Indicating soil quality in cacao-based agroforestry systems and old-growth forests: The potential of soil macrofauna assemblage

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A B S T R A C T

Soil quality or health is a fuzzy concept that has been vigorously criticized due to the extreme variability of soil and the difficulty of linking soil indicators to soil functions and sustainability. In most soil quality studies some obvious factors or typologies are used as a basis to select the “best indicators” of soil quality, i.e. those that best explain the differences among the plots under study. This is not the case for a variety of natural or agro-ecosystems including the Talamance cacao-based agroforestry systems (AFS), which present neither a pre-established typology nor a clear framework to evaluate their soil quality. This situation required a selection of indicators based on the literature that was oriented by the non-equilibrium thermodynamic theory. A framework was elaborated through full and minimum indicator sets of baseline soil physical and chemical indicators, along with macrofauna groups. A minimum set of four well-accepted abiotic soil quality indicators (bulk density, sum of bases, pH and carbon) was able to separate cacao AFS plots and forests into five distinct clusters along a low-to-high “soil quality” gradient. The AFS rated as “good” soil quality did not differ from the forest. Abundances of selected macrofauna groups were well correlated with these indicators and helped elucidate the soil quality clusters identified. In particular, high predator abundance indicated proper energy flow and confirmed the high abiotic soil quality, thus confirming the potential of macrofauna groups as apt soil quality indicators. However, these indicators need to be tailored to local conditions. Consequently, cacao-based AFS in Talamance are able to conserve soil and provide a high level of soil-related ecological services. Considering the soil an open system where the non-equilibrium thermodynamic theory applies successfully guided indicator selection and could help to reformulate the soil quality definition.

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1. Introduction

Soil quality or health is a fuzzy concept officially defined as “the continued capacity of the soil to function within ecological and land-use boundaries, to sustain productivity, promote the quality of air and water, and maintain plant, animal and human health” (Doran and Safley, 1997). This concept was vigorously criticized (Lancaster, 2000; Letey et al., 2003; Rossi et al., 2009) and considered non-objective (Lancaster, 2000), mainly because no absolute reference to an optimal soil quality could be identified (Letey et al., 2003; Rossi et al., 2009). This is a consequence of extreme soil variability and the difficulty of linking soil indicators to sustained productivity, air or water quality or health. Determining soil quality as officially defined requires long-term experiments with indica-

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explain the differences among the plots under study. In the case of Talamanca, the cacao-based agroforestry systems (AFS) have no pre-established typology, as they represent a population of highly diverse agrosystems, all of which are unique. This situation applies to a variety of natural or agro-ecosystems that require a clear framework to evaluate and monitor their soil quality. In this context, soil quality must rely only on indicators previously established in the literature. Among the large number of indicators that efficiently detect differences between soils and management practices, the physical and chemical indicators are the most used (see Appendix). Soil biological indicators are also required to indicate soil quality as officially defined (Bastida et al., 2008; Ritz et al., 2009), but no consensus exists on “universal” indicators. Soil macrofauna assemblage efficiently compared soil quality among land uses (Lavelle et al., 2006; Rossi and Blanchart, 2005; Rousseau et al., 2010), agricultural intensification levels (Decaëns and Jiménez, 2002) and AFS (Barros et al., 2003), including cacao AFS (Moço et al., 2010). However, only earthworms are scarcely used as soil quality indicators while other macrofauna were never mentioned in the “soil quality” literature (see Appendix). Given the essential role of macro-invertebrates in soil formation and nutrient cycling and their potential as soil quality indicator, the conditions in which they may be used as indicators need to be clarified with particular respect to their relation to soil abiotic indicators.

Agroforestry systems have been increasingly promoted as sustainable productive systems for their continuous vegetation cover, diversification of production and effective nutrient cycling (Schroth et al., 2001; Hartemink, 2005). Their use is particularly relevant when soils have low agricultural potential and farmers have poor access to inputs. Therefore, simple and adapted methods of soil quality indication that include biologically mediated soil processes are required to enhance the management and promote the use of these systems. In Talamanca, the region is suffering forest fragmentation due to the cultivation of monocropped bananas and plantains. In this context, indigenous cacao-based AFS are good ecological connectors (Harvey and González-Villalobos, 2007; Harvey et al., 2006) and provide many of the forest ecological functions and associated services (Schroth and Harvey, 2007). Additionally, the forest matrix degradation severely erodes soil biodiversity (Mathieu et al., 2005; Rossi et al., 2010); thus, cacao AFS could act as sources or connectors to conserve soil biodiversity in the landscape.

We elaborated a framework to evaluate and compare soil quality among different cacao AFS and old-growth forest patches in Talamanca using a full indicator set (FIS) and a minimum indicator set (MIS) of physical and chemical soil indicators along with macrofauna groups (Lavelle et al., 2003). The specific objectives of this study were: (1) to define a minimum indicator set of soil quality based on the literature; (2) to classify cacao AFS and forest patches according to the minimum indicator set; (3) to select soil macrofauna groups that best explain abiotic soil quality indicators and evaluate their potential to indicate soil quality.

2. Materials and methods

2.1. Study area and cacao agroforestry systems selection

The Cordillera de Talamanca mountain range runs from south central Costa Rica to north central Panama and hosts the largest pristine forest remnant in Central America, the Amistad Biosphere Reserve. This is one of the most bio-diverse regions in the world, crucial for the conservation of the Central American diversity hotspot (Brooks et al., 2006). The area is also a cultural sanctuary for several indigenous peoples (Bribri, Cabécar, Ngöbé) from both countries (Hedström, 2006). The Bribri and Cabécar now inhabit the Talamanca valley (Costa Rica) and foothills where they grow banana, plantain and cacao-based agroforestry systems (AFS) for their livelihoods (Dahlquist et al., 2007). The study was conducted between August and November 2008 in the Bribri Indigenous Reserve, Talamanca, southeast Costa Rica (9°00′–9°50′N, 82°35′–83°05′W). The Reserve covers 43,690 ha and falls within tropical humid forest and premontane wet forest life zones (Holdridge et al., 1975). Mean daily air temperature is 25.9 °C, and average annual precipitation increases with altitude from 2600 mm at 40 masl to 6400 mm at 1000 masl with two short dry periods in March–April and September–October (Borge and Castillo, 1997). Forest cover of the Reserve is 70% with 75% of afforested land uses located in the valley. Banana and plantain monocultures are the most predominant in the agricultural landscape of the valley followed by banana and cacao agroforestry systems and pastures. The foothills are a complex mosaic of cacao and banana AFS, upland rice and corn in slash-and-burn shifting agriculture as well as forest patches of varying ages and degrees of intervention (Somarriba et al., 2003; Dahlquist et al., 2007). Soil biogeochemical patterns determined in the neighbouring Cabécar indigenous territory showed that Ultisols occupy both ridgetop and midslope landscape positions, Inceptisols occupy the footslopes, and Inceptisols and Entisols occupy the floodplain (Winowiecki, 2009).

Thirty-six cacao farms in 4 communities (Uatsi, Amburí, Soki and Namuwoki) were selected to ensure as much contrast as possible in terms of: (1) landscape structure; (2) topography; (3) botanical composition and structure (see Deheuvels et al., 2012 for details). Three patches of old-growth forest near cacao plots were also selected in the foothills. In Panama, a few kilometres from Talamanca, primaeval forest actually dates from the time of Spanish colonization whereas the rainforest was cleared between 7000 and 4000 years ago for slash-and-burn agriculture (Piperno et al., 1991). As a consequence, present forest remnants are at least 400 years old. Due to strict forest law enforcement these remnants suffer very few perturbations, confined mainly to hunting and medicinal plant gathering; therefore, their botanical structure and soil integrity is well conserved. Permanent plots of 50 m × 20 m were installed at the centre of each farm/forest and oriented along the main slope. The centre was positioned using the farm/forest sketch drawn by the GPS tracking function.

2.2. Sampling and soil analysis

The soil macrofauna was sampled according to the TSBF methodology (Anderson and Ingram, 1993) modified as follows: five soil monoliths 25 cm × 25 cm × 10 cm (minimum required to assess plot soil biodiversity; Rossi et al., 2006) were sampled every 10 m along a transect in the middle of each plot. Soil and litter were sampled separately and macrofauna was hand-sorted immediately after sampling. Arthropods were preserved in ethanol 70% while earthworms were preserved in formaldehyde 4% for 1 month before transfer to ethanol 70%. Macrofauna groups were sorted, classified into large taxonomic units and counted in the laboratory (Table 1). Physical and chemical analyses were performed on two 0–10 and two 10–20 cm deep soil samples taken within 2 m of the macrofauna sampling point. Soil was taken with a 4.24 cm steel cylinder to determine soil bulk density (Arshad et al., 1996). Soil was stored at 4 °C for 2 weeks prior to determination of bulk density and water content. Afterwards the soil was air-dried and sieved at 2 mm. Soil chemical and particle-size analyses were performed on one composite sample aggregated from the 20 samples collected in each plot. Soil particle size was assessed by the hydrometer method (Bouyoucos, 1951); pH was determined in water; levels of P, K, Mn, Cu, Zn and Fe were determined through modified Olsen extraction at pH 8.5 (Olsen and Sommers, 1982); Ca, Mg and exchangeable acidity were determined through KCl 1 N extraction.
Table 1
Abundance of soil and litter macrofauna groups (SD) in soil quality clusters of cacao-based agroforestry systems and old-growth forests of Talamanca, Costa Rica.

<table>
<thead>
<tr>
<th>Macrofauna groups (ind. m⁻²)</th>
<th>Soil quality clusters</th>
<th>P*</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>High Bases</td>
<td>Medium Bases</td>
</tr>
<tr>
<td>Oligochaeta</td>
<td>170 (57)</td>
<td>260 (92)</td>
</tr>
<tr>
<td>Coleoptera Adult</td>
<td>67 (30)</td>
<td>64 (28)</td>
</tr>
<tr>
<td>Coleoptera Larvae</td>
<td>87 (59)</td>
<td>105 (34)</td>
</tr>
<tr>
<td>Diptera Larvae</td>
<td>31 (15)</td>
<td>39 (24)</td>
</tr>
<tr>
<td>Formicidae</td>
<td>575 (200)</td>
<td>381 (205)</td>
</tr>
<tr>
<td>Isoptera</td>
<td>72 (148)</td>
<td>56 (67)</td>
</tr>
<tr>
<td>Blattaria</td>
<td>8.3 (7.0)</td>
<td>4.6 (4.5)</td>
</tr>
<tr>
<td>Dermaptera</td>
<td>44 (27)</td>
<td>29 (32)</td>
</tr>
<tr>
<td>Orthoptera</td>
<td>4.5 (4.3)</td>
<td>5.5 (4.8)</td>
</tr>
<tr>
<td>Hemiptera</td>
<td>3.8 (2.7)</td>
<td>3.2 (4.9)</td>
</tr>
<tr>
<td>Homoptera</td>
<td>7.7 (10.8)</td>
<td>3.7 (4.7)</td>
</tr>
<tr>
<td>Chilopoda</td>
<td>94 (54)</td>
<td>84 (57)</td>
</tr>
<tr>
<td>Diplopoda</td>
<td>116 (50)</td>
<td>176 (63)</td>
</tr>
<tr>
<td>Isopoda</td>
<td>67 (33)</td>
<td>74 (52)</td>
</tr>
<tr>
<td>Araneae</td>
<td>46 (35)</td>
<td>38 (17)</td>
</tr>
<tr>
<td>Opilionesida</td>
<td>34 (24)</td>
<td>19 (19)</td>
</tr>
<tr>
<td>Pseudoscorpiones</td>
<td>14 (12)</td>
<td>1.4 (2.5)</td>
</tr>
<tr>
<td>Schizomidae</td>
<td>2.6 (3.5)</td>
<td>0.5 (1.2)</td>
</tr>
<tr>
<td>Symphyla</td>
<td>9.0 (6.2)</td>
<td>5.5 (5.5)</td>
</tr>
<tr>
<td>Gastropoda</td>
<td>65 (60)</td>
<td>53 (24)</td>
</tr>
<tr>
<td>Unknown Larvae</td>
<td>97 (82)</td>
<td>32 (32)</td>
</tr>
<tr>
<td>Isoxolidae</td>
<td>3.2 (3.9)</td>
<td>2.7 (2.9)</td>
</tr>
<tr>
<td>Thysanotomidae</td>
<td>1.3 (1.8)</td>
<td>1.8 (1.7)</td>
</tr>
<tr>
<td>Total density</td>
<td>1620 (519)</td>
<td>1440 (410)</td>
</tr>
</tbody>
</table>

Diversity
Richness
23.4 (1.8) 21.3 (2.5) 21.0 (3.7) 20.4 (3.8) 23.1 (2.9) 0.24
Shannon
3.6 (0.5) 3.6 (0.3) 3.1 (0.7) 3.2 (0.3) 3.5 (0.5) 0.28
Evenness
0.80 (0.18) 0.81 (0.05) 0.71 (0.11) 0.74 (0.06) 0.77 (0.09) 0.29
Simpson
0.18 (0.06) 0.14 (0.02) 0.23 (0.07) 0.21 (0.07) 0.18 (0.09) 0.18
Margalef
3.0 (0.2) 2.7 (0.3) 2.7 (0.4) 2.6 (0.4) 3.1 (0.3) 0.02*

* Macrofauna group abundance and diversity differences between soil quality clusters was significant at *P < 0.10; **P < 0.05 according to between-class analysis and Monte Carlo permutation test (9999 permutations).

Table 2
Soil indicators (0–20 cm) for the soil quality clusters identified among the cacao-based agroforestry systems and old-growth forests in Talamanca, Costa Rica.

<table>
<thead>
<tr>
<th>Soil indicators</th>
<th>Soil quality clusters</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>High Bases</td>
<td>Medium Bases</td>
</tr>
<tr>
<td>Minimum data set</td>
<td></td>
<td></td>
</tr>
<tr>
<td>BD g cm⁻¹</td>
<td>0.91</td>
<td>0.80</td>
</tr>
<tr>
<td>pH</td>
<td>6.09</td>
<td>5.61</td>
</tr>
<tr>
<td>KCaMg kg ha⁻¹</td>
<td>11,297</td>
<td>5390</td>
</tr>
<tr>
<td>C Mg ha⁻¹</td>
<td>43.6</td>
<td>48.5</td>
</tr>
</tbody>
</table>

Other indicators
Clay %
25.68
Silt %
35.36
Sand %
38.96
H₂O₂ % weight
54.64
H₂O % volume
48.42
Porosity %
65.52
N kg ha⁻¹
5062
P kg ha⁻¹
9.57
K kg ha⁻¹
312
Ca kg ha⁻¹
9476
Mg kg ha⁻¹
1508
Mn kg ha⁻¹
10.66
Cu kg ha⁻¹
13.13
Zn kg ha⁻¹
8.20
Fe kg ha⁻¹
113
Acidity mol ha⁻¹
1244
CEC Mn mol ha⁻¹
609
C:N
8.62
Mg/K
5.05

* Ranges are optimum for agriculture in Costa Rica according to Bertsch (1995) (calculated for bulk density = 1) and numbers between () are cacao requirements, on a 550 plant ha⁻¹ basis (Talamanca average cacao plant density), for mineral nutrients under conventional management (no shade) (Wessel, 1985).
* Not available.
* Minimum C requirement of 2% (40 Mg ha⁻¹) calculated for bulk density = 1) for structural stability (Albrecht et al., 1992), aeration and water availability (Thomasson, 1978).
* Water-filled pore space.
* Cation exchange capacity.
(Diaz and Hunter, 1978); total C and N were determined by total combustion. Soil bulk density and soil chemical concentration were used to calculate soil nutrient stocks (0–20 cm top layer) for each plot (Table 2).

2.3. “Objective” abiotic soil quality indicators

Based on the recent reviews by Bastida et al. (2008) and Vezzani and Mielniczuk (2009), along with local studies from Costa Rica (Porras, 2006; George, 2006; Cerda, 2008), Central America and the Caribbean (Rosales et al., 2008), 53 publications were reviewed to summarize the most updated set of soil quality indicators currently in use. Given that the studies in the literature rarely share the same indicators and do not provide the statistics required to perform meta-analysis, a vote-counting procedure was applied (DeCoster, 2004). Each indicator was listed and its frequency (number of citations as a relevant soil quality indicator) calculated. A total of 95 indicators were listed and classified by category: organic matter, nutrients, chemistry, physics, biology, biochemistry and crop productivity (Appendix). Closely related indicators were then pooled (e.g. organic matter, total organic C and total carbon = organic matter [OM]; Particulate Organic Matter [POM] and C-POM = POM; bulk density and soil porosity = bulk density [BD]; available N, NO3 −, NH4 + = available N; available K, Ca, Mg = KCaMg [sum of bases]; aggregate stability and water stable aggregates = aggregate stability; water retention, available water and water-holding capacity = water retention; crop yield and seed yield = crop yield; crop residues and litter biomass = crop residues) resulting in a new set of 86 soil quality indicators. The minimum indicator set (MIS) was then selected among the most frequently reported indicators.

2.4. Data analysis

2.4.1. Abiotic soil quality indicators

The first step of data analysis consisted of a principal component analysis (PCA) on the full indicator set (FIS). The PCA was performed on the standardized data set to extract the main patterns of abiotic soil quality among plots (identify potential clusters) and explore the correlations between the objective indicators and the others. The second step was to evaluate the information lost when the full set was reduced to the objective indicators. In other words: is the MIS a good proxy for the abiotic soil quality evaluated by the FIS? A redundancy analysis (RDA) was then performed to calculate the fraction of FIS variance explained by MIS. The RDA is an ordination method that can be considered a multivariate extension of multiple linear regressions. Specifically, RDA is a principal component analysis modified to constrain the ordination axes to be linear combinations of a set of explanatory variables (the MIS) given in a separate matrix (Legendre and Legendre, 1998). This variance fraction is calculated by a forward selection procedure to build the model (the combination of best indicators) that best explains the FIS. Each variable entering the model is tested by permutation (Monte Carlo; 9999 permutations). The permutation test consists of randomly permuting the data set and counting how many times the observed data structure appears. For example, if it appears 1 time in 10,000 permutations, the observed structure significance is P = 0.0001 (Legendre and Legendre, 1998). The third step of analysis was to test whether the abiotic soil quality pattern detected by PCA in the first step was conserved after the reduction of the indicator set, and if the groups of cacao and forest plots identified had significantly different soil quality. A hierarchical agglomerative clustering method (the method of Ward; Legendre and Legendre, 1998) was performed on MIS, and clusters that separated half of the total distance on the dendrogram were retained, tested by permutation (Monte Carlo; 9999 permutations) and ranked for soil quality (Table 2). The ranking of clusters was based on the assumptions that more bases, higher pH and C content, along with lower bulk density would positively and linearly correlate with soil quality. These assumptions were based on the objective soil quality indicators selected from the literature (Appendix) with particular emphasis on the local studies available (Porras, 2006; George, 2006; Cerda, 2008; Rosales et al., 2008). The effect of soil quality clusters was assessed individually on each soil physico-chemical indicator through a between-class PCA and permutation test (Monte Carlo; 9999 permutations) to determine which indicator confirmed the literature-based soil quality typology (Table 2). Between-class analysis is an extension of PCA that allows the consideration of groups of individuals and calculates their contribution to the table, which is tested by permutation (Chessel et al., 2004).

2.4.2. Macrofauna soil quality indicators

In the fourth step of data analysis, we performed a PCA on standardized macrofauna abundances in order to extract the main patterns of group distributions among plots. Groups with less than 5 individuals were removed from the analysis to minimize the occurrence of 0 in the matrix. The fifth step of analysis consisted of the selection of the macrofauna groups that best correlated (or explained) the MIS in order to: (i) determine the groups significantly affected by (or affecting) soil quality; (ii) identify groups with potential to indicate differences in soil quality. The abiotic soil quality typology was then tested on each macrofauna group individually through a between-class PCA and permutation test (Monte Carlo; 9999 permutations) (Table 1). The macrofauna group combination best correlated with MIS was determined by a forward selection procedure: a 0.05 probability was defined as a condition for a variable to enter the forward selection model while the probability of being dropped out of the model was 0.1. All analyses were performed with R (R Development Core Team, 2009). The package “ade4” was used for principal component analyses and for testing between soil quality clusters (between and randtest function); “cluster” package was utilized to build the soil quality clusters (agnes function); the “vegan” package was used to perform redundancy analyses and forward selections (ordistep function).

3. Results

3.1. Selection and test of “objective” soil quality indicators from the literature

The most reported indicators were: OM (17 times), C biomass (16), BD (16), Bases (15) and pH (11). Twenty-two indicators were used 3–8 times while the remaining 59 were used 1–2 times (Appendix). The FIS for Talamancan was composed of 25 indicators (Table 2) that were selected from previous studies on cacao AFS in Talamancan (Cerda, 2008) and coffee AFS in Turrialba (George, 2006; Porras, 2006). Four of the five most reported indicators were available for cacao AFS and old-growth forests in Talamancan: OM, BD, Bases and pH (Table 2); they were then retained as the MIS. The first two axes of the full indicator set PCA accounted for 63.4% of the variance. The first axis (eigenvalue = 43.0%) represented mainly a bulk density gradient with BD, Silt and P as opposed to porosity, water content, clay, N/P and C. The second axis (20.4%) represented an exchangeable base concentration and pH gradient with KCaMg, Ca, Mg, CEC as opposed to Fe and C/N and, to a lesser extent, to acidity and sand (Fig. 1a). Plots were clearly separated into three clusters along these two axes. PCA 1 (higher BD, P and Fe) was positively correlated with the plots from the lowlands (Amubri) but negatively correlated with the plots from Soki and Namuwoki foothills (higher water content, N/P, clay and C). Forests and Uatsi plots (except U29) were negatively correlated with PCA 2 and associated with
base-related variables and water-filled pore space (WFPS; Fig. 1b). The first two axes of the minimum indicator set PCA accounted for 88.5% of the total variance and axes represented the same gradients as in the full set analysis (Fig. 2a). The same three clusters were segregated but plots inside clusters were more clearly separated and Soki forests were more closely associated with other Soki plots than in the full set PCA (Fig. 2b). The RDA analysis where the MIS (explanatory variables) explained the FIS (response variables) revealed a 62.5% shared variance, which means that the additional 21 soil indicators were explained largely by the selected objective indicators. In the forward selection model BD, KCaMg, pH and C were all significant at $P \leq 0.05$.

### 3.2. Classification of cacao AFS and forest plots by abiotic soil quality indicators

The cluster analysis based on the BD, KCaMg, pH and C indicators separated five clusters of cacao AFS and forests. Forests did not form an isolated cluster but entered the first two soil quality clusters. The clustering was significant at $P<0.001$ according to the between-class PCA and explained 74.3% of the total variance. The five clusters were ranked for their relative soil quality according to the indicators: 1. High Bases (Uatsi cacao plots 28, 30, 31 and the Uatsi forest 39); 2. Medium Bases (Amubri plots 3 and 8, Soki plots 10, 13 and forests 37, 38 and Namuwoki plot 36); 3. High BD (Amubri plots 1, 2, 6, 7, 9); 4. High C (Namuwoki plots 19, 20, 22, 27, 35 and Soki plots 11, 15); 5. Low Bases (Namuwoki plots 16, 17, 18, 21, 23, 24, 25, 26, 33, 35, Amubri plots 4, 5, Soki plots 12, 14 and Uatsi plot 29) (Fig. 3). Comparison of nutrients levels found in soil quality clusters with cacao requirements (Wessel, 1985) and optima for Costa Rican agriculture (Bertsch, 1995) showed that the micronutrient content met requirements for all clusters. Available K met basic requirements for agriculture in High Bases and High BD clusters but did not reach cacao requirements. Available P met basic agriculture requirements in High BD cluster but remained far short of cacao requirements. The C:N ratio met basic agriculture requirements in all clusters as did pH for Clusters 1–3 (Table 2).

### 3.3. Selection of macrofauna groups that best explain abiotic quality indicators

The first two PCA axes of macrofauna groups accounted for 34.7% of the variance. The first axis (22.7%) was explained primarily by an "effect size" with all macrofauna densities negatively
correlated with PCA 1. The groups better correlated with PCA 1 were mainly litter-dwelling animals (Isopoda, Coleoptera, Blattaria, Chilopoda, Opilionidae, Diplopoda). The second axis (12%) represented mainly small-sized groups (Schizimidae, Symphyla, Pseudoscorpions) and Gastropoda density gradient (Fig. 4). The abundances of macrofauna groups in the soil quality clusters are displayed in Table 1. The forward selection retained 12 macrofauna groups (among 23): Homoptera, Dermaptera, Larvae Coleoptera, Larvae Diptera, Diplopoda, L.Coleo, Larvae Sypm, L.Dip, L.Diplo, Lforms, Liso, Symp, Symphyla, Gastr., Pseudosc., Arach., A.Bas, Oligochaeta, Oligo, Olo, Otho, Homoptera, Blattaria, Diplip., Homoptera, Hom., Droso., Chilo, Diplopoda, Isop., Symp., Symphyla, Pseudosc., Schizo, Symphyla, Gastro., L.Dip, Lforms, Liso, Symp., Symphyla, Homoptera, C.N., C.P., C.G., C.D.

Fig. 4. PCA correlation circle of soil macrofauna groups in the 39 cacao AFS and forest plots of Talamancan, Oligo=Oligochaeta, A.Coleo=Coleoptera Adult, L.Coleo=Larvae coleoptera, L.Dip=Larvae diptera, Formi=Formicidae, Isopt=Isoptera, Blatt=Blattaria, Diplip=Diplura, Otho=Orthoptera, Hemi=Hemiptera, Hom=Homoptera, Chilo=Chilopoda, Diplo=Diplopoda, Isop=Isopoda, Arach=Arachnidae, Opilio=Opilionidae, Psicropo=Pseudoscorpiones, Schizo=Schizimidae, Symp=Sympylina, Gastro=Gastropoda, Lform=Larvae Indeterminate, Ixo=Ixiidae, Thela=Thelastomatidae.

4. Discussion

4.1. Selection and test of “objective” soil quality indicators from the literature

As revealed by a review of the literature, the most used indicators were present in less than one third of the articles which may indicate a need to tailor the choice of indicators to each situation (Andrews and Carroll, 2001; Barrios et al., 2006) or the absence of a consensus for such choice. The framework allowed testing of the relevancy of indicators regardless of the a priori classification of sites. The approach is simpler than the development of indices and avoids the bias introduced by over-generalizing calculations (Letey et al., 2003; Rossi et al., 2009) or selection based on expert opinion (Ritz et al., 2009). Dominguez and Rousseau (2011) applied the same framework to a similar population of cacao-based AFS in Guatemala with similar results: the four abiotic variables retained were BD, KCaMg, C:N and N:P. The study confirmed that the framework is relevant in the cacao AFS context and presents highly similar baseline indicators, except for the finding that MO quality was more relevant than total C in Guatemala.
The lack of consensus on indicators is related to the absence of clear and universal criteria that link them to soil quality/functions (Bastida et al., 2008); however, crucial information that links soil quality to ecosystem thermodynamics is available but under-exploited (Vezzani and Mielniczuk, 2009). Addiscott (1995) suggested that soil quality was synonymous with sustainability and a consequence of a steady state of the ecosystem characterized by minimum production of entropy. Processes such as photosynthesis that build small molecules into larger ones lessen entropy as does humification through the reorganization of the soil organic matter (SOM) during its decomposition into complex high-density, high-energy and redox power molecules (Baldotto et al., 2005; Garcés and Savich, 2005). Entropy reduction gives resilience to the soil, is powered by solar energy and critically relies on soil self-organization capacity which is provided by the biota (Addiscott, 1995) and particularly the so-called ecosystem engineers (roots, earthworms, termites, ants, etc.) that build the soil structure and develop mutualistic digestive strategies (Lavelle et al., 2006). The soil is therefore considered an open system where the non-equilibrium thermodynamic theory can be applied and where the soil functionality (quality) emerges from the soil–plant–biota interactions. To achieve adequate soil quality we should then focus on all the structures and processes that favour energy conservation, i.e. minimizing entropy (Vezzani and Mielniczuk, 2009). The four baseline indicators selected in this study are consistent with the energy conservation view. The soil’s bulk density enables the estimation of its structuring capacity, a major determinant and well-accepted soil quality indicator (Arshad et al., 1996). Low BD enhances soil biological activity which, in a positive feedback loop typical of self-organized systems, reduces BD (Lavelle et al., 2006). The soil’s ability to retain bases (K, Ca, Mg), as an ordering process, also minimizes entropy (Addiscott, 1995), and largely determines soil fertility/productivity. In addition, Ca was proved useful to compare nutrient cycling efficiency among a wide range of situations (Jordan and Herrera, 1981). The close relationship among soil pH, base concentrations and nutrient availability renders acidic soils more susceptible to leaching (dissipative process), limits growth of many organisms including roots and thereby augments entropy. Finally, total soil C content is the most frequently used indicator of soil quality (Vezzani and Mielniczuk, 2009; Bastida et al., 2008) and the most directly related to energy conservation, structuring processes and self-organization capacity. Native soils (that do not show evidence of anthropogenic disturbance) could thus serve as a reference for soil quality and guide the management and design of sustainable agrosystems.

4.2. Classification of cacao AFs and forest plots by abiotic soil quality indicators

The suitability of these soils for cacao production is apparently low if compared to the requirements of conventional cacao management because of low K and P availability. This may explain, in part, the low cacao productivity measured in these plots that averaged 136 kg ha⁻¹ (Deheuvels et al., 2012). The low C:N ratio and high total N reserve suggest that this element is not a limiting factor in cacao production in these soils (Hartemink, 2005), so that the potential to increase and sustain augmented production is high. In practice, a routine soil analysis backed by a more objective soil quality classification would help to better manage soil fertility: P and K amendments can be recommended for the best soil quality plots while trials implemented with farmers in selected low-quality plots may test amendment innovations. The segregation of forest plots with the first two soil quality clusters suggests that the forest-like structure provided by these AFs (Schroth et al., 2004) has a positive impact on soil conservation and provides soil characteristics and functions that are similar to those of the selected old-growth forests remnants (Jordan, 1982). It also confirms that multistraata AFs are better for soil than annual crops (Schroth et al., 2001) or Musa sp. mono-crop (Cerda, 2008). Moreover, Hartemink (2005) reported that the nutrient balance in conventional or low-shade-diversity (1–2) cacao plantations is usually negative compared to forest; thus, high shade diversity in Talamancan (4–11; Deheuvels et al., 2012) enhances the forest-like structure and nutrient cycling in selected AFs.

4.3. Macrofauna and abiotic quality indicators

The macrofauna group selection revealed one community associated with the High Bases and/or High C plots and the other with the High BD plots. The High Bases/C community was characterized by high spider, chilopod and Coleoptera larval abundances, groups with the highest and most diverse predator populations. Similarly, Moço et al. (2010) reported a positive indirect effect of sum of bases and a positive direct effect of pH on macrofauna predators from cacao AFs and forests in Brazil. This community also showed high diplopod and Diptera larval populations, groups with a huge diversity of litter decomposers (Lavelle et al., 2003) that probably supported the predators. More specifically, Diptera larvae seemed to develop better at higher pH which may have special implications for cacao production as its pollination is exclusively dependent on Diptera (Ceratopogonidae) species (Young, 1986). Coleoptera larvae were correlated with soil C content and thus probably dominated by their decomposer members and not predators. Similarly, in Brazil cacao AFs Coleoptera larvae were directly associated with high lignin content and probably fed predominantly on wood, which should contribute to efficient C and nutrient cycling (Moço et al., 2010). The High BD community was characterized by Pseudoscorpiones, small predator arachnids and Symphyla, which are very small decomposers (Borror et al., 1992). The lower porosity of these soils could confer an advantage on small invertebrates by limiting the mobility of larger competitors. The Homoptera were also more abundant in these soils and, as this group is mainly represented by digging nympha (Borror et al., 1992), High BD could provide them with better stability for their gallery network. The higher abundance of predators with more bases was consistent with their “high quality” status. Indeed, high predator abundance reflects high prey abundance and proper energy flow in the food web (Neutel et al., 2002). Soil functionality is thus conserved in these cacao plots similarly to the old-growth forests. Conversely, the plots of High BD and Low Bases harboured limitations according to macrofauna distribution, thus corroborating their “medium-poor quality”. When the framework was applied in Guatemala, the macrofauna responded differently to the same abiotic variable (Dominguez and Rousseau, 2011) which confirmed that macrofauna indicators need to be tailored locally, as do the abiotic ones (Andrews and Carroll, 2001). The framework performed well in the cacao AFs context and can be tested in other settings. As a comparison, Ritz et al. (2009) presented a “semi-objective” framework of biological soil quality indicators selected for the United Kingdom based on a selection from the literature by scientific and public policy experts. Although the resulting indicator selection is robust for the UK, it is dominated by genetic profiling methods unavailable in most Southern Hemisphere laboratories. Soil macrofauna was selected among the best indicators through pitfall-trapped invertebrates and onsite visual recording. In the selection criteria the cost of labour rather than hardware was determinant, which evidenced the influence of social context in the choice of indicators. Unfortunately, pitfall traps sample a very specific fraction of soil invertebrates while onsite visual recording has not yet been developed for most environments (Ritz et al., 2009). The framework we
constructed was easier to implement and may avoid social bias as the only selection criterion is the “indicator fitness”.

5. Conclusions

A reduced set of four well-accepted abiotic soil quality indicators is able to separate cacao AFS plots and forests into five distinct clusters along a low-to-high “soil quality” gradient. A small number of selected indicators could then be retained for monitoring purposes. Abundances of selected macrofauna groups are highly correlated with these indicators and help elucidate the soil quality clusters identified. In particular, high predator abundance in selected AFS and forests indicates proper energy flow and confirms the high abiotic soil quality. The potential of macrofauna groups to indicate soil quality is confirmed by the present study; however, they need to be tailored to local conditions. As a consequence, cacao-based AFSs in Talamanca are able to conserve soil and provide a high level of soil-related ecological services. Considering the soil to be an open system where the non-equilibrium thermodynamic theory applies could orient the reformulation of soil quality definition. In this context, the framework developed herein may ease a more objective and locally adapted selection of indicators.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.ecolind.2012.05.008.

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