than in the other management systems. We also hypothesized that there would be positive relationships among earthworms and microbial biomass.

Materials and Methods

Study sites

The study was conducted at the experimental coffee fields located at the "Centro Agronómico Tropical de Investigación y Enseñanza" (CATIE) facilities in Turrialba, Costa Rica (9°53′44″N, 83°40′7″W). The study area was located at 600 m above sea level, where annual precipitation was approximately 2600 mm yr^{-1} and the mean annual temperature was 21.8°C (Zuluaga Peláes 2004). Soils were classified as Typic Endoaquepts and Typic Endoaquults using the USDA Soil Taxonomy classification system (Soil Survey Staff 1999), with extensive drainage channels. The experimental fields were planted with two coffee cultivars, *Coffea arabica* L. 'Caturra', and in minor extent, *C. arabica* 'Costa Rica 95'. However, the present study was conducted in the areas planted with Caturra exclusively. The experimental design was an incomplete factorial treatment arrangement, in a randomized complete block design with three blocks and one replicate per block. Previous to the development of this study, the site had been in sugarcane (*Saccharum officinarum* L.) for at least 5 years.

Among the coffee management treatments established were sun and shade with either *Erythrina poepiggiana* (Walpers) O.F. Cook (nitrogen fixer), or with *Terminalia amazonia* (J.F. Gmel.) Exell a timber species that does not fix nitrogen. The number of shade trees in the *Erythrina* treatments was 49 trees ha^{-1} and in the *Terminalia* treatments was 63 trees ha^{-1}. The total area of the sun, shade with *Erythrina* and shade with *Terminalia* treatments was 4000 m^2, 4088 m^2 and 3200 m^2, respectively. These management systems were initially planted in 2000, but organic treatments had to be reestablished in 2001. Initially, the organic treatments were established with a lower shade tree density and with young shade trees that were too short to provide sufficient shade during the first year. The relatively high light intensity and low nutrient status of the soil resulted in a very high mortality of coffee plants. In 2001, a temporary shade (*Ricinus communis* L.) was introduced in the organic treatments, and in 2004 these trees were eliminated as appropriate shade levels were obtained.

Sub-treatments within the main coffee management treatments included: high, medium conventional and intensive organic. There was no organic sub-treatment within the sun coffee systems. Growers in the area do not use this combination due to the excessive cost of weed control. In high conventional treatments, agrochemical fertilizers and fungicides were used as in commercial fields and herbicides were applied to eliminate all the herbaceous cover. In the medium conventional treatment, fertilizer applications were half the amount of those within the high conventional treatment, and fungicides were used. Herbicides were applied to eliminate the herbaceous vegetation among individual coffee plants, but selected herbaceous species were left among coffee plants in a row. In organic treatments, organic fertilizers were used, no herbicides were applied, and undesired herbaceous species were removed manually and mechanically with a string trimmer. Fertilizer, herbicide and fungicide application rates within each sub-treatment are shown in Table 1. The annual inputs of key nutrients are shown in Table 2. In the high conventional *Erythrina* treatments only, the branches of the *Erythrina* trees were completely pruned twice a year as is typically done in the coffee farms of the region. All the organic material was left on the soil surface after pruning events. In shade medium conventional and organic treatments, the shade was regulated through pruning to control for irregular

TABLE 1. Fertilizer and herbicide applications and other inputs in the sub-treatments of the experimental coffee agroforestry systems

Sub-treatment	Fertilizer application	Herbicide application	Other inputs
High conventional	800 kg ha^{-1} yr^{-1} 18-15-6-2 (N, P, K, Mg and B) 45 kg ha^{-1} yr^{-1} NH_4NO_3 Foliar application: B, Zn (three times per year)	10 ml l^{-1} Roundup® to eliminate all herbaceous vegetation	fungicides: 2.5 g l^{-1} H_2O per block of Atemi or Copper sulfate (twice a year)
Medium conventional	400 kg ha^{-1} yr^{-1} 18-15-6-2 (N, P, K, Mg and B) 45 kg ha^{-1} yr^{-1} NH_4HO_3 Foliar application: B, Zn (once a year)	10 ml l^{-1} Roundup® to eliminate herbaceous species among coffee plants within a row	fungicides: 2.5 g l^{-1} H_2O per block of Atemi or Copper sulfate (once a year)
Organic	20 tons ha^{-1} yr^{-1} coffee pulp 7.5 tons ha^{-1} yr^{-1} chicken manure 200 kg ha^{-1} yr^{-1} KMAG 200 kg ha^{-1} yr^{-1} Phosphoric rock	No application of herbicides. Weeds were removed manually and mechanically with a string trimmer	No application of fungicides

TABLE 2. Fertilization rates for nitrogen (N), phosphorus (P) and potassium (K) in the sub-treatments of the experimental coffee agroforestry systems. Nutrient inputs from decomposition of shade tree biomass were not considered in these estimates.

Sub-treatment	N (kg ha^{-1} yr^{-1})	P (kg ha^{-1} yr^{-1})	K (kg ha^{-1} yr^{-1})
High conventional	221	17	98
Medium conventional	110	8	49
Organic	365	205	327

branching and, trees were never completely pruned. A detailed description of the sub-treatments and pruning regimes is presented in Zuluaga Peláes (2004) and Montenegro Gracia (2005). Nutrient additions to the soil through the decomposition of branches removed during pruning were not included in Table 2.

Earthworm collection

Earthworms were sampled in each of the three replicates of each treatment during July 2003. Five randomly assigned soil pits of 25 × 25 cm and 10 cm depth were located among the coffee plants rows. Earthworms were collected by hand sorting in the field and taken to the laboratory for counting and weighing. We obtained earthworm fresh weight after earthworms were rinsed with water and dried with paper towels on the same day of collection. Individuals were classified into morphospecies based on external morphological features, and a sub-sample of individuals from each group was preserved. The eco-taxonomic guide for peregrine earthworms developed by Blakemore (2002) was used to identify the earthworm species.

Microbial biomass and soil organic matter (SOM) fractionation

Soils were sampled during July and August 2004 in each replicate of the sun medium conventional, and *Erythrina* and *Terminalia* medium conventional and organic treatments. Microbial biomass and SOM measurements were not made in high conventional treatments. Twelve soil samples were collected from the upper 10 cm of each sub-treatment replicate and combined into a single representative sample (~500 g) per replicate. Soil samples were collected from the area between rows of coffee plants.

Microbial biomass carbon (C) was measured using the chloroform fumigation-extraction procedure using 0.5 M potassium sulfate (K_2SO_4) for extraction, and the Nelson and Sommer's method as described in Anderson and Ingram (1992). The factor for microbial C calculation was 2.64 (Anderson and Ingram 1992). Soil organic matter fractions were isolated by particle size fractionation (Cambardella and Elliott 1992). Soils were dispersed with sodium hexametaphosphate $(NaPO_3)_6$ and passed through a 53-μm sieve. The coarse fraction was defined as SOM greater than 53 μm, and the fine fraction was defined as SOM smaller than 53 μm. Organic carbon percent of each soil fraction was determined using the Nelson and Sommers's titration method for total organic carbon in soil extracts (Anderson and Ingram 1992).

Coffee production

Coffee yield was defined as ripe coffee berries that were hand picked from the coffee plants from June 2003 to January 2004, and from June 2004 to January 2005. Hereafter we will refer to these coffee harvesting periods as production 2003 and production 2004, respectively. The coffee production was measured in *fanegas* per hectare, the standard measurement for coffee bean production in Costa Rica. One *fanega* equals 2 hectoliters or 0.2 m^3. We used the standard accepted conversion (1 *fanega* = 258 kg or 0.258 Mg) to convert yields to a weight per unit area basis.

Data analysis

We used a one-way analysis of variance (ANOVA) using the Mixed Model to compare total earthworm density and fresh weight, earthworm density and fresh weight by species, and microbial biomass C and SOM fractions (dependent variables) among the eight combinations of coffee management systems (independent variable). Where the data violated the normality and homogeneity of variance assumptions, we performed a Friedman nonparametric ANOVA using the General Linear Model to compare earthworm density and fresh weight for the specific earthworm species. Treatment means were compared using the Tukey's Least Square Means analysis when statistical differences were detected. We used a repeated measure ANOVA using the General Linear Model to compare coffee production between years 2003 and 2004 and among treatments. The data for coffee production were log transformed before the analysis to fulfill the normality and homogeneity of variance assumptions. Simple linear correlations were used to determine the relationship between total earthworm density and microbial biomass C, and the relationship between earthworm fresh weight and microbial biomass C.

To test the effect of shade and level of agrochemical inputs on earthworm density, fresh weight and coffee production independently, we used a linear contrast test. We used this test instead of a two-way ANOVA due to the incomplete design. To test the effect of shade, we contrasted the sun treatments results versus the shade treatments, and *Erythrina* treatments versus *Terminalia* treatments. To test the effect of agrochemical inputs, we contrasted the organic versus the conventional treatments, and high versus medium conventional treatments. All the statistical analyses were preformed using SAS® Version 9.1 statistical software (SAS Institute Inc. 2004) and the significance level was set at $\alpha = 0.05$.

RESULTS

Earthworm populations

We found differences among coffee management systems for earthworm total density (Fig. 1a) and fresh weight (Fig. 1b). Mean earthworm density and fresh weight values were significantly lower in the sun high conventional treatments (63 ind. m^{-2}; 20 g m^{-2}) than in medium conventional sun treatments (91 ind. m^{-2}, 28 g m^{-2}). Under *Erythrina* shade, earthworm density and fresh weight were lowest in the high conventional treatment (131 ind. m^{-2}, 55 g m^{-2}), intermediate in the medium conventional treatment (186 ind. m^{-2}, 68 g m^{-2}), and highest in the organic treatment (265 ind. m^{-2}, 99 g m^{-2}). Similarly under *Terminalia* shade, earthworm density was lowest in the high conventional treatment (73 ind. m^{-2}, 24 g m^{-2}), intermediate in the medium conventional treatment (108 ind. m^{-2}, 32 g

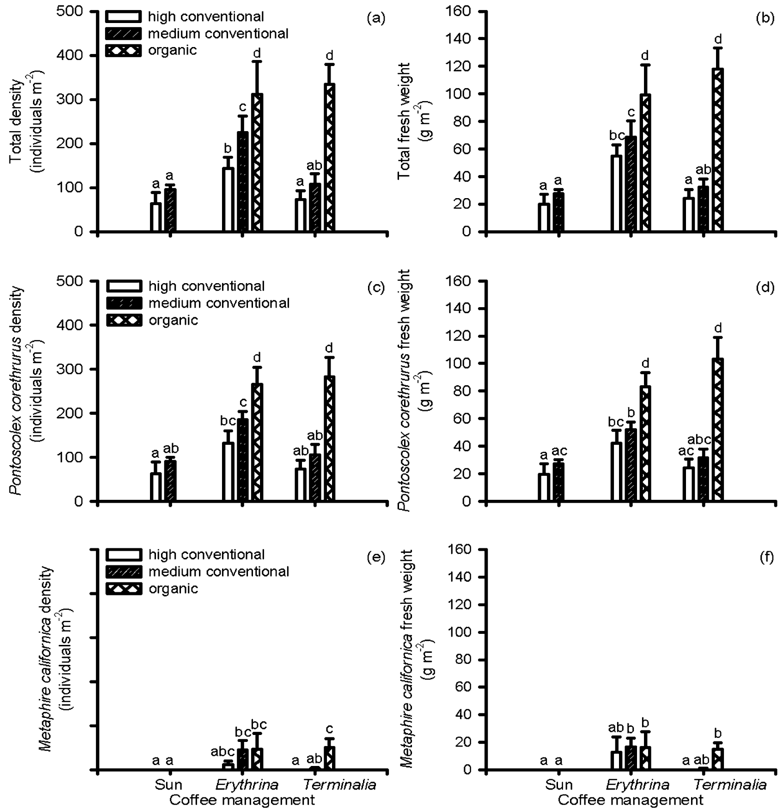

FIG. 1. Mean (±SE) earthworm density and fresh weight from total earthworms (a, b), *Postocolex corethrurus* (c, d) and *Metaphire californica* (e, f) under sun, *Erythrina* shade and *Terminalia* shade coffee management systems. Common letters indicate no significant differences among coffee management systems. Friedman non-parametric ANOVA analysis was used to determine significant differences among treatments for *M. californica* only.

m^{-2}), and highest in the organic treatment (334 ind. m^{-2}, 118 g m^{-2}).

Only the exotic earthworm species, *Pontoscolex corethrurus* (Müller) and *Metaphire californica* (Kinberg) were found in the study sites. *Pontoscolex corethrurus* was dominant and represented 76-100% of the total earthworm density (Fig. 1c) and fresh weight (Fig. 1d) in all treatments studied. Both species were present in shade treatments, however *M. californica* was absent from sun treatments and *Terminalia* high conventional treatments. *Metaphire californica* mean values for density (Fig. 1e) and fresh weight (Fig. 1f) were lowest in *Terminalia* high conventional treatment (3.2 ind. m^{-2} and 0.73 g m^{-2}) and highest in the organic systems (51.2 ind. m^{-2} and 16 g m^{-2}) ($P < 0.001$). The contrast analysis showed that there was an effect of shade and level of agrochemical input for both earthworm species densities (Table 3). However, type of shade (*Terminalia* vs. *Erythrina*) and type of conventional system (high vs. medium) had no effect on *P. corethrurus* fresh weight.

Microbial Biomass C and soil organic matter (SOM) fractionation

Mean microbial biomass ranged from 583 mg kg^{-1} in *Terminalia* medium conventional treatments to 913 mg kg^{-1} in *Erythrina* organic treatments (Fig. 2) and did not differ significantly among treatments. Percentages of SOM fractions were statistically different within management systems. The fine fraction percent by weight

TABLE 3. Statistics of linear contrast tests for the density and fresh weight of the earthworm species *Pontoscolex corethrurus* and *Metaphire californica* and coffee production 2003 (degrees of freedom for all test were equal to one)

	Treatments contrasted	F	P
Earthworm density			
Pontoscolex corethrurus	Sun vs. shade	29.55	<0.01
	Erythrina vs. *Terminalia*	5.19	0.02
	Organic vs. Conventional	86.72	<0.01
	High vs. medium conventional	4.57	0.04
Metaphire californica	Sun vs. shade	26.10	<0.01
	Erythrina vs. *Terminalia*	8.88	<0.01
	Organic vs. Conventional	40.78	<0.01
	High vs. medium conventional	7.66	0.02
Earthworm fresh weight			
Pontoscolex corethrurus	Sun vs. shade	28.82	<0.01
	Erythrina vs. *Terminalia*	1.01	0.32
	Organic vs. Conventional	99.52	<0.01
	High vs. medium conventional	1.85	0.18
Metaphore californica	Sun vs. shade	19.98	<0.01
	Erythrina vs. *Terminalia*	10.94	<0.01
	Organic vs. Conventional	21.61	<0.01
	High vs. medium conventional	3.20	0.01
Coffee production 2003	Sun vs. shade	4.80	0.04
	Erythrina vs. *Terminalia*	0.10	0.75
	Organic vs. Conventional	21.75	<0.01
	High vs. medium conventional	1.18	0.29

was always higher than the coarse fraction within each treatment (Fig. 3a). Differences among treatments were observed with higher mean percent of the fine SOM fraction in *Erythrina* medium conventional treatments and lowest mean percent in *Terminalia* organic systems (P = 0.035). The inverse pattern was observed for the coarse SOM fraction with the highest mean coarse SOM fraction in *Terminalia* organic systems and the lowest in *Erythrina* medium conventional systems (P = 0.042) (Fig. 3a).

Organic carbon content did not differ between fractions across management systems. Mean organic carbon percentages in the fine SOM fraction ranged from 5.3% in *Erythrina* medium conventional treatments to 6.3% in *Terminalia* organic systems (Fig. 3b). Mean organic carbon percentages in the coarse SOM fraction ranged from 4.4% in *Terminalia* medium conventional treatments to 5.3% in *Erythrina* organic systems (Fig. 3b).

Significant positive correlations were found among some of the measured variables in this study. Microbial biomass was positively correlated with total earthworm density ($y = 1.03x + 511.86$, $r = 0.65$, $P = 0.008$) and with total earthworm fresh weight ($y = 2.89x + 533.99$, $r = 0.63$, $P = 0.011$) across treatments. No significant correlations were found among SOM fractions and carbon percent within fractions and microbial biomass, or SOM fractions and total earthworm density and total earthworm fresh weight.

Coffee production

Coffee production mean values were higher in the sun high conventional (17.6 Mg ha^{-1}) and sun medium conventional (14.7 Mg ha^{-1}) compared to that measured in the rest of the treatments for year 2003 (P = 0.0045) (Fig. 4a). Coffee production under *Erythrina* shade was lowest in the organic treatments (3.2 Mg ha^{-1}) intermediate in medium conventional (9.9 Mg ha^{-1}) and highest in high conventional treatments (14.5 Mg ha^{-1}). Similarly, coffee production under *Terminalia* shade was lowest for organic treatments (4.5 Mg ha^{-1}) intermediate

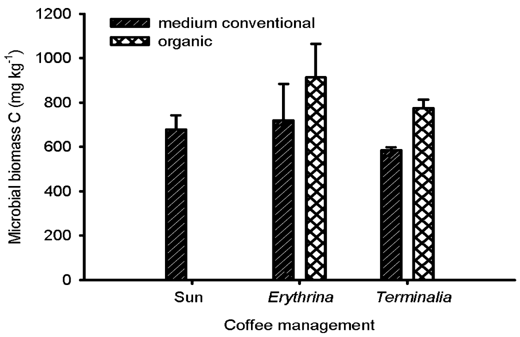

FIG. 2. Mean (±SE) microbial biomass C under sun, *Erythrina* shade and *Terminalia* shade coffee management systems. Microbial biomass C was not measured for high conventional treatments. There was no significant difference among treatments for microbial biomass.

in medium conventional (10.1 Mg ha^{-1}) and highest in the high conventional (13.3 Mg ha^{-1}). The contrast analysis showed that type of shade (*Terminalia* vs. *Erythrina*) and level of inputs (high vs. medium) did not significantly influence coffee production for year 2003 (Table 3).

In contrast to 2003 results, coffee production in 2004 was not statistically different among treatments (Fig. 4b). Coffee production ranged from in 5.1 Mg ha^{-1} in sun high conventional treatments to 4.5 Mg ha^{-1} in medium conventional treatments. Coffee production within *Erythrina* sub-treatments was not significantly different, however the organic systems produced the most coffee (8.2 Mg ha^{-1}), followed by high conventional (6.7 Mg ha^{-1}), and medium conventional (4.7 Mg ha^{-1}). *Terminalia* treatments produced similar results to those found in *Erythrina* systems, with organic systems producing 9.2 Mg ha^{-1}, followed by high conventional (6.6 Mg ha^{-1}) and lowest production in the medium conventional (2.9 Mg ha^{-1}). The repeated measures ANOVA also showed a significant interaction between treatment and time (P = 0.0049).

DISCUSSION

Our hypothesis, that earthworm species diversity, density and biomass would be higher under shade-organic compared to the other management systems was partially supported. We found the two earth-

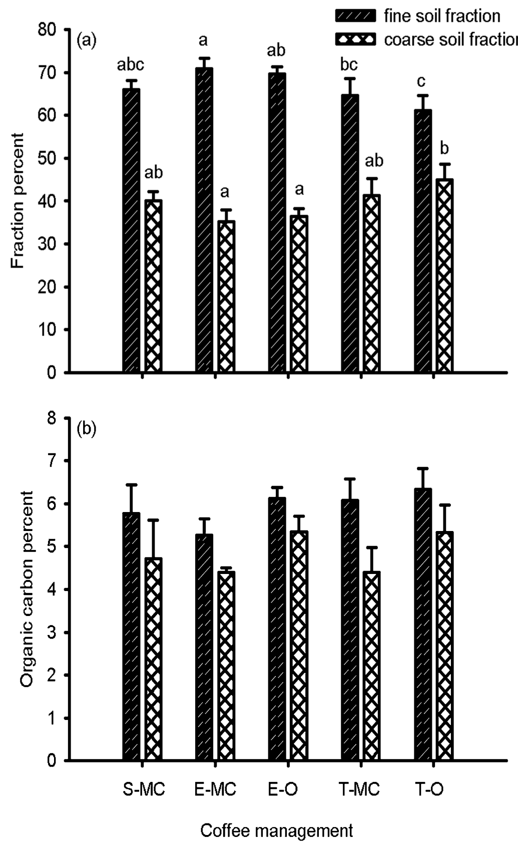

FIG. 3. Mean (±SE) SOM fractions (a) and organic carbon percent within SOM fractions (b) under sun medium conventional (S-MC), *Erythrina* medium conventional (E-MC), *Erythrina* organic (E-O), *Terminalia* medium conventional (T-MC), and *Terminalia* organic (T-O) coffee management systems. SOM fractions and organic percent carbon were not measured for high conventional treatments. Common letters indicate no significant differences among coffee management systems. There was no significant difference among treatments for organic carbon percent.

worm species in the shade-organic treatments and higher earthworm density and fresh weight than in the remaining treatments. In addition, we found that earthworm species composition was different among coffee management systems with *Metaphire californica* being absent from sun treatments and *Terminalia* high conventional treatments, and a clear dominance of *Pontoscolex corethrurus*. There are very few published studies on earthworm species composition in Costa Rican agroecosystems (Fragoso et al. 1999). Fraile (1989) described

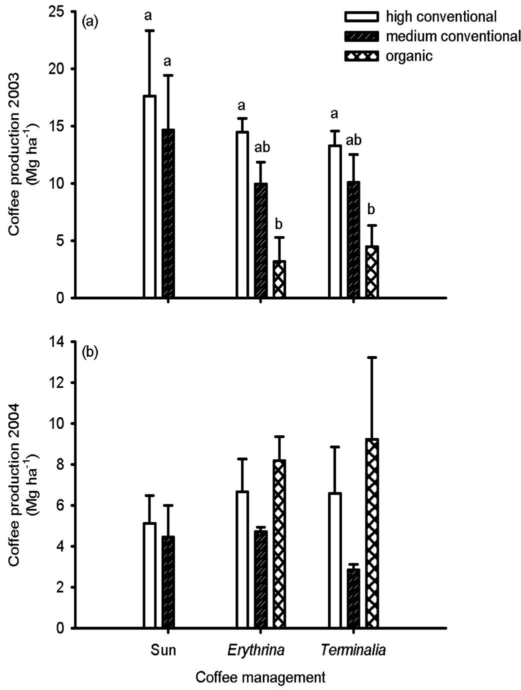

FIG. 4. Mean (±SE) coffee production (measured as ripe berries) under sun, *Erythrina* shade and *Terminalia* shade coffee management systems for year 2003 (a) and 2004 (b). Common letters indicate no significant differences among coffee management systems. There was no significant difference among treatments in year 2004.

earthworm populations for non-grazed pastures and pastures associated with the tree species *Erythrina poeppigiana* and the grass species *Cynodon plectostachyus* also in the region of Turrialba, Costa Rica. Fraile (1989) found that *P. corethrurus* was largely dominant in all the agroecosystems studied, *M. californica* was present in highest densities in pastures associated with *E. poeppigiana*, and only one native earthworm species *Glossodrilus nemoralis* was found in low densities. In a more recent study, Lapied and Lavelle (2003) sampled earthworms in banana plantations, primary forests and villages located along the Caribbean coast of Costa Rica. Lapied and Lavelle (2003) found that *P. corethrurus* was the dominant species at all study sites except for those within the Tortuguero National Park primary forest where it was absent, and densities were highest in banana plantations (361 individuals m^{-2}). Our results, therefore, are consistent with past studies showing that *P. corethrurus* is a dominant earthworm in agricultural systems in Costa Rica, and that this species is capable of living under a variety of conditions.

Our results also show that *M. californica* is not tolerant of habitat conditions under sun and *Terminalia* high conventional treatments. In contrast, the presence of *M. californica* in the *Erythrina* high conventional treatments suggests a shade species effect on the earthworm species composition. The ecological classification of these earthworms provides a possible explanation for our results. *Metaphire californica* is classified as an epi-anecic earthworm (Fragoso et al. 1999) which indicates that it lives in the surface soil, but feeds on leaf litter (Barois et al. 1999). *Pontoscolex corethrurus* is classified as a meso-humic earthworm which means that it lives in the upper 20 cm of the soil and feeds on soil in the upper 10 cm (Barois et al. 1999). In sun treatments and in *Terminalia* high conventional treatments, leaf litter quantity and/or quality is limited to that provided by the coffee plants or coffee and *Terminalia* plants, and this might not be sufficient to maintain *M. californica* populations. Furthermore, our contrast analysis showed that the shade species (*Erythrina* vs. *Terminalia*) had a significant effect on both earthworm species. These results show that *Erythrina* can provide enough aboveground and/or belowground inputs to maintain both *M. californica* and *P. corethrurus* populations. Other indirect influences of shade trees and their biomass inputs, such as differences in microclimate, and protection from predators by the litter layer, can also be affecting the presence of *M. californica* in the *Erythrina* agroforestry coffee systems.

Coffee management system had a significant impact on earthworm density and fresh weight. Organic systems had the highest density and fresh weight of total earthworms, *P. corethrurus* individuals and *M. californica* individuals followed by shade medium conventional treatments. The lowest mean total earthworm density and fresh weight was in sun and shade high conventional treatments. These results suggest that organic and shade medium conventional coffee management systems provided more favorable conditions for earthworm growth and reproduction than in sun and shade high conventional treatments. Brown et al. (1999) and Lavelle et al. (2001) suggested agricultural management practices that promote a diverse earthworm community in tropical agroecosystems. These suggestions included: mulching, restricted use of pesticides, incorporation of legumes, returning plant residues to the soil, and use of organic manures (Brown et al. 1999; Lavelle et al. 2001). In our study, the organic and shade medium conventional coffee management systems incorporated most of these practices, meanwhile sun and high conventional management included few or none of them. The presence of herbaceous plants could also influence earthworm populations. Herbaceous plants provide aboveground and/or belowground organic inputs that can be another food source for earthworms (Edwards and Bohlen 1996). In addition, the high use of agrochemicals (e.g., herbicides and fertilizers) can have a detrimental effect on earthworm populations (Edwards and Bohlen 1996; Brown et al. 1999) in the high conventional treatments when compared to organic and medium conventional systems.

Contrary to the prediction of our first hypothesis, microbial biomass and carbon in the fine and coarse SOM fractions did not differ among coffee sun and shade medium conventional and organic treatments. However, fine SOM fractions were higher in the sun and *Erythrina* treatments and lower in the *Terminalia* treatments, and the inverse results were observed with the coarse SOM fraction. These results show that having *Erythrina* or *Terminalia* as a shade species can influence SOM dynamics. Beer et al. (1998) and Schroth (2001) emphasize the importance of biomass production by the shade species as a way to maintain high SOM levels, and the associated soil fertility benefits, in tropical agroecosystems. Montenegro Gracia (2005) measured the biomass added to the soil-plant system after pruning of the shade species *Erythrina* and *Terminalia* in these experimental fields, and found a higher maximum contribution from *Erythrina* (11790 kg ha^{-1} yr^{-1}) than from *Terminalia* (3453 kg ha^{-1} yr^{-1}). Furthermore, Beer (1988) showed that the influence of nitrogen fixing trees, such as *Erythrina*, over SOM dynamics in fertilized plantations is more important than their influence on the soil nitrogen status. Zuluaga Peláes (2004) found higher total C and N in the top 10 cm of the soil in the *Erythrina* organic treatments than in the *Erythrina* medium conventional treatments, and suggested that the type of agricultural management (organic vs. agrochemical) had a significant effect over the C and N dynamics of these experimental agroforestry systems.

Coffee production in 2003 was greater in the high and medium conventional treatments in both sun and shade than within any of the organic treatments. In 2004, however, no significant difference was found. We also found a significant effect of the interaction between time and treatment in these coffee agroecosystems. This could be explained by the one-year lag in the establishment of plants in the organic treatments. For year 2003 results, we are comparing three-year-old coffee plants in high and medium conventional treatments with two-year-old plants in the organic treatments. The coffee plants in the organic systems were too young to produce a meaningful coffee harvest in 2003; however these plants were mature enough to have high coffee production the following year.

When high levels of agrochemical inputs are used, sun coffee management systems usually have higher yields than shade grown coffee (Beer et al. 1998). A general pattern of higher coffee yields in systems with sun coffee however, has not been demonstrated (Beer et al. 1998). Lyngbæk et al. (2001) performed a 3 year, paired comparison of coffee production in organic coffee farms and conventionally managed farms, and found that organic farms had mean coffee yields 22% lower than conventional farms. However, yields for some organic farms were higher than their conventional farm counterparts depending on inputs and labor of farm management (Lyngbæk et al. 2001). Our results for year 2004 support Lyngbæk et al. (2001) findings that intensive organic agroforestry systems can have equal or higher coffee production as compared to conventional systems if sufficient organic amendments and labor of farm management are provided. Our organic management systems had higher yields than most of the organic coffee producers in the Turrialba region. The coffee production in our shade organic management systems had mean values of 8.2 Mg ha^{-1} and 9.2 Mg ha^{-1} in the *Erythrina* and *Terminalia* treatments respectively, while the organic producers of the area produce less than 3.9 Mg ha^{-1} due to their minimal management practices. A recent study showed that more than 50% of the Turrialba organic coffee farmers do not apply fertilizers at all, prune or replant coffee plants in their farms (C. M. Porras personal communication).

Our second hypothesis was that there would be positive relationships between earthworm populations and microbial biomass. We found a positive correlation between microbial biomass and earthworm density and biomass. These results suggest that there exist positive interactions between earthworms and microbes, and/or that the conditions that positively influence earthworm populations also positively influence microbial biomass in these management systems. Inoculations of *P. corethrurus* have been shown to increase microbial biomass in microcosm (Araujo et al. 2004) and pot (Pashanasi et al. 1992) experiments. Earthworms can have a direct positive influence on microbial biomass through the production of mucus and other excreted compounds that serve as nutrient-rich substrates for microorganisms (Pashanasi et al. 1992; Araujo et al. 2004). Our data for earthworms and microbial biomass were taken one year apart, during the same time of the year (July). We expect, however, that in the absence of disturbance, the relationship between earthworm density and biomass and microbial biomass will be consistent from year to year. Although earthworm density may fluctuate from year to year, differences between tillage management systems have been found to be consistent (Butt et al 1999). For future studies, we suggest that both variables are measured at the same time.

The influence of microbial biomass and earthworm density and biomass on coffee production is less clear than the influence of earthworms on microbial biomass. A direct relationship between these soil biological parameters and coffee yields has not been described. Brown et al. (1999) performed a meta-analysis of earthworm effects on crop productivity. Their analysis showed that earthworm impact was mostly on plant root growth, shoot growth and whole plant growth and no significant effect was observed in other aspects of plant production (e.g. grain production). Coffee agroecosystems were not part of the Brown et al. (1999) analysis. However, an important consideration of the studies used in Brown et al. (1999) is that earthworm populations were manipulated specifically to measure their effects on plant production. In our study, earthworm populations were not manipulated. To elucidate the effect of earthworm populations and microbial biomass on coffee yields, experimental manipulation of these variables is necessary. We cannot demonstrate long-term benefits of any of these systems since our data were collected only 3 and 4 years after the treatments were established. This is especially true considering that it normally takes 5 to 6 years after coffee planting to get a profitable harvest (Aguilar and Klocker 2000). However, a more intense management regime that includes fertilization, weed management, and pruning, among other practices for organic systems may increase coffee production and earthworm populations in the local organic coffee farms.

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LITERATURE CITED

Aguilar, B., and J. Klocker. 2000. The Costa Rican coffee industry. In *Quantifying Sustainable Development: The Future of Tropical Economies*, ed. C. S. Hall, P. Van Laake, G. Leclerc, C. Leon Perez, 595-627. New York: Academic Press.

Alvarez, R., and C. R. Alvarez. 2000. Soil organic matter pools and their associations with carbon mineralization kinetics. *Soil Sci. Soc. Am. J.* 64:184-189.

Anderson, J. M., and J. S. I. Ingram. 1992. Tropical Soil Biology and Fertility: A Handbook of Methods. Wallingford: CAB International.

Araujo, Y., F. J. Luizao, and E. Barros. 2004. Effect of earthworm addition on soil nitrogen availability, microbial biomass and litter decomposition in mesocosms. *Biol. Fertil. Soils* 39:146-152.

Barois, I., et al. 1999. Ecology of earthworm species with large environmental tolerance and extended distribution. In *Earthworm Management in Tropical Agroecosystems*, ed. P. Lavelle, L. Brussaard, P. Hendrix, 57-85. New York: CABI Publishing.

Beer, J., D. Muschler, D. Kass, and E. Somarriba. 1998. Shade management in coffee and cacao plantations. *Agrofor. Syst.* 38:139-164.

Beer, J. W. 1988. Litter production and nutrient cycling in coffee (*Coffea arabica*) or cacao (*Theobroma cacao*) plantations with shade trees. *Agrofor. Syst.* 7:103-114.

Blakemore, R. J. 2002. *Cosmopolitan Earthworms—an Eco-Taxonomic Guide to the Peregrine Species of the World***.** 1st ed. CD-ROM. Australia: VermEcology.

Brown, G. G., et al. 1999. Effects of earthworms on plant production in the tropics. In *Earthworm Management in Tropical Agroecosystems*, ed. P. Lavelle, L. Brussaard, P. Hendrix, 87-148. New York: CABI Publishing.

Brown, S., J. M. Anderson, P. J. Woomer, M. J. Swift, and E. Barrios, 1994. Soil biological processes in tropical ecosystems. In *The Biological Management of Tropical Soil Fertility*, ed. P. L. Woomer and M. J. Swift, 15- 46. New York: John Wiley & Sons.

Butt, K. R., M. J. Shipitalo, P. J. Bohlen, W. M. Edwards, and R. W. Parmelee. 1999. Long-term trends in earthworm populations of cropped experimental watersheds in Ohio, USA. *Pedobiologia* 43:713-719.

Cambardella, C. A., and E. T. Elliot. 1992. Particulate soil organic-matter changes across a grassland cultivation sequence. *Soil Sci. Soc. Am. J.* 56:777-783.

Carter, M. R. 1996. Analysis of soil organic matter in agroecosystems. In *Structure and Organic Matter Storage in Agricultural Soils*, ed. M. R. Carter, and B. A. Stewart, 3-11. New York: Lewis Publishers.

Coleman, D. C., D. A. Crossley Jr., and P. F. Hendrix. 2004. Fundamentals of Soil Ecology. New York: Academic Press.

De Goede, R. M. G., and L. Brussaard. 2002. Soil zoology: an indispensable component of integrated ecosystem studies. *Eur. J. of Soil Biol.* 38:1-6.

Edwards, C. A., and P. J. Bohlen. 1996. *Biology and Ecology of Earthworms*. New York: Champman & Hall.

FAOSTAT data, 2004. http://faostat.fao.org/. Verified on January 12, 2005.

Fragoso, C., et al. 1999. Earthworm communities of tropical agroecosystems: origin, structure and influences of management practices. In *Earthworm Management in Tropical Agroecosystems*, ed. P. Lavelle, L. Brussaard, and P. Hendrix, 27-55. New York: CABI Publishing.

Fraile, J. M. 1989. Poblaciones de lombrices de tierra (Oligochaeta: Annelida) en una pastura de *Cynodon plectostachyus* (pasto estrella) asociada con árboles de *Erythrina poeppigiana* (poró), una pastura asociada con árboles de *Corida alliodora* (laurel), una pastura sin árboles y vegetación a libre crecimiento en el CATIE, Turrialba, Costa Rica. Tesis MSci, Universidad de Costa Rica y Centro Agronómico Tropical de Investigación y Enseñanza.

Groffman, P. M., and P. J. Bohlen. 1999. Soil and sediment biodiversity. *Bioscience* 49:139-148.

Lapied, E., and P. Lavelle. 2003. The peregrine earthworm *Pontoscolex corethrurus* in the East coast of Costa Rica. *Pedobiologia* 47:471-474.

Lavelle, P., et al. 2001. SOM management in the tropics: Why feeding the soil macrofauna? *Nutr. Cycl. Agroecosys.* 61:53-61.

Lyngbæk, A. E., R. G. Muschler, and F. L. Sinclair. 2001. Productivity and profitability of multistrata organic versus conventional coffee farms in Costa Rica. *Agrofor. Syst.* 53:205-213.

Montenegro Gracia, E. J. 2005. Efecto del aporte de nutrientes de la biomasa de tres tipos de árboles de sombra en sistemas de manejo de café orgánico y convencional. Tesis MSci, Centro Agronómico Tropical de Investigación y Enseñanza. Escuela de Posgrado. http://orton.catie.ac.cr/repdoc/A0295e/A0295e.html

Pashanasi, B., G. Melendez, L. Szott, and P. Lavelle. 1992. Effect of inoculation with endogeic earthworm *Ponstoscolex corethrurus* (Glossoscolecidae) on N availability, soil microbial biomass and the growth of three tropical fruit tree seedlings in a pot experiment. *Soil Biol. Biochem.* 24:1655-1659.

Powlson, D. S. 1994. The soil microbial biomass: Before, beyond and back. In *Beyond the Biomass. Compositional and Functional Analysis of Soil Microbial Communities*, ed. K. Ritz, J. Dighton, and K. E. Giller, 3-20. New York: John Wiley & Sons.

SAS Institute Inc. 2004. SAS OnlineDoc® 9.1.3. Cary, NC: SAS Institute Inc.

Scholes, R. J., R. Dalal, and S. Singer. 1994. Soil physics and fertility: the effects of water, temperature and texture. In *The Biological Management of Tropical Soil Fertility*, ed. P.L. Woomer and M.J. Swift, 117-136. New York: John Wiley & Sons.

Schroth, G., J. Lehmann, M. R. L. Rodrigues, E. Barros, and J. L. V. Macedo. 2001. Plant-soil interactions in multistrata agroforestry in the humid tropics. *Agrofor. Syst.* 53:85-102.

Senapati, B. K., et al. 1999. In-soil earthworm technologies for tropical agroecosystems. In *Earthworm Management in Tropical Agroecosystems*, ed. P. Lavelle, L. Brussaard, P. Hendrix, 199-237. New York: CABI Publishing.

Soil Survey Staff. 1999. *Soil Taxonomy. A Basic System of Soil Classification for Making and Interpreting Soil Surveys*. Washington D.C.: United States Government Printing Office.

Sollins, P., P. Homann, and B. A. Caldwell. 1996. Stabilization and destabilization of soil organic matter: mechanisms and controls. *Geoderma* 74:65-105.

Somarriba, E., et al. 2004. Biodiversity conservation in neotropical coffee (*Coffea arabica*) plantations. In *Agroforestry and Biodiversity Conservation in Tropical Landscapes*, ed. G. Schroth, G. A. B. da Fonseca, C. A. Harvey, C. Gascon, H. L. Vasconcelos, and A. N. Izac, 198-226. Washington: Island Press.

Woomer, P. L., A. Martin, A. Albrecht, D. V. S. Resck, and H. W. Scharpenseel. 1994. The importance and management of soil organic matter in the tropics. In *The Biological Management of Tropical Soil Fertility*, ed. P. L. Woomer, and M. J. Swift, 47-80. New York: John Wiley & Sons.

Zuluaga Peláes, J. J. 2004. Dinámica de la materia orgánica del suelo en sistemas agroforestales de café con *Erythrina poeppigiana* (Walpers) O.F. Cook en Costa Rica. Tesis MSci, Centro Agronómico Tropical de Investigación y Enseñanza. Escuela de Posgrado. http://orton.catie.ac.cr/repdoc/A0281e/A0281e.html