ELSEVIER

Agriculture, Ecosystems and Environment 73 (1999) 19–28

Agriculture Ecosystems & Environment

Agroforestry system effects on soil characteristics of the Sarapiquí region of Costa Rica

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Received 10 March 1998; accepted 20 November 1998

Abstract

Agroforestry systems have been considered sustainable land-use alternatives for the humid tropics because they may imitate characteristics of natural ecosystems – notably those that have beneficial effects on soil properties. The objective of this study was to compare the effects of agroforestry systems on selected soil properties of Haplic Acrisols and Dystic Fluvisols, in the Atlantic Region of Costa Rica, approximately five years after their establishment. The agroforestry systems were established on unmanaged pastures near the La Selva Biological Station in 1989 and 1990. The original forest had been removed on most of these areas at least 25 years earlier. Tree components of the agroforestry systems were the tropical hardwoods *Vochysia ferruginea* (Botarrama), *V. guatemalensis* (Chancho), *Stryphnodendron microstachyum* (Vainello) and *Hieronyma alchorneoides* (Pilón). The soil properties studied included physical (soil bulk density; 0–10 cm), chemical [pH, exchangeable bases, extractable P, soil organic C (SOC) and total soil N; 0–50 cm] and biological parameters (mineralizable C and N and microbial biomass C and N; 0–15 cm). Soils were sampled in August 1995. Lower exchangeable bases and soil pH were noted in agroforestry treatments as compared to pastures. Extractable P was higher in the surface 25 cm of agroforestry plots. Total soil N, soil organic C and soil C : N ratios were not influenced by agroforestry systems. Higher mineralizable C levels were observed in pasture surface soils, but no differences in mineralizable N in soils under pasture and agroforestry systems were observed. Soil microbial biomass C and N and specific respiratory activity were not significantly different in pastures and agroforestry systems. Agroforestry systems did not appear to improve soils in this study compared to pasture.

Keywords: Soil quality; Sustainable agriculture; Agroforestry; Tropical agriculture

1. Introduction

Agroforestry systems have long been considered viable alternatives to degradative land uses in the tropics (Nye and Greenland, 1960), though some have questioned this assertion (Sanchez et al., 1985). Agroforestry systems theoretically may duplicate many characteristics of undisturbed ecosystems and incorporate several soil-conserving attributes of tree crops. The soil's capacity to sustain biological productivity, sometimes referred to as soil quality, can be estimated

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0167-8809/99/$ – see front matter
PII: S0167-8809(99)00004-3

by the evaluation of physical, chemical and biological parameters (Karlen et al., 1997). If agroforestry systems have a stabilizing or beneficial effect upon the soil resource, this practice might be employed to help reverse land degradation in the tropics. Fisher (1995) suggested that trees might improve soil quality in several ways. Many tropical tree species can fix atmospheric N_2 and may increase soil N content. The large root system of trees potentially accumulates nutrients from a large volume of soil, while litter fall concentrates nutrients near the soil surface. Litter fall and fine-root turnover may increase soil organic matter concentration. Trees may also enhance above- and belowground microclimate, while meso- and microfauna and microflora around plant roots may alter soil chemical, biological, and physical properties.

Soil parameters that strongly influence ecosystem functionality have been given high priority as indicators of soil quality (Visser and Parkinson, 1992), but no consensus has been reached about their exact nature or number (Karlen et al., 1997). Soil microbial biomass C (SMBC), a labile component of the soil organic C (SOC) pool, has been shown to be a short-term indicator of the effect of distinct management practices upon soil biological properties (Carter and Rennie, 1982; Campbell et al., 1991; Franzluebbers et al., 1994). For example, disturbed soils usually contain lower SMB than forests and grasslands (Jenkinson and Powlson, 1976). Specific respiratory activity, defined as the ratio between soil respiration and SMBC, is another effective indicator of soil management influence on microbial substrates and ecosystem health (Odum, 1969; Campbell et al., 1991), though Gregorich et al. (1994) raised concerns about applying such indices across soil types and cropping systems.

The specific objective of the present study was to evaluate the effects of agroforestry systems compared to pasture on selected soil chemical, physical and microbiological parameters.

2. Methodology

2.1. Study site

Agroforestry systems were established on unmanaged pastures on small farms in the Sarapiquí Cantón of the Atlantic region of Costa Rica as part of a larger project called TRIALS, in 1989 and 1990 (Butterfield, 1994). This region is tropical humid, with mean annual temperature of 25.6°C and mean annual precipitation of 3912 mm. Rainfall is somewhat seasonally distributed with drier months being February and March, but is >100 mm in all months (Sanford et al., 1994).

Soils of the Atlantic region of Costa Rica are highly weathered and very deep, with moderate-to-very low fertility and high in clay and organic matter (Parker, 1994). About 85% of the soils sampled in this study were classified as Haplic Acrisols, with the remainder being classified as Dystic Fluvisols (Stoorvogel and Eppink, 1995). Particle size distribution was determined on samples from three soil depths (0–10, 10–25, and 25–50 cm) in each plot using the hydrometer method (Gee and Bauder, 1986). Most soils in the study were clay textured (Acrisols), except for soils from two farms located in floodplains which had loamy textures (Fluvisols). Clay content of the floodplain soils decreased with depth (170, 135, and 83 g kg^{-1} at 0–10, 10–25, and 25–50 cm, respectively), whereas clay increased with depth in the other soils (434, 544, and 637 g kg^{-1} at the respective depths).

As a consequence of the mineralogy, organo-Al complexes control the 'active' Al in surface horizons as amorphous Al stabilizes and favors accumulation of organic matter. Upper horizons have a low pH, predominantly due to dissociation of carboxyl groups of soil organic matter (Shoji et al., 1993).

2.2. Characterization of agroforestry systems

All farms in the study are located within a 15-km radius of the La Selva Biological Station (LSBS) (10° 26′N, 83° 59′W), which served as a base for the field work. Agroforestry systems were previously established in 0.25 ha plots utilizing tree species in a 3 × 3 m pattern in monoculture. Nine farms were selected, comprising fifteen agroforestry plots. A plot (also ≈0.25 ha) of perennial pasture adjacent to the agroforestry plots was selected at each farm for comparison. Care was taken that the pasture represented the same terrain and general soil characteristics as the agroforestry areas.

The tree species utilized in the on-farm plots and selected for subsequent soil sampling were tropical

Table 1
List of species used in the on-farm agroforestry systems and associated characteristics

Scientific name	Common name	Family	Characteristics
Trees			
Hieronyma alchorneoides	Pilón	Euphorbiace	Good litter-producer
Stryphnodendron microstachyum	Vainillo	Mimosacea	Nitrogen-fixing, low litter-producer
Vochysia guatemalensis	Chancho	Vochysiaceae	Good litter-producer, 'Al accumulator' [a]
Vochysia ferruginea	Botarrama	Vochysiaceae	Good litter-producer, 'Al accumulator'

[a] According to González (1996).

hardwoods (Table 1) that performed well (as determined by growth rate and economic value) in previous screening trials at the LSBS (González and Fisher, 1994; Fisher, 1995). Canopy closure occurred approximately three years before our soil sampling in August 1995. Cattle (*Bos taurus*) grazing was observed on six farms. Cattle were not confined to plots, but had unlimited access to adjacent pastures (mostly *Panicum stenatale* and *Melinis* sp.). Stocking rates were apparently very low.

2.3. Soil physical analyses

Bulk density measurements (0–10 cm) were made in triplicate in each study plot using coring devices (42.2 mm diameter PVC tubes) carefully driven into the soil to avoid compaction. Bulk density was calculated from oven-dried soil core weight and volume.

2.4. Chemical analyses

Soil samples for chemical analyses consisted of 10 composited cores (25.4 mm diameter) taken from three depths (0–10, 10–25 and 25–50 cm) in each plot. Samples were air-dried at Texas A&M University upon arrival and sieved to pass a 2 mm mesh. All chemical analyses were done in triplicate according to methods described in Page et al. (1982).

Soil pH was measured in a 1 : 10 soil : water dilution (w/v) with a glass electrode. Exchangeable bases were extracted with neutral 1 M NH_4OAc solution with concentrations determined by inductively coupled plasma (ICP) spectrometry. Phosphorus was extracted using Olsen's modified extractant (Fisher, 1995) with concentrations determined by ICP spectroscopy.

2.5. Soil carbon, nitrogen and biological analyses

Soil samples for C, N and biological analyses consisted of 20 composited cores taken at two depth increments (0–5 cm and 5–15 cm). Samples were air-dried within a few hours after collection at LSBS with forced ventilation. Analyses were conducted in triplicate.

Soil organic C was determined by the modified Mebius method (Nelson and Sommers, 1982). Total soil N was determined according to a Kjeldahl procedure, followed by analysis of NH_4-N by autoanalyzer techniques.

Mineralizable C (CMIN) was determined directly by measuring CO_2-C evolution (Anderson, 1982) during an incubation period as proposed by Campbell et al. (1991) with modifications (Franzluebbers et al., 1994). Total CMIN was calculated from the 21-day cumulative CO_2 evolution.

Mineralizable N (NMIN) was obtained by determining NH_4-N + NO_3-N concentrations in the incubated soil samples from the CMIN experiment (Franzluebbers et al., 1994) following extraction with 2 M KCl and analysis by an autoanalyzer.

Soil microbial biomass C (SMBC) was determined by the chloroform fumigation/incubation method proposed by Jenkinson and Powlson (1976) with modifications (Franzluebbers et al., 1994), using $k_C = 0.41$ (Voroney and Paul, 1984). This constant represents the fraction of microbial C mineralized in the 10-day incubation following fumigation. Soil samples were rewetted and pre-incubated for seven days prior to fumigation. Franzluebbers et al. (1996) demonstrated that air-dried samples that were rewetted and pre-incubated for seven days prior to fumigation resulted in similar SMBC values as samples that were continuously field moist.

Soil microbial biomass N (SMBN) was determined from mineral N concentrations of subsamples from the SMBC experiment following fumigation/incubation minus mineral N concentrations of unfumigated soils rewetted and incubated for the same time period (Franzluebbers et al., 1994) with $k_N = 0.41$ (Carter and Rennie, 1982). Ammonium-N concentrations in 2 M KCl extracts were determined by autoanalyzer techniques. Specific respiratory activity (SRAC) was determined from C mineralization and SMBC as described by Franzluebbers et al. (1994).

2.6. Statistical analyses

Comparisons were made among individual agroforestry systems (i.e. tree species) and pastures and between pooled agroforestry systems and pastures. The statistical procedure used in this study was a mixed model ANOVA that supported unbalanced data sets in which the number of treatments was not equal in each block, that is to say not all farms had all agroforestry systems. Comparison of means of individual agroforestry systems and pastures was performed with Tukey's honestly significant difference test. Student's *t*-test was employed in the pooled agroforestry systems vs. pastures comparisons. All analyses were performed using a statistical software package (SAS Institute Inc., 1994).

3. Results and discussion

3.1. Soil bulk density

No differences in surface soil bulk density were observed between individual agroforestry systems or pooled systems and pastures (mean bulk density of 0.96 Mg $m^{-3} \pm$ SD 0.071). Cattle grazing increased bulk density slightly (0.11 Mg m^{-3}), though not significantly. Our results conflict with those of Fisher (1995) who showed a significant decrease in soil bulk density associated with many of the same tree species used in our study. Although several tree species in our study are heavy litter producers (most notably, *Vochysia* sp.), the effect of this factor on soil bulk density was not statistically significant. One counteracting factor, not present in Fisher's study, was cattle trampling, which has been reportedly associated with soil compaction (Payne, 1985).

3.2. Soil pH

Pasture compared to the individual agroforestry systems had significantly higher pH in the soil surface (0–10 cm) than plots with *S. microstachyum* (Fig. 1). Pastures also exhibited higher pH at 10–25 cm depth compared to all agroforestry systems. No pH difference was observed at the lowest depth. Pooled comparisons also showed that soil pH in the agroforestry plots was lower than pastures for the first two depths sampled (Table 2).

Regenerating vegetation (as in a fallow period) will frequently decrease pH in soils with low nutrient stocks (Juo and Manu, 1996). This phenomenon might be related to several mechanisms that release H^+ ions, such as cation uptake by biomass, decomposition of organic matter to organic acids and CO_2, root respiration and nitrification. These processes are counterbalanced to some extent by several sinks for H^+ – the weathering of soil minerals, anion uptake by biomass and release of cations from soil organic matter (Binkley and Richter, 1987). The increased accumulation of aboveground biomass and associated cation uptake by the tree component of agroforestry systems is possibly one of the causes for decreased pH in these soils. Agroforestry systems showed significantly lower pH at the 10–25 cm depth (Fig. 1), probably because tree root abundance is higher at this depth (Bowden, 1985). Although pastures often exhibit root abundances at least one order of magnitude higher at the surface (Bowden, 1985), the lower soil pH with agroforestry systems at 0–10 cm (Table 2) might be associated with greater litter production. Likewise, pasture

Table 2
Pooled comparisons between agroforestry systems and pastures for soil pH at three soil depths

Treatment	Soil pH [a]		
	0–10 cm	10–25 cm	25–50 cm
Agroforestry systems	4.75b	4.75b	4.77a
Pasture	5.13a	5.13a	5.04a

[a] Means within depths followed by the same letter are not significantly different ($p < 0.01$).

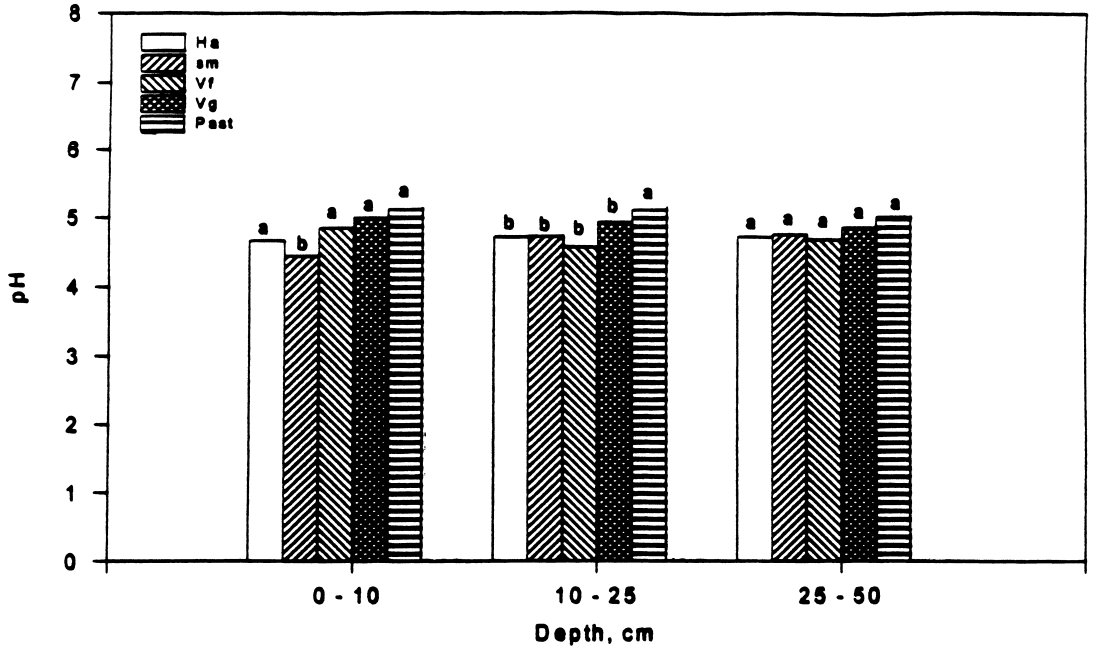

Fig. 1. Soil pH at three depths as affected by agroforestry systems. Sm – *Stryphnodendron microstachyum*, Ha – *Hieronyma alcheorneoides*, Vg – *Vochysia guatemalensis*, and Vf – *Vochysia ferruginea*, Past-pastures. Means with the same letter and depth are not statistically different ($p \leq 0.10$).

grasses produce less total biomass and consequently accumulate fewer cations.

3.3. Exchangeable bases

Comparisons among individual agroforestry systems and pastures yielded few significant differences for exchangeable Ca, Mg, K and Na (data not shown). Potassium was significantly lower in the *V. guatemalensis* treatment than in pastures in the 10–50 cm depths.

Differences in exchangeable bases utilizing pooled comparisons between agroforestry systems and pastures were observed (Table 3). Calcium was significantly higher at 0–25 cm in pasture as compared to agroforestry systems. Magnesium was higher in pas-

Table 3
Pooled comparisons between agroforestry systems and pastures for exchangeable bases at three soil depths

Treatment	Ca ($cmol_c\ kg^{-1}$)[a]	Mg	K	Na
0–10 cm depth				
Agroforestry systems	2.10b	0.88a	0.40b	0.41b
Pastures	3.95a	1.27a	0.63a	0.51a
10–25 cm depth				
Agroforestry systems	1.04b	0.37b	0.18b	0.72a
Pastures	2.34a	0.79a	0.29a	0.78a
25–50 cm depth				
Agroforestry systems	0.89a	0.31a	0.14b	0.52a
Pastures	1.57a	0.57a	0.21a	0.46a

[a] Means within a depth and exchangeable base followed by the same letter are not significantly different ($p < 0.10$).

ture soils at the 10–25 cm depth, while K was higher in soils under pasture at all depths. Pasture soils also had greater Na concentration in the surface 0–10 cm compared with agroforestry systems.

The foregoing observations regarding K may indicate that this nutrient is being taken up mostly from the zone of higher tree root density (Bowden, 1985) and may be accumulating in tree biomass. Montangnini and Sancho (1994) found high amounts of K in the aboveground biomass of *V. guatemalensis*. Moreover, K has been considered the second most limiting nutrient for plant growth in the region (Parker, 1994). Therefore, indications of K depletion may be evident before other bases are affected.

3.4. Soil organic C and total N

No difference in SOC was observed between individual agroforestry systems and pasture (data not shown) nor between pooled agroforestry systems and pasture (Table 4). Plots containing the heavy litter producer *V. guatemalensis* showed slightly, though not significantly, greater SOC than other treatments. Fisher (1995) reported greater SOC after three years with this tree species and *V. ferruginea*. Pasture soils maintained a relatively high SOC status even though they undoubtedly received less organic matter input than soils under agroforestry systems.

Veldkamp (1994) showed that soils in this region exhibited a very slow decrease in SOC after conversion to pasture. Lugo and Brown (1993) claimed that new pastures in the tropics could have greater SOC than adjacent forests because grass root biomass and turnover may have a greater role in SOC accumulation than surface inputs.

No difference in total soil N was noted among individual agroforestry systems or pasture (data not shown). This result might be expected since no differences in SOC were observed. Pooled comparisons between agroforestry treatments and pasture for soil total N also revealed no significant differences (Table 4). Soil total N levels were near the top of the range reported for mineral soils (Smith, 1994). Our results were similar to those reported in previous studies of soil total N status at LSBS (Montangnini and Sancho, 1994; Fisher, 1995). Parker (1994) suggested that high N levels occur in undisturbed forests due to the greater number of nitrogen-fixing trees in the area. However, soils under the agroforestry system with a leguminous tree species (*S. microstachyum*) actually exhibited the lowest soil total N of all treatments (3.81 and 2.76 g N kg^{-1} soil at 0–5 and 5–15 cm). Fisher (1995) also reported little effect of nitrogen-fixing tree species (including *S. microstachyum*) on soil N levels at LSBS. One possible explanation for this phenomenon is the low litter production of *S. microstachyum*.

3.5. Extractable P

No significant differences in extractable soil P were observed among individual agroforestry treatments and pasture (data not shown). A pooled comparison of agroforestry systems and pasture showed that agroforestry systems contained greater extractable soil P at a depth of 0–25 cm (Table 5) which might be related to tree root exudates (mostly low atomic weight organic acids) as suggested by Fisher (1995). This phenomenon might also be associated with P uptake from a greater soil volume followed by return to the soil surface through litterfall (Harcombe, 1980). Grasses apparently do not exhibit these mechanisms to the same degree.

3.6. Mineralizable soil C and N

A comparison between individual agroforestry systems and pastures did not distinguish any differences for mineralizable C (CMIN) (data not shown). A pooled comparison between agroforestry systems and pasture, however, demonstrated that the latter had significantly greater CMIN in the 0–5 cm depth (Table 4). Greater CMIN in the surface of pasture plots might be attributed to factors affecting soil organic matter quality, such as higher root biomass and turnover in the topsoil of permanent pastures (Lugo and Brown, 1993) and greater content of lignin in tree litter. Lignin content is one of the major factors controlling litter decomposition (Meentemeyer, 1978).

Mineralizable N (NMIN) was not different among individual agroforestry systems and pastures at the two depths studied (data not shown). Pooled comparisons also did not detect any differences between agroforestry systems and pasture (Table 4). Mineralizable N was consistently high in all plots. Because NMIN is coupled to CMIN, our results correspond

Table 4
Pooled comparisons between agroforestry systems and pastures for several biologically-related soil characteristics at two soil depths

Treatment	Soil organic C (SOC) [a] ($g\ kg^{-1}$)	Total soil N [a] ($g\ kg^{-1}$)	Microbial biomass C (SMBC) [a] ($mg\ kg^{-1}$)	Microbial biomass N [a] ($mg\ kg^{-1}$)	C mineralized [a] ($mg\ kg^{-1}$)	N mineralized [a] ($mg\ kg^{-1}$)	SMBC/SOC [a] (%)	Specific respiratory activity [a] ($mg\ CO_2$-C g^{-1} SMBC d^{-1})
0–5 cm depth								
Agroforestry systems	42a	4.2a	1616a	185a	1100b	147a	3.7a	19.2a
Pastures	45a	4.7a	758a	204a	1324a	156a	3.9a	22.5a
5–15 cm depth								
Agroforestry systems	31a	3.2a	1142a	103a	639a	102a	3.6a	17.2a
Pastures	31a	3.7a	319a	119a	642a	103a	4.2a	15.3a

[a] Means within a soil characteristic and depth followed by the same letter are not significantly different ($p < 0.10$). C mineralized assessed at $p < 0.05$.

Table 5
Pooled comparisons between agroforestry systems and pastures for extractable soil P at three soil depths

Treatment	Extractable P (mg kg^{-1})[a]		
	0–10 cm	10–25 cm	25–50 cm
Agroforestry systems	7.24a	4.55a	2.36a
Pastures	6.19b	3.33b	2.05a

[a] Means within a depth followed by the same letter are not significantly different ($p < 0.10$).

with the high CMIN reported earlier. Luizao et al. (1992) reported no differences in soil N mineralization indexes for a one-year old pasture and undisturbed forest in the Amazon.

3.7. Soil microbial biomass C and N

Differences in soil microbial biomass C (SMBC) between individual treatments were not observed (data not shown). Pooled comparisons also did not reveal any difference between agroforestry systems and pastures (Table 4). Comparison of our results with other studies using fumigation-incubation methods showed that these soils have considerably higher SMBC than many other ecosystems throughout the world (Ayanaba et al., 1976), but fell within the range reported by Luizao et al. (1992) for Amazon Basin soils and that reported by Vance et al. (1987) for temperate forest soils. Any differences in litter quantity and quality in these systems apparently had no effect on SMBC. *Vochysia* sp. have been shown to accumulate Al at levels of 20 000 mg kg^{-1} in the foliage, with potential deleterious effect on microbial activity (González, 1996). In spite of this observation, SMBC in the *Vochysia* plots was comparable to the other agroforestry systems and the pasture plots possibly because these species are the highest litter producers (Montangnini and Sancho, 1994; Byard et al., 1996). Luizao et al. (1992) reported no difference in SMBC in soils under Amazonian rain forest and adjacent soils under pasture grasses.

The ratio of SMBC/SOC (Table 4) was near 4%, which is considered the upper bound of the range of values commonly found in soils (Theng et al., 1989). These ratios were greater than those associated with secondary growth in tropical Africa (Ayanaba et al., 1976).

Our study also did not identify any significant differences in SMBN between individual agroforestry systems and pastures (data not shown) and pooled comparisons further revealed no significant differences (Table 4). The C/N ratio of soil microbial biomass was similar for all treatments, averaging 8.7 and 8.6 for agroforestry plots and pasture, respectively, in the upper 5 cm of soil.

As with SMBC, agroforestry systems did not enhance SMBN compared to pastures. These biological components were significantly related ($r^2 = 0.52$, $p < 0.05$), but this correlation was less than anticipated possibly because other labile N pools, such as soluble organic N, may have been present (Duxbury and Nkambule, 1994).

3.8. Specific respiratory activity

Specific respiratory activity (SRAC) was not significantly affected by treatments, although it tended to be lower in soils under *Vochysia sp*. (data not shown). Lower SRAC in soil under *Vochysia sp*. might be the result of differences in organic substrate quality since this genus is known to accumulate Al in foliage with potential suppression of litter decomposers (González, 1996). Pooled comparisons between agroforestry systems and pasture also showed no differences for SRAC (Table 4). The slightly higher SRAC in the surface soil of pastures corresponded to the higher CMIN for pasture soil.

4. Conclusions

Agroforestry systems in the Sarapiquí region of Costa Rica, compared with pasture, had generally lowered soil pH, exchangeable bases, and C mineralization, increased extractable soil P, and had no effect on soil organic C, soil total N, soil microbial biomass C and N, soil N mineralization, and specific respiratory activity of microbial biomass. Agroforestry systems did not improve soil quality compared to pasture in this study.

Acknowledgements

This research was a contribution of the Texas Agricultural Experiment Station, partly funded by a

Fulbright Commission Fellowship. The authors thank the La Selva Biological Station (Puerto Viejo, Costa Rica) personnel for their cooperation during the field work. They also thank the lab technicians in the Texas A&M University Agricultural Extension Service Soil Testing Lab for ICP analyses.

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