Research Article

The Influence of Strata on the Nutrient Recycling within a Tropical Certified Organic Coffee Production System

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Received 20 February 2012; Accepted 29 March 2012

Academic Editors: M. P. F. Fontes, B. Trognitz, and X. Xu

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In tropical Bolivia coffee plantations, the plant community can be separated into high (trees), middle (coffee), and low (weed) strata. Understanding the importance of each stratum is critical for improving the sustainability of the system. The objective of this study was to determine the importance of strata on nutrient recycling. Litter falls from the upper and middle strata were collected monthly using cone-shaped traps and divided by species into leaves, branches, flowers, and fruits. Dry biomass additions to the soil from high and middle strata totaled 12,655 kg (ha yr)⁻¹ annually. About 76% of the biomass was provided by plants of the genus *Inga* (*I. adenophylla* and *I. oerstediana*). The middle stratum (*Coffea arabica* L.) provided 24% litterfall biomass. This stratum also produced 1,800 kg coffee bean per ha (12% moisture) which sold for \$2.94 kg⁻¹. In the lower stratum, *Oxalis mollissima* returned 36 kg N ha⁻¹, while *Solanum nodiflorum* returned 49 kg K ha⁻¹, and *Urtica* sp. returned 18 kg Ca ha⁻¹. The nutrients recycled through plants in three strata exceeded the amount of nutrients removed in green coffee beans.

1. Introduction

Organic coffee production is an important industry in Brazil, Colombia, Mexico, and Bolivia. In these countries, the best quality coffee is produced at altitudes ranging from 1,200 to 2,000 meters above sea level with an annual temperature ranging from 17 to 23°C and between 1,600 and 2,800 mm yr⁻¹ of precipitation [1, 2]. The soil must have good drainage, fertility, and depth of at least 1 m [3–5]. The long-term resilience of this system requires that more nutrients be returned to the soil than are removed in the harvested fruit [6].

In Bolivia, the plant communities on the plantation can be separated into high, medium, and low strata. In the high stratum, two trees commonly found in coffee plantations are *Inga adenophylla* and *Inga oerstediana*. These trees (1) provide shade [7–12] that improves coffee quality; (2) recycle nutrients from deeper soil layers [13–17]; (3) protect the coffee bush from extreme wind and rain and excessive light; (4) help regulate climate variability [18, 19]; (5) help stabilize the soil, reduce soil erosion and bulk densities, and

increase water infiltration [20–22]; (6) as native leguminous plants provide N through symbiotic N₂-fixation [23–35]. The nutrients returned to soil by the higher strata can be substantial. Babbar and Zak [36] reported that the total N contribution was 145 kg N (ha year)⁻¹, while Aranguren et al. [37] and Bornemisza [38] had slightly lower estimates, with contributions ranging from 86 kg N (ha year)⁻¹ to 100 kg N (ha year)⁻¹.

In the middle stratum, coffee is grown and ripe fruits are harvested and processed, resulting in a green coffee “bean” that is commercialized. Branches and leaves from the coffee plant fall and return nutrients to the soil. The amount of N contained in these leaves can range from 28 to 35 kg N (ha year)⁻¹ [16, 37, 39]. Medina et al. [40] had similar results and reported that the leaves and branches from the coffee plant returned 41, 3, 10, 39, and 11 kg (ha year)⁻¹ of N, P, K, Ca, and Mg, respectively, to the soil.

In the lower stratum the typical plant community structure consists of *Oxalis mollissima*, *Urtica* sp., *Commelina* cf. *virginica* L., and *Solanum nodiflorum*. In organic systems,

FIGURE 1: Interaction of species with months for leaf falls over one year (interaction month $\times$ type of litter: $P = 0.0267$).

these plants are generally controlled through mechanical techniques. Benefits of these and other plants include reduced runoff and erosion, increased carbon sequestration, N fixation, and a habitat for beneficial insects [41–47]. The sustainability of organic coffee production systems requires that the interconnectivity of individual components be understood. The objective of this study was to determine the importance of strata on nutrient recycling in a certified mature tropical organic coffee plantation in Bolivia.

2. Materials and Methods

A field experiment was conducted in the Yungas Valley of Carmen Pampa located on the eastern slopes of the Andes. The latitude, longitude, and elevation at the site are $16^{\circ} 15' 31.17''$ S, $67^{\circ} 41' 32.77''$ W, and 1851 m.a.s.l. The region is characterized by mountain ranges with wide slopes and long valleys formed from sedimentary and metamorphic rock. In this region, elevation can range from 400 to 3500 m.

Soils at the research site were Humic Dystrudepts [48–50]. These soils have pH values that range from 4.3 to 4.5 [49, 51], have a loamy soil texture, a subangular, blocky structure, high organic matter levels (68 g kg^{-1}), moderate to high permeability, high Al content ($2.5\text{--}3.8 \text{ cmol}_c \text{ kg}^{-1}$), and low cation exchange capacity ($6.5\text{--}9.5 \text{ cmol}_c \text{ kg}^{-1}$).

The upper stratum is composed of two tree species, *I. adenophylla* and *I. oerstediana*. These trees were planted over 40 years ago. The spacing between trees is approximately 4 m. The medium stratum contained coffee (*Coffea arabica* L.) >10 years old. Litterfall samples from the upper and middle strata were collected with cone-shaped traps that were 1 m long by 1 m wide by 0.30 m tall [52, 53]. The traps were placed at random at a distance of 2 to 3 m from the trees and fixed at 10 cm above the ground. The traps are supported by four stakes at the corners. Litterfall was collected monthly and divided into species and vegetative parts (leaves, branches, flowers, and fruits of the upper and middle strata). The low stratum consisted of weeds that were less than 50 cm tall. Plant samples from the lower stratum were collected randomly three times in a year using a $75 \text{ cm} \times 75 \text{ cm}$ square frame and divided into species.

Collected litter fall samples were dried at 70°C , ground, and analyzed to determine N, P, K, Ca, Mg, and S content. Total nitrogen was determined by the Kjeldahl digestion

method followed by distillation. After ashing, phosphorus (P) was determined by the molybdenum blue colorimetric method, and potassium (K), calcium (Ca), and magnesium (Mg) were determined using an atomic absorption spectrophotometer.

To determine the diversity of soil macrofauna, above-ground litter samples were collected from the soil surface at ten random sites using a $20 \text{ cm} \times 20 \text{ cm}$ square frame. Macrofauna were extracted from approximately 100 g of this material using a Berlese funnel [54–56] for a period of five days. Individual macrofauna were identified and classified using comparison and taxonomy keys. Individuals of the same order were separated, quantified, and stored in ethanol.

Within the upper and middle strata each measurement was replicated at least 5 times. The amount of biomass and nutrients returned to the soil from major plant types within strata were determined. Litterfall was measured monthly from January to December of 2006. The importance of the 2 tree species (*Inga adenophylla* and *Inga oerstediana*) within the upper stratum was determined using a mixed model methodology in a two-stage approach (Statistical Analysis System version 9.2 for Windows). The first stage attempted to select an appropriate covariance model by the criterion with the minimum value of Akaike Information Criterion (AIC), the finite-population corrected AIC (AICC), and Schwarz's Bayesian Information Criterion (BIC), and the second stage assessed treatment and time effects using generalized least squares with the estimated covariance [57–59].

3. Results and Discussion

3.1. Biomass from the Upper and Middle Strata. Leaves returned to the soil from the upper and middle strata are a mechanism for returning nutrients to the soil. Leaf fall data showed a heterogeneous behavior during the year of collection, correlating with the phenological growth stage of each species. The high stratum (*I. adenophylla* and *I. oerstediana*) provided more total biomass in May, June, July, and August than the middle stratum, while in February, September, and October the middle stratum contributed more leaves than the upper stratum (Figure 1). These unexpectedly high contributions were most likely associated with the senescence due to nutritional deficiencies [60]. Leaf litterfall may also be affected by wind and rain [61], excess

TABLE 1: Annual litter and nutrient additions from different components of litterfall in the coffee agroecosystems.

Species			Inputs from litterfall (kg (ha yr) ⁻¹ , dry weight)						
			Litterfall	N	P	K	Ca	Mg	S
Upper stratum	<i>Inga</i> spp.								
		Leaves	3199	65.26	4.79	10.09	15.36	3.20	4.80
		Branches	814	6.43	0.47	1.62	4.31	0.49	0.81
	<i>I. adenophylla</i>	Flowers	1593	34.41	3.57	7.01	10.67	2.07	3.19
		Fruits	204	0.12	0.29	1.85	0.86	0.18	0.43
		Total	5810	106.22	9.11	20.56	31.20	5.94	9.23
		Leaves	2627	54.12	1.85	7.63	19.18	2.36	4.99
		Branches	417	3.04	0.29	0.80	2.84	0.25	0.38
	<i>I. oerstediana</i>	Flowers	675	nd	nd	nd	nd	nd	nd
		Fruits	94	1.95	0.12	1.25	0.57	0.12	0.17
		Total	3813	59.11	2.26	9.68	22.59	2.74	5.54
Middle stratum		Leaves	2210	54.15	3.60	27.51	40.22	4.64	5.97
		Branches	29	0.27	0.03	0.04	0.18	0.04	0.03
	<i>Coffea arabica</i>	Flowers	nd	nd	nd	nd	nd	nd	nd
		Fruits	793	0.87	1.08	9.08	1.67	0.95	1.27
		Total	3032	55.29	4.71	36.64	42.06	5.63	7.26
Lower stratum	Weed								
	<i>Commelina</i> cf. <i>virginica</i> L.		1136	35.22	4.65	46.48	8.75	3.07	1.48
	<i>Urtica</i> sp.		1028	32.07	3.94	25.60	18	2.78	2.26
	<i>Solanum nodiflorum</i> Jacq.		1476	43.25	4.68	48.88	14.17	2.36	4.87
	<i>Oxalis mollissima</i> R. Knuth		1272	36.12	4.03	43.39	10.56	3.18	2.16
	<i>Drymaria cordata</i> L.		1224	30.23	4.15	44.40	5.88	2.94	5.75
	Total	6136	176.89	21.44	208.75	57.34	14.32	16.52	

humidity, and foliar diseases caused by pathogenic fungi (*Mycena citricolor*, Berk and Curt) [62–65]. American leaf spot is one of the most serious fungal diseases in coffee production across Latin America [66, 67], causing premature defoliation [67–69].

Over the year, *Inga adenophylla* (3199 kg (ha yr)⁻¹) contributed more biomass from leaves to the soil than *Inga oerstediana* (2627 kg (ha yr)⁻¹). Both trees contributed more total biomass than coffee (2210 kg (ha yr)⁻¹), although coffee leaf loss under *I. adenophylla* was slightly greater in September. Fallen leaves are important to the cropping system as they cover the soil and thereby reduce erosion, recycle nutrients, and provide habitat for beneficial organisms [70, 71]. The litterfall becomes an important source of organic matter and activates the biogeochemical cycle [72–77]. The trees allow for more efficient capture of solar energy and favor the adsorption, retention, or capture of carbon and nitrogen above and below the ground [78–80].

3.2. Nutrient Return in Biomass from Upper and Middle Strata. The annual input of leaf litterfall returned to the soil was 8,036 kg dry weight (ha yr)⁻¹. Of this, 28% was from coffee, which contained 54, 4, 28, 40, 5, and 6 kg (ha yr)⁻¹ of N, P, K, Ca, Mg, and S. The 5,826 kg ha⁻¹ from the upper stratum contained 119, 7, 18, 35, 6, and 10 kg (ha yr)⁻¹ of N, P, K, Ca, Mg, and S, respectively (Table 1). The contributions from

the upper stratum were higher than those reported by OIRSA [81], Sánchez et al. [82], and lower than those by Alpizar et al. [83].

In organic coffee production it is critical to minimize N deficiencies. N deficiencies can cause yellowing in coffee leaves making the plant more susceptible to diseases such as *Cercospora* leaf spot and cherry/berry blotch [67, 84], which impacts quality and caffeine content [85–89]. Shade trees can reduce stress by providing N through N-fixation and by reducing N leaching losses [25, 90–95]. A comparison between the N content of the organically produced green beans and the well-fertilized production fields of this study suggests that N was above the critical level.

For long-term stability, the N removed by the crop must be less than the N returned to the soil. Assessing the nutrient balance is an important step in determining the long-term resilience of the system [96–98]. An important part of organic coffee systems is the shade trees. They take in N from the atmosphere and contribute this N to coffee through litterfall and subsequent decomposition [36, 99–103].

Branches from the upper and middle stratum contributed 1,260 kg (ha yr)⁻¹ of biomass to the soil. Of this, 98% was from *Inga* spp. and 2% was from coffee (Table 1). The annual nutrient return through branch litterfall in the upper stratum (*I. adenophylla* and *I. oerstediana*) was 9, 1, 2, 7, 0.7, and 1.2 kg (ha yr)⁻¹ of N, P, K, Ca, Mg, and S,

respectively. Branches from coffee provided 0.27, 0.03, 0.04, 0.18, 0.04, and 0.03 kg (ha yr)⁻¹ of N, P, K, Ca, Mg, and S, respectively.

Flowers made a relatively minor contribution to the soil. Although the two trees in the upper stratum flowered from June to December, the maximum contribution occurred in September. Flowers returned 34, 4, 7, 11, 2, and 3 kg (ha yr)⁻¹ of N, P, K, Ca, Mg, and S, respectively (Table 1). Nutrients returned to the soil from the coffee flowers in the middle stratum were insignificant.

Trees in the upper stratum and coffee in the middle stratum also returned nutrients to the soil in the form of fruit litterfall. The combined contribution from genus *Inga* and *Coffea arabica* was 1,091 kg (ha yr)⁻¹ dry biomass (Table 1). The total fruit biomass collected from the upper stratum was 298 kg (ha yr)⁻¹. Fruit provided 2.07, 0.41, 3, 1.43, 0.30, and 0.6 kg ha⁻¹ of N, P, K, Ca, Mg, and S, respectively. In the middle stratum, the contribution of coffee fruit litter was 793 kg (ha yr)⁻¹. Coffee fruit litter contributed 0.87, 1.08, 9, 2, 0.95, and 1.27 kg ha⁻¹ of N, P, K, Ca, Mg, and S, respectively.

3.3. Nutrient Removal in Harvested Coffee Fruit. The harvested coffee cherry was 1,800 Mg ha⁻¹. Nutrients removed in whole fruit were 57, 12, 122, 22, 13, and 17 kg (ha yr)⁻¹ of N, P, K, Ca, Mg, and S, respectively. Skin, pulp, and parchment were not returned to the field. Based on these values the N concentration in the harvested green beans was 31.7 kg (1,000 kg green beans)⁻¹. This concentration is similar to the values reported for well-fertilized systems [104, 105], which suggests that the system is above the critical level.

Chaves and Molina [106] reported that, in Costa Rica, a yield of 2,480 kg ha⁻¹ of parchment coffee can contain 242 kg N. Other studies showed that nutrient removal in whole fruit (*Coffea arabica*) was 35, 3, 54, 5, 10, and 3 kg (1,000 kg green beans)⁻¹ of N, P, K, Mg, Ca, and S [39, 104, 107]. Romero-Alvarado et al. [108] indicated that between 20 and 80% of a plant's N requirement can be supplied through the mineralization of soil organic matter.

3.4. Biomass and Nutrient Returned in the Lower Stratum. The dominant weeds in the lower stratum were *Solanum nodiflorum* Jacq., *Commelina* cf. *virginica* L., *Oxalis mollissima* R. Knuth, *Urtica* sp., and *Drymaria cordata* L. (Table 1). These weeds returned 6,136 kg (ha yr)⁻¹ of dry biomass. The contribution of biomass by weeds in the lower stratum was quite variable. The nutrients returned by the weeds in the lower stratum were 177, 21, 209, 57, 14, and 17 kg (ha yr)⁻¹ of N, P, K, Ca, Mg and S, respectively. The nutrients contained in the lower stratum were returned to soil following mechanical weed control that occurred at the beginning of the rainy season (November), harvest period, and prior to flowering.

3.5. Edaphic Mesofaunal Diversity. The lower strata also contained many insects that assisted in the degradation of plant residues and maintenance of soil quality [109–113].

FIGURE 2: Soil mesofauna in the shaded coffee agro-forest system.

These mesofaunal groups were extremely diverse. The largest group, which was 37% of the total, included the orders Glomerida, Plecoptera, Arachnida, and Mesogastropoda.

The second largest group, which represented 33% of the total, were Collembola (Figure 2). The least prevalent orders were Hymenoptera, Coleoptera, Diptera, Pauropodina, Acarina, Hemiptera, Dermaptera, Phalangida, and Protura which represented 29% of the total. These mesofauna play important roles in the decomposition processes of plant residues and accelerate nutrient recycling. In addition, they are excellent indicators of soil quality.

These results are comparable to studies conducted by Culik et al. [55] and Perfecto et al. [21] who stated that collembola populations are always relatively high (50 and 67%). Collembola have an important function in the decomposition process, carbon and nitrogen cycling in soil [114–116].

The high numbers of collembola and others were due to the contribution of litter fall residue during the annual cycle provided by the upper stratum of *Inga*, the middle shrub coffee stratum and the low stratum of weeds which increased the soil's ability to hold moisture, influenced the nutrient cycle and temperature, and protected the microfauna from large fluctuations in temperature and water.

4. Conclusion

In the upper stratum, legume trees for shade of the genus *Inga* (*I. adenophylla* and *I. oerstediana*) provided 9,623 kg (ha yr)⁻¹ dry biomass. In the middle stratum, cultivation of coffee (*Coffea arabica* L.) contributed 3,032 kg (ha yr)⁻¹ of dry biomass. In the coffee-legume system, a high proportion of N could be derived from litterfall. Also, the fallen leaves from the leguminous trees could be the main source of organic nitrogen to the soil, and the litter produced by the coffee is low. The low stratum is influenced by mechanical weed control performed three times per year. Soil mesofaunal communities were very diverse, and further research is required to fully understand the impact of the strata on edaphic mesofaunal diversity. An N mass balance indicates that the coffee plants were above the critical level and that N additions exceeded N removal.

Acknowledgments

Funding is provided by CN SARE and the South Dakota State Experiment Station.

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