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# Protective shade, tree diversity and soil properties in coffee agroforestry systems in the Atlantic Rainforest biome

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ABSTRACT

Sustainable production and biodiversity conservation can be mutually supportive in providing multiple ecosystem services to farmers and society. This study aimed to determine the contribution of agroforestry systems, as tested by family farmers in the Brazilian Rainforest region since 1993, to tree biodiversity and evaluated farmers' criteria for tree species selection. In addition, long-term effects on microclimatic temperature conditions for coffee production and chemical and biological soil characteristics at the field scale were compared to full-sun coffee systems. A floristic inventory of 8 agroforests and 4 reference forest sites identified 231 tree species in total. Seventy-eight percent of the tree species found in agroforests were native. The variation in species composition among agroforests contributed to a greater γ-diversity than α-diversity. Monthly average maximum temperatures were approximately 6 °C higher in full-sun coffee than in agroforests and forests. Total soil organic C, N mineralization and soil microbial activity were higher in forests than in coffee systems, whereas the chemical and biological soil quality in agroforests did not differ significantly from full-sun coffee after 13 years. Given its contribution to the conservation of biodiversity and its capacity to adapt coffee production to future climate change, coffee agroforestry offers a promising strategy for the area.



## 1. Introduction

High input agriculture as developed during the last decades has focused mainly on increasing the production of marketable products (Evenson and Gollin, 2003). Despite successes in terms of agricultural productivity on a global scale, these developments have been accompanied by soil degradation, biodiversity decline and environmental pollution with negative feedbacks on food security and farm incomes at local scales (Perfecto and Vandermeer, 2008). The decline in biodiversity has disrupted ecological interactions and dramatically increased the reliance of agricultural production on external inputs. In contrast, diversification of agroecosystems to enhance agrobiodiversity and ecological processes can simultaneously support biodiversity conservation and the delivery of a range of supporting, provisioning and regulating ecosystem services that enhance the sustainability and resilience of agricultural systems (MEA, 2005; Knoke et al., 2009) and the surrounding landscape (Bennett and Balvanera, 2007; Kibblewhite et al., 2008).

Farmers in the Zona da Mata of Minas Gerais state, located in the Brazilian Atlantic Rainforest, have been facing problems of soil degradation, decreased production and declining biodiversity. The Atlantic Rainforest is a biodiversity hotspot (Myers et al., 2000) that is highly fragmented due to historic agricultural expansion. Only 12% of native vegetation remains, more than 80% of the fragments is <50 ha and the average distance between fragments is 1440 m (Ribeiro et al., 2009). Seventy percent of Brazil's human population lives within this biome.

The Zona da Mata is an important coffee producing region (CONAB, 2009). Conventional agricultural activities on the steep slopes have caused serious soil erosion and soil quality problems. Moreover, climate change scenarios for the Zona da Mata predict that temperature conditions will make large parts unsuitable for coffee growing by 2050 (Assad et al., 2004). As in the rest of Brazil, coffee in the Zona da Mata has mainly been cultivated in full-sun systems. In several other countries, however, coffee has traditionally been cultivated under a diverse canopy of local tree species. These trees provide shade (Moguel and Toledo, 1999) and create microclimate conditions commensurate with the ecophysiology of the coffee plant (DaMatta, 2004). Moreover, the tree cover

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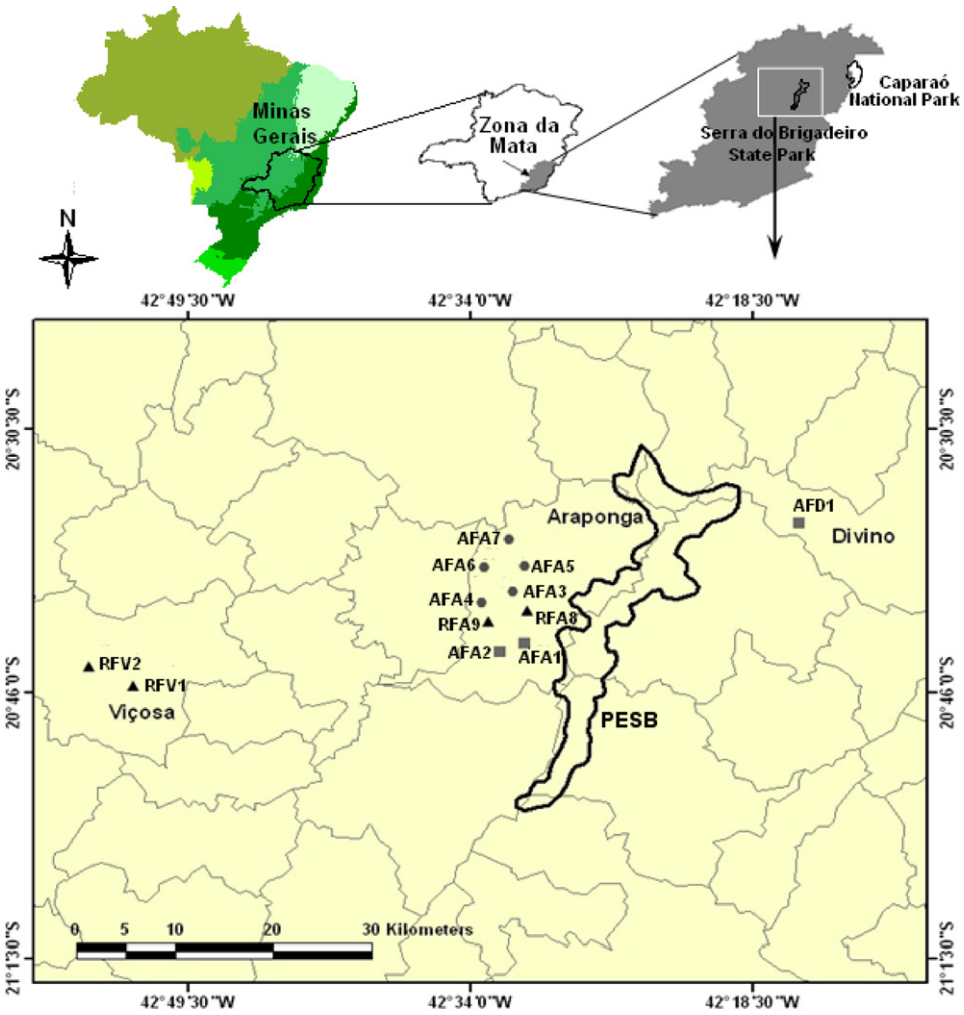


**Fig. 1.** Location of the study sites in different municipalities of the Zona da Mata of Minas Gerais state: Viçosa (reference native forest fragments RFV1 and RFV2), Araponga (agroforests AFA1 to AFA7 and native forest fragments RFA8 and RFA9) and Divino (agroforest AFD1). The black line in the bottom map indicates the limits of the Serra do Brigadeiro State Park (PESB). The boundaries of the Caparaó National Park are shown in the upper map).

protects the soil against erosion and provides a continuous input of organic matter to the soil. The soil quality in tropical agroecosystems depends to a large extent on biomass production, plant residue inputs (Tian et al., 2007) and litter residence times (Hairiah et al., 2006) that provide soil protection and food for soil organisms, contribute to improved soil structure, soil moisture retention and nutrient supply (Kibblewhite et al., 2008).

Starting in 1993 a group of coffee growers, in collaboration with local NGOs and researchers, have implemented and monitored experiments with agroforestry (AF) coffee systems (Cardoso et al., 2001). AF can be defined as a form of multiple cropping of annual or perennial crops intercropped with trees (Somarriba, 1992). The successful adoption of agroforestry systems depends on their proper design, including tree species selection, and management. Therefore, it is necessary to have a better understanding of how locally available natural resources and local and scientific knowledge can be combined to develop systems that allow for coffee and food production and provide multiple ecosystem services at the same time (WinklerPrins and Sandor, 2003). This also requires monitoring of the long-term effects of agroforestry versus full-sun coffee (SC) systems on biodiversity conservation, soil quality and ecosystem services across scales from the coffee field to the wider landscape. Here, we propose that scientific data will make up for the general lack of documentation and understanding of (local) strategies and experiences and will serve as guidance for regional and global policies (Harvey et al., 2008).

The objectives of our study were (1) to evaluate farmers' criteria for selection of tree species in AF systems; (2) to determine the contribution of coffee agroforestry to regional tree biodiversity conservation; (3) to determine the contribution of agroforestry systems to microclimatic conditions for coffee production in the Zona da Mata, as compared to full-sun coffee systems and neighboring reference forest fragments on the same farms; (4) to determine the effects of agroforestry on soil chemical and biological soil characteristics, as compared to full-sun coffee systems and neighboring reference forest fragments on the same farms, and to assess leaf litter quality of locally selected AF tree species.

Objective 1 required a descriptive, retrospective study, which is not open to hypothesis formulation. As to the other objectives, we hypothesized:

**H1.** The majority of the trees in coffee agroforests are native tree species, and also occur in surrounding reference forest fragments (refers to objective 2).

**H2.** AF moderates microclimate fluctuations compared to SC, thereby reducing mean daily maximum temperatures, which makes coffee production more resistant to temperature rise resulting from climate change (refers to objective 3).

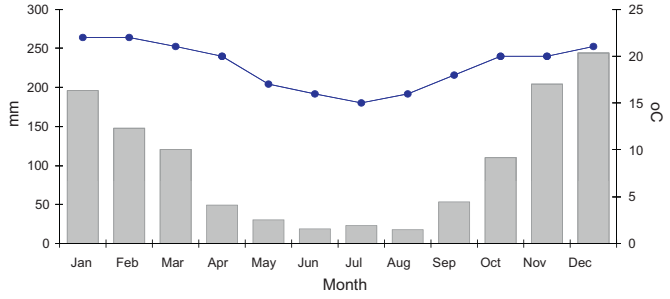


**Fig. 2.** Mean monthly temperatures (bars) and total monthly rainfall (dots) in the Zona da Mata, Minas Gerais state, Brazil (1960–1990; data source: www.inpe.br).

**H3.** Chemical and biological soil characteristics are improved under AF as compared to SC and these improvements are related to leaf litter quality (refers to objective 4).

## 2. Materials and methods

### 2.1. Study area

The study area is located in the Zona da Mata (ZM), Minas Gerais State, Brazil. Since the nineteenth century the rainforest has been replaced by agriculture (mainly coffee production) due to favorable climate and market conditions (Dean, 1995). Few forest fragments have been conserved as forest reserves while coffee plantations extend to the top of the hills. As a result, biodiversity and natural soil fertility have severely declined (Dean, 1995; Padua, 2002). Full-sun coffee (*Coffee arabica* L.) and degraded pasture are scattered across the landscape surrounding hundreds of small and isolated forest fragments (Ribeiro et al., 2009; Teixeira et al., 2009). Two protected areas are located in the region, the Serra do Brigadeiro State Park (PESB, by its Portuguese acronym, 14984 ha) and the Caparaó National Park (26200 ha) (Fig. 1).

The Zona da Mata region has a tropical highland climate. The average temperature is 19 °C and the average precipitation is 1300 mm, with 2–4 dry months per year (Fig. 2). In general, the slopes range from 20% to 45%, and the altitude ranges from 200 to 1800 masl (Golfari, 1975). Nowadays, around 18% of the population lives in rural areas. Forty-two percent of the farms in the region are smaller than 10 ha, and are managed mainly by family farmers (IBGE, 2000). Agriculture is characterized by continuous cultivation and conventional farming practices. Pasture and full-sun coffee, often inter-cropped with maize and/or beans, are the most important agricultural land uses. Other crops are sugarcane, cassava, fruits and vegetables. Use of agrochemicals such as fertilizers, lime, biocides and growth inductors are common, which reaches up to 54% of the total costs for coffee production.

Dominant soil types are Oxisols which are deep, well drained, acid and poor in nutrients (FAO, 1985). More information about pedology, agriculture and sociology of the Zona da Mata region can be found in Cardoso et al. (2001).

### 2.2. Study sites

From 1994 to 1995, 37 on-farm agroforestry experiments were established by farmers across 7 municipalities bordering the Serra do Brigadeiro and Caparaó National Parks. The AF plots had an average size of 0.5 ha and were established on the most degraded soils within the farms, often presenting sheet erosion due to the historic land use. Among these 37 farms we selected our study sites, following four steps. From the 37 farms, 17 took part in an evaluation study. The evaluation consisted of several meetings where farmers, technicians and researchers gathered information about the composition and management of AF and to reflect on its impact on soil quality and productivity (Souza, 2006). Eight out of these 17 AF experiments and four reference forests (RF) were selected to to compare tree diversity and composition, as indicated by objective 1 of this study. The 8 AFs were best examples in terms of productivity and biodiversity, according to the evaluation by farmers and technicians (Souza, 2006) (Fig. 1). Two RF fragments were located in Araponga (50 years old, with a size of 4 ha and located at a distance of 1–5 km from the AF experiments) and two in Viçosa (15 and 30 years old, with a size of 5 ha and located at a distance of 60–100 km from the AFs). The forest fragments were selected because of the availability of botanical studies, and because they were representative examples of different successional stages of secondary forest on abandoned agricultural land in the Zona da Mata (Marangon et al., 2003).

For a detailed study on microclimate and soil quality aspects at the field scale, as proposed by our objective 3, we selected a subset of 3 farms, out of the 8 farms that were used for the floristic study. Each of these 3 farms comprised 3 different systems within the farm boundaries: an agroforestry system, full-sun coffee cultivation and a reference forest fragment. The AF and SC systems were side by side, within 300 m distance from the RF. All three systems were comparable in terms of slope and solar incidence. The AF and SC systems had been established at the same time, between 1993 and 1995, and coffee plants were in the same growing stage. The RFs were on average 30–40 years old, had a size of 0.5–1.0 ha, and had a history of agricultural use. The farmers represented comparable conditions in terms of labour availability and economic endowment (Miranda, 2002). The location of the various research sites is given in Fig. 1.

The AFs consisted of plantations of selected tree species in close association with coffee plants (*Coffea arabica* L.) on former arable land or degraded pastures. SC differs from AF mainly in terms of the absence of trees and shrubs (other than coffee) and the rate of chemical fertilizer used (Souza, 2006). Sometimes manual tillage was used in both systems. Due to local agreements, dating back to more than 20 years ago when the agroecological transition process started in the Zona da Mata, biocides have vanished from both coffee systems on all the participating farms. The RFs were kept on the farms in accordance with Brazilian environmental law. The trees reached up to 20 m in height. The RFs used for the floristic comparison were not the same fragments as the ones kept within the farms.

Location and slope of the coffee fields were measured using GPS (Garmin eTrex H, 10 m of precision) and clinometers. The farms and systems differed in terms of the slope, size of the SC, AF and RF systems, the density of coffee plants, the composition of the AFs, and coffee production (Table 1). The farm activities depended on the types of crops, number of farm workers and the season of the year. At farm A1, the soil in AFA1 and SCA1 was fertilized in 1994 with 100–150 g of NPK (4-18-8) per coffee plant and limed to recover soil fertility. The coffee plant density and fertilization were similar in both systems (Table 1). At Farm A2 trees were mostly planted in lines between the coffee plants to control erosion, and severely pruned. SCA2 was installed immediately down slope of AFA2 and had the same historical land use. The coffee planting density was 56% higher in SCA2 than in AFA2. Liming rates were twice as high in SCA2 as in AFA2. At farm D1, AFD1 and SCD1 were established where forest had been converted to pasture for several years (exact time unknown) and further to coffee cultivation. The main goals of the establishment of AFD1 were soil protection and diversification of production. AFD1 was intercropped with coffee. From 2003 till 2006, AF received 10 Mg of cow manure over a period of 4 years. In 2007 950 kg of limestone was applied in AFD1.

**Table 1**
Characteristics of the three selected farms, in Zona da Mata, Brazil.

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Sites | Farm | | Farm A1 | | | Farm A2 | | | Farm D1 | | |
| | Location | | 20º 41' S ; 42º 31' W | | | 20° 42' S ; 42° 31' W | | | 20° 33' S ; 42° 11' W | | |
| | Altitude | (m asl) | 1062 | | | 1040 | | | 1160 | | |
| Systems[1] | | | AFA1 | SCA1 | RFA1 | AFA2 | SCA2 | RFA2 | AFD1 | SCD1 | RFD1 |
| Area | size | (ha) | 0.15 | 0.75 | 2.00 | 0.72 | 0.77 | 3.00 | 0.27 | 0.45 | 1.00 |
| | slope | (%) | 33 | 33 | 40 | 75 | 70 | 70 | 35 | 35 | 42 |
| | former use | | rice cultivation for 10 years | rice cultivation for 10 years | annual crops | heavily eroded coffee field | eroded coffee field | forest | cut forest and pasture | cut forest and pasture | forest |
| Fertilization | N-P-K (20-5-20) | (g plant$^{-1}$ yr$^{-1}$) | 200 | 200 | 0 | 0 | 180 | 0 | 100 | 150 | 0 |
| | Cow manure | (Mg.yr$^{-1}$/field) | 0 | 0 | 0 | 2.9 | 0 | 0 | 10 [5] | 0 | 0 |
| | Lime | (g. m$^{-2}$/plant) | 200 [3] | 200 [3] | 0 | 20 [4] | 40 [4] | 0 | 950 [6] | 0 | 0 |
| Coffee plants | Density | (# ha$^{-1}$) | 3300 | 3300 | - | 1670 | 2600 | - | 2200 | 2200 | - |
| | Spacing | (m) | 3.0 x 1.0 | 3.0 x 1.0 | - | 4.0 x 1.5 | 3.2 x 1.2 | - | 3.0 x 1.5 | 3.0 x 1.5 | - |
| | Age | (yr) | dez/14 | dez/14 | - | dez/14 | dez/14 | - | out/14 | out/14 | - |
| | Production | (kg.ha$^{-1}$. yr$^{-1}$)[2] | 1650 | 1350 | - | 313 | 1320 | - | 1644 | 1602 | - |
| Trees and crops | Main species, besides coffee plants | (# ha$^{-1}$) | 380 | 0 | not counted | 370 | 0 | not counted | 257 | 0 | not counted |
| | | Current (2008-2009) | *I. sessilis* .*I subnuda* guava, papaya, citrus, | - | Secondary succession | *P.americana,* sugarcane, lemon, banana + fruits/crops | - | Secondary succession | banana, orange, cassava and lemon | - | Secondary succession |
| | | Past (1994-2004) | *Hovenia spec., Colubrina spec., Pennisetum spec., Inga* spp., fruits (guava, papaya, citrus, avocado*)* | - | Secondary succession | *A.sellowiana, P.americana* | - | Secondary succession | *Luehea* spec., banana, orange, cassava and lemon | - | Secondary succession |
| | | (# ha$^{-1}$) | ~20 | 0 | Not counted | ~20 | 0 | Not counted | ~40 | - | Not counted |
| | Current pruning | | December to March | - | - | December to March, low branches in July | - | - | December to March | - | - |

[1]AF: agroforestry system, SC: full sun coffee system, RF: reference forest, A1 and A2 in Araponga and D1 in Divino municipality; [2]three year average (2007, 2008 and 2009); [3]total applied in 1999, 2001, 2004 and 2006; [4]applied annually; [5]total applied during the organic cultivation from 2003 till 2006; [6]applied in 1997.

### 2.3. Sampling and data collection

#### 2.3.1. Interviews

Information on the characteristics of the farms, management of the coffee systems and uses of the trees (objective 2) was obtained through semi-structured interviews between February 2008 and January 2009. While a map of the farm was drawn to locate each farm component, we asked the farmer about physical features of the property and the reasons for choosing the exact places for crops (annuals or perennials), buildings, pastures and roads. The structure and composition of agroforestry systems and sun coffee systems were gathered during excursions to the systems while undertaking the questionnaires on the influence on soil quality and coffee production, distances, height, and shade between trees and crops. The types of farm operations and time spent on different farming activities, and the type and amount of inputs and outputs in each system were collected during field visits and a calendar of field operations was created for each farm. Selected characteristics of the farms are presented in Table 1.

#### 2.3.2. Tree species

Data on floristic composition (objective 1) of AFA1 until AFA7, RFA8 and RFA9 (in Araponga) were collected by Fernandes (2007) and Siqueira (2008). Tree composition in RFV1 and RFV2 (in Viçosa) was identified by Ribas et al. (2003) and we identified the floristic composition of AFD1 (in Divino). For identification of the RFs in Viçosa, 20 plots of 10 m × 20 m, corresponding to a total area of 0.40 ha, were delineated and all trees with circumference ≥5 cm at breast height (1.3 m) were identified (Ribas et al., 2003). In the AF plots with an average size of 0.38 ha (ranging from 0.15 to 0.72 ha), all trees were counted and identified. In Araponga, observations on flowering and fruiting and sampling of botanical material of all trees were done monthly, from February 2006 to May 2007, in the two RFs and seven AFs (Fernandes, 2007; Siqueira, 2008). In AFD1 (Divino) species identification was based on the morphology of collected plants, taxonomic literature, consultation with specialists and comparison with collection materials of the VIC Herbarium of the Federal University of Viçosa. Matrices of presence and absence of tree families and species were made. The floristic composition was evaluated through cluster analysis and is presented in a dendrogram as described in paragraph 2.4. Taxonomic richness at species level was calculated by counting the number of different tree families and species found in each plot.

#### 2.3.3. Microclimate

Thermometers for recording of maximum and minimum temperatures (Digilab) and rain gauges (0–130 mm $m^{-2}$, Walmur) were installed in the agroforestry, sun coffee and reference forest systems at the three farms. One device per system was placed at a height of 1.0 m above the soil surface. Data were collected by the farmers, every 2–3 days during from January 2007 to January 2008.

#### 2.3.4. Soil quality

Soil samples were collected at 0–10 and 10–20 cm soil depth during the dry season (end of June 2007 in A1 and A2; and August 2007 in D1). On each farm four sub-plots were established within each treatment. In each sub-plot four soil samples were taken between the coffee rows and bulked into one sample per sub-plot. Immediately after sampling, biological analysis was performed. The remaining soil was air-dried, sieved through a 2-mm sieve and stored at room temperature.

Soil texture was determined by the sieving and pipette method (Day, 1965). The soil pH was determined in water (soil:water ratio 1:2.5). Exchangeable cations ($Ca^{2+}$, $Al^{3+}$, $Mg^{2+}$) were measured after extraction with 1 mol $L^{-1}$ KCl; K and P were extracted by Mehlich-1; H + Al was extracted with 0.5 mol $L^{-1}$ $Ca(OAc)_2$ at pH 7.0 (EMBRAPA, 1997). The cation exchange capacity (CEC) and base saturation (%BS) were calculated using the concentrations of the exchangeable cations. Total organic C (TOC) was quantified by wet combustion with a mixture of potassium dichromate and sulfuric acid and subsequent titration with standardized $FeSO_4$ (Yeomans and Bremner, 1988). Total soil nitrogen (TN) was measured after sulfuric digestion followed by Kjeldahl distillation (Tedesco et al., 1995).

Measurement of soil respiration was based on the alkali absorption technique (Stotzky, 1965; Curl and Rodrigues-Kabana, 2001) and performed as follows: 100 g of fresh soil was placed in a plastic container. The moisture content was adjusted to 70% of field capacity by adding distilled water. The samples were incubated in a closed container at 25 °C. $CO_2$ was captured in a 0.5 mol $L^{-1}$ NaOH solution and was quantified after 3, 5, 7, 9, 12, 16, 19, 23, 27, 31, 38, 45 and 48 days by titration with 0.25 mol $L^{-1}$ HCl. From this incubation, samples (5 g) were taken weekly during seven subsequent weeks to determine N mineralization (Nmin). $N–NH_4^+$ and $N–NO_3^-$ were measured colorimetrically in a 1 mol $L^{-1}$ KCl extract (Kempers and Zweers, 1986; Yang et al., 1988). Microbial biomass C (Cmic) was determined by irradiation-extraction method, using a microwave (Ferreira et al., 1999). The conversion factor (Kc) used to convert extracted C to Cmic was 0.33 (Ferreira et al., 1999). The metabolic quotient (qMet) was estimated by dividing the mean values of $C–CO_2$ emission by Cmic (Franchini et al., 2007). The microbial quotient (qMic) was obtained by dividing Cmic by TOC.

#### 2.3.5. Leaf quality

Based on their N, lignin and polyphenol contents, the leaf materials of selected tree species from the AF systems were classified into four quality classes according to Palm et al. (2001). These quality classes have been related to nutrient release patterns with important implications for soil fertility management in tropical agroecosystems. Seven trees selected by the farmers and cultivated currently in their AF with coffee to improve soil characteristics were used for this leaf quality study (objective 4). The tree species *Aegiphila sellowiana, Erythrina verna, Inga subnuda, Luehea grandiflora, Persea americana, Senna macranthera,* and *Zeyheria tuberculosa* were considered compatible with coffee, due to their amount and quality of biomass, food and fodder production and the ease of pruning (Souza et al., 2010). From each tree species fresh leaf material was collected in June 2006 from low, medium and high parts of the canopy and one composite sample per tree species was made. The leaf material was dried in a forced-air circulation oven (65 °C, 72 h) and ground. Lignin, cellulose, hemicellulose and polyphenol contents were assessed by the acid–detergent fiber method (Goering and VanSoest, 1975). The soluble polyphenols were extracted through 50% aqueous methanol and determined colorimetrically using Follin–Denis reagent (Anderson and Ingram, 1993). Nitrogen (N) was determined by the Kjeldahl method (Tedesco et al., 1995). For the species *Cassia ferruginea*, *Croton urucurana, Solanun variabile*, and *Piptadenia gonoacantha* leaf quality data were obtained from Mendonça and Stott (2003) who used the same methodology for sampling and analysis.

### 2.4. Statistical analysis

For the comparative analysis of species composition among agroforestry systems and reference forest fragments, cluster analysis using the Unweighted Pair Group Method with Arithmetic Mean (UPGMA) was performed for the botanical dataset, using MVSP 3.13m software (MVSP, 2006). The Sørensen Index (SI) was calculated for each AF and RF fragment according to the formula

**Table 2**
Number of tree families and tree species and the percentage of the total number of identified tree species in eight agroforestry coffee systems and four reference forest fragments, in Zona da Mata, Brazil.

| Item | AFA1 | AFA2 | AFA3 | AFA4 | AFA5 | AFA6 | AFA7 | AFD1 | RFA8 | RFA9 | RFV1 | RFV2 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| # tree species | 23 | 15 | 41 | 26 | 27 | 21 | 32 | 28 | 54 | 70 | 66 | 68 |
| # tree families | 16 | 12 | 20 | 17 | 14 | 13 | 13 | 20 | 24 | 26 | 25 | 28 |
| % of total# tree species | 10 | 6 | 18 | 11 | 12 | 9 | 14 | 12 | 23 | 30 | 28 | 29 |
| % of RF species found | 43 | 53 | 27 | 50 | 33 | 48 | 25 | 21 | – | – | – | – |

AFA1–AFA7 refer to the agroforestry systems located in Araponga, AFD1 is located in Divino; RFA8 and RFA9 are about 50 years old and are located in Araponga (not within the selected farms), RFV1 and RFV2 are 15 and 30 years old, respectively, and located in Viçosa.

$SI = 2j/(a+b)$, where $j$ is the number of species occurring at both sites, $a$ is the number of species in site 1, $b$ is the number of species in site 2 (Sorensen, 1948).

ANOVA with repeated measures was performed to test the effects of system on temperature over time, followed by Tukey's test ($p < 0.05$). The three farms were considered as 3 replicates. SPSS Statistic 17 was used for microclimate data (SPSS, 2007) and PASW for soil data (PASW Statistics, 2009). The effects of system (AF, RF, SC) and site (farm A1, A2, D1) on soil quality parameters were tested using a Mixed Model with site and system as fixed effects and sub-plots as random effects. To account for the split-plot layout (system was nested within site) and the two levels of replication of the factor system (sites as real replicates; sub-plots as pseudoreplicates), subplots were nested within system and both were nested within site (Onofri et al., 2010). In case of statistically significant effects a pairwise comparison of means using a Bonferroni post hoc test ($p < 0.05$) was applied. To meet the requirements for normality and homogeneity of variance, variables were transformed prior to statistical analyses ($1/x$ for qMet, Nmin, Silt, Total N; SQR for Ca, Mg, Al, Base saturation; and $\log(x+1)$ for P and CEC).

To analyze the relationships between sites, systems and soil characteristics we used redundancy analysis (RDA) using CANOCO 4.0 for Windows (Ter Braak, 1986). Sites (A1, A2, D1) and systems (AF, SC, RF) were used as independent variables. The data set was log-transformed, centered, and standardized. All statistical analyses were performed separately for the two soil depths (0–10 and 10–20 cm).

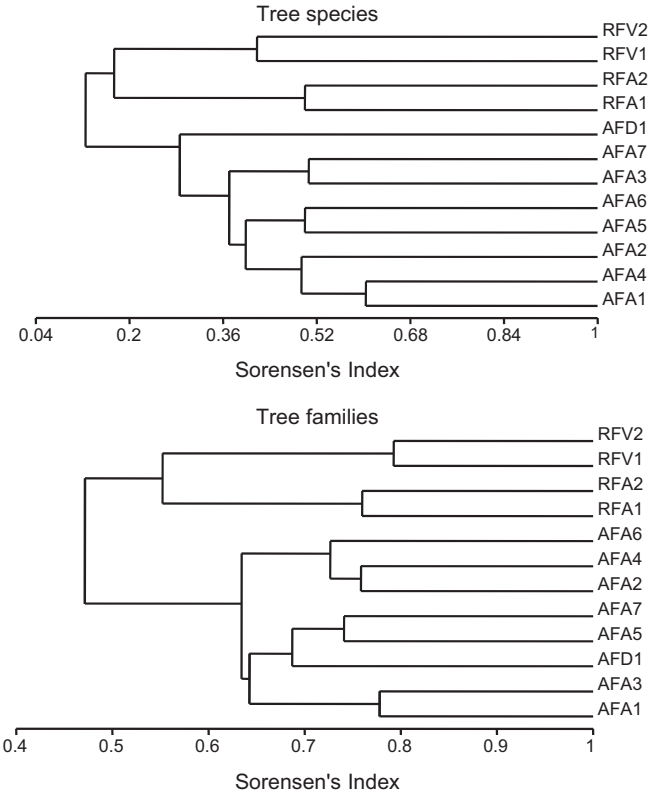


**Fig. 3.** Cluster analysis dendrogram of floristic composition (Sørensen's coefficient) from eight agroforestry systems (AFA1 to AFA7 in Araponga and AFD1 in Divino) and four reference forest fragments (RFV1, RFV2 and RFA8, RFA9) in the Seasonal Semideciduous Forest of the Atlantic Rainforest domain.

## 3. Results

### 3.1. Tree species composition among agroforests and forest fragments

The list of all species found in the agroforestry coffee systems and reference forest fragments is shown in Appendix A. A total of 231 tree species was found in the eight AFs (87 species) and four RF fragments (178 species). The tree species richness in the individual AFs ranged from 15 to 41 species and 12 to 20 families, which was lower than in the RFs (54–70 species and 24–28 families). The percentage of the total number of species found in the individual systems ranged from 6% to 18% for the AFs and from 23% to 30% for the RFs (Table 2). Overall, 38% of the tree species (33 species) that were present at least one of the AFs also occurred in at least one of the RFs. Seventy-eight percent (68 species) of the species in the AFs were native and 22% (19 species) were exotic. The percentage of species per individual AF system is listed in Table 2 and ranged from 21% to 53%.

The cluster analysis for tree species and families, which indicates the similarity among the 12 sites, distinguished two groups: one group is formed by the RFs and the other group is formed by the AFs (Fig. 3). Among the RF fragments, there are two groups, separated by location (Fig. 3). The similarity in tree species between the AFs and the RF fragments of our study, as expressed by the Sørensen Index, was 13%.

### 3.2. Leaf material quality

The N content of the leaf materials ranged from 1.6% to 3.8%, lignin content (LG) ranged from 7.7% to 27.3% and polyphenol content (PP) ranged from 1.9% to 11.0% (Table 3). Quality class II (indicated to be used in combination with fertilizers) and class III (high LG and PP content, recommended to be composted before applying to the soil) were dominant with 4 species each, followed by class IV (recommended to be used as mulch for erosion control) with 2 species, whereas class I (nutrient-rich organic matter) was represented by one species (Table 3). The actual on-farm use of these tree species was as wood, soil cover, fertilizer and food/fodder.

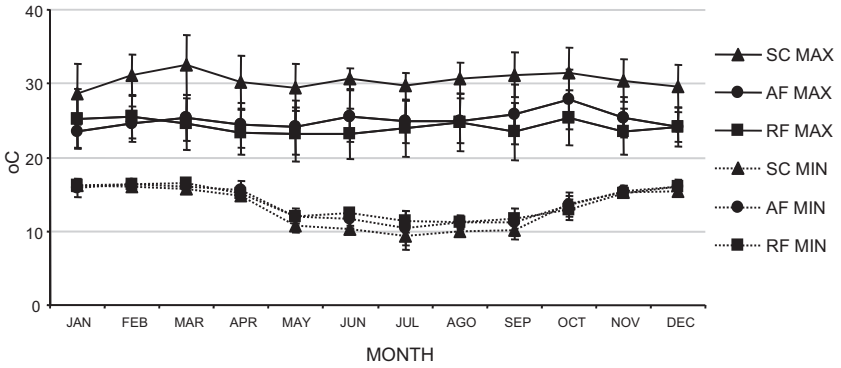


**Fig. 4.** Monthly average maximum (MAX) and minimum (MIN) temperatures in reference forest fragments, coffee agroforestry and full-sun coffee systems. Average data collected at three different farms in 2007/2008. Bars represent standard errors.

### 3.3. System effects on temperature

The monthly average maximum temperatures differed significantly between systems ($p < 0.001$). The sun coffee system consistently presented the highest mean daily maximum temperatures, which were 6.3 °C higher than in the reference forest and 5.4 °C higher than in agroforestry system when averaged across all months (Fig. 4). The highest temperatures were reached in February and March (32 °C) and September and October (31 °C). There was no difference between RF and AF for monthly average maximum temperature ($p = 0.79$). The mean daily minimum temperatures did not show significant differences among any of the systems ($p = 0.12$).

### 3.4. System effects on soil parameters

The redundancy analysis that described the variation in soil chemical and biological properties (response variables) as a function of the experimental variables site and system separated the farm in Divino from the two farms in Araponga (axis 1), and secondly, the reference forests from the coffee systems (sun coffee, SC and agroforestry system, AF). These results were consistent for both soil depths (Fig. 5). The displayed graph explained 64% and 58% of the variance in soil factors and 79% and 77% of the variance in the fitted soil factors for the 0–10 cm and 10–20 cm soil depth, respectively. The sum of all canonical eigenvalues was 0.805 and 0.751, respectively (Fig. 5).

At 0–20 cm depth, the Divino site had a silty clay texture (28% clay, 22% silt and 50% sand), whereas the Araponga sites had a clay texture (44% clay, 12% silt and 44% sand). Moreover, potential acidity (H + Al) was lower ($p = 0.005$) and base saturation (Base Sat) higher ($p = 0.018$) at Divino (H + Al = 5.6, Base Sat = 52.1) than at Araponga (A1: H + Al = 11.8 and Base Sat = 5.5; A2: H + Al = 8.4 and Base Sat = 14.4).

At 0–10 cm soil depth, the chemical parameters potential acidity (H + Al) and total organic carbon, and the biological parameters microbial carbon, nitrogen mineralization and microbial respiration ($CO_2$) were higher ($p \leq 0.05$) in RF compared to AF and SC (Table 4). None of the measured soil parameters distinguished the AF treatments from the SC treatments. Also at 10–20 cm soil depth, H + Al, TOC, Cmic and $CO_2$ were higher ($P \leq 0.05$) in RF compared to AF and SC.

**Table 3**
Residue category, use and leaf quality of common tree species used in coffee agroforestry systems in Zona da Mata, Brazil.

| Residue categories[a] | Plant species | Uses[b] | % N[c] | % LG[d] | % PP[e] |
|---|---|---|---|---|---|
| I | *Solanum variabile*[g] | w, sc | 2.6 | 10.4 | 1.9 |
| II | *A. sellowiana* | w, fe | 3.8 | 18.2 | 4.9 |
| II | *E. verna*[f] | fe | 3.3 | 7.7 | 6.4 |
| II | *I. subnuda*[f] | fe, f, w | 3.2 | 27.3 | 4.8 |
| II | *S. macranthera*[f] | fe, w | 3.6 | 15.4 | 7.6 |
| III | *C. ferruginea*[f] | sc, w | 1.6 | 12.5 | 11.0 |
| III | *C. urucurana*[h] | w | 2.0 | 13.8 | 10.7 |
| III | *L. grandiflora* | w, sc | 2.0 | 13.6 | 8.3 |
| III | *Z. tuberculosa* | W | 2.2 | 14.5 | 4.4 |
| IV | *P. Americana* | f, w, sc | 2.1 | 21.0 | 7.3 |
| IV | *P. gonoacantha*[f,h] | w | 2.4 | 18.5 | 6.1 |

[a] Palm et al. (2001).
[b] w: wood, sc: soil cover, fe: fertilizer, f: food/fodder.
[c] N: nitrogen.
[d] LG: lignin.
[e] PP: polyphenols.
[f] N-fixing trees.
[g] Nowadays classified as *Solanun mauritianum*.
[h] These species are no longer indicated as suitable to be intercropped with coffee in the region (Souza et al., 2010).

## 4. Discussion

### 4.1. AF and tree diversity conservation

Diversified agroecosystems, such as the agroforestry systems studied here, can support the conservation of biodiversity in the surrounding landscape and *vice versa,* depending on their design and management (Moguel and Toledo, 1999; Cassano et al., 2009). The similarity in tree species between the AFs and the reference forest fragments of 13%, as expressed by the Sørensen Index, is in the lower part of the range of 12–39% found by Scales and Marsden (2008) who reviewed species richness and abundance shifts in small-scale tropical agroforests. However, the design and management of the agroforestry systems were geared to the characteristics of each farm and the farmers' preferences which resulted in large differences in tree species composition (SI 29–61%) and taxonomic richness (15–41 species and 13–20 families) between farms. We found that 38% of the AF species was also found in at least one of the RF fragments. At the same time, 20% of the native tree species found in AF was not detected in the RF fragments. This analysis partly confirms the first hypothesis as it was shown that the majority of the tree species used in AF was native, even though the percentage of AF tree that also occurred in RFs was below 50%. This is explained by the observation that some tree species, that were not detected in the RF fragments, but were present in the AF, such as *Aspidosperma* sp., *Joanesia* sp., *Caesalpina* sp., *Schizolobium* sp., *Anadenanthera* sp. and *Zeyheria* sp., belong to more advanced stages of succession or to climax rainforest. The RF fragments consisted of secondary forest on former agricultural land.

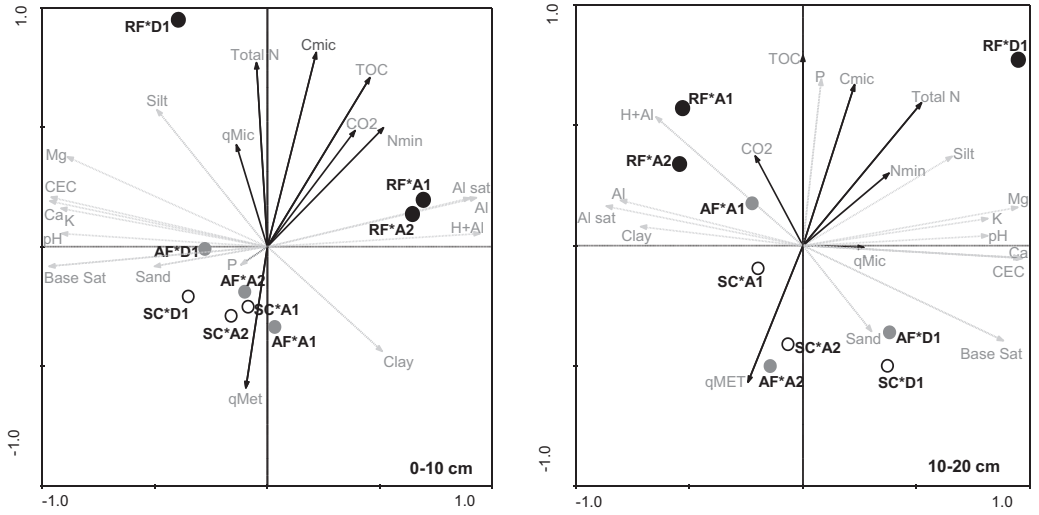


**Fig. 5.** Correlation biplot based on redundancy analysis (RDA) of the independent factors location and system and the dependent chemical and biological soil parameters at 0–10 cm and 10–20 cm soil depth at 3 farms in Zona da Mata, Minas Gerais State, Brazil.

**Table 4**
Average ($n = 12$) of soil parameters in reference forest, agroforestry systems, and full sun coffee at two soil depths, in Zona da Mata, Brazil.

| Soil parameters | Units | RF | | AF | | SC | | *P*-value |
|---|---|---|---|---|---|---|---|---|
| 0–10 cm | | | | | | | | |
| Sand | % | 47.9 | | 48.9 | | 48.1 | | 0.602 |
| Silt | % | 16.3 | | 12.2 | | 14.4 | | 0.981 |
| Clay | % | 35.8 | | 38.9 | | 37.5 | | 0.662 |
| pH $H_2O$ | (1:2.5) | 5.4 | | 5.8 | | 6.0 | | 0.309 |
| P[1] | mg $dm^{-3}$ | 4.3 | | 3.9 | | 7.0 | | 0.607 |
| K[2] | mg $dm^{-3}$ | 108.1 | | 123.5 | | 135.8 | | 0.361 |
| Ca[3] | $cmol_c$ $dm^{-3}$ | 4.5 | | 4.1 | | 4.3 | | 0.662 |
| Mg[4] | $cmol_c$ $dm^{-3}$ | 1.0 | | 1.1 | | 1.0 | | 0.683 |
| Al[5] | $cmol_c$ $dm^{-3}$ | 0.70 | | 0.02 | | 0.01 | | 0.181 |
| H + Al[6] | $cmol_c$ $dm^{-3}$ | 127.8 | | 6.0 | | 5.3 | | 0.086 |
| CEC[7] | $cmol_c$ $dm^{-3}$ | 5.8 | | 5.5 | | 5.7 | | 0.444 |
| Base sat[8] | % | 27.4 | | 48.4 | | 51.3 | | 0.183 |
| Al sat[9] | % | 54.47 | | 0.45 | | 0.19 | | 0.112 |
| TOC[10] | g $kg^{-1}$ | 61 | a | 30 | b | 26 | b | 0.006 |
| Total N[11] | % | 0.55 | | 0.25 | | 0.24 | | 0.115 |
| Nmin[12] | mg $kg^{-1}$ $wk^{-1}$ | 0.15 | a | 0.13 | b | 0.11 | b | 0.001 |
| C mic[13] | µg $g^{-1}$ | 839 | a | 383 | b | 332 | b | 0.028 |
| $CO_2$[14] | mg $kg^{-1}$ $day^{-1}$ | 1378 | a | 1060 | b | 921 | b | 0.018 |
| /q Mic[15] | % | 14.7 | | 15.9 | | 9.7 | | 0.932 |
| q Met[16] | mg $C–CO_2$ $mg^{-1}$ Cmic $day^{-1}$ × 100 | 0.57 | | 1.24 | | 1.01 | | 0.092 |
| 10–20 cm | | | | | | | | |
| Sand | % | 47.8 | | 50.0 | | 47.7 | | 0.874 |
| Silt | % | 15.1 | | 11.0 | | 13.9 | | 0.664 |
| Clay | % | 37.2 | | 38.4 | | 38 | | 0.841 |
| pH $H_2O$ | (1:2.5) | 5.4 | | 5.4 | | 5.4 | | 0.994 |
| P | mg $dm^{-3}$ | 2.4 | | 1.6 | | 1.5 | | 0.338 |
| K | mg $dm^{-3}$ | 100.4 | | 65.2 | | 88.7 | | 0.742 |
| Ca | $cmol_c$ $dm^{-3}$ | 2.8 | | 1.6 | | 1.7 | | 0.970 |
| Mg | $cmol_c$ $dm^{-3}$ | 0.9 | | 0.5 | | 0.3 | | 0.918 |
| Al | $cmol_c$ $dm^{-3}$ | 0.46 | | 0.27 | | 0.29 | | 0.793 |
| H + Al | $cmol_c$ $dm^{-3}$ | 11.02 | a | 7.56 | b | 7.26 | b | 0.021 |
| CEC | $cmol_c$ $dm^{-3}$ | 4.02 | | 2.28 | | 2.28 | | 0.933 |
| Base sat | % | 21.7 | | 26.2 | | 24.1 | | 0.418 |
| Al sat | % | 53.99 | | 17.72 | | 18.71 | | 0.144 |
| TOC | g $kg^{-1}$ | 42 | a | 22 | b | 19 | b | 0.019 |
| Total N | % | 0.38 | | 0.18 | | 0.18 | | 0.162 |
| Nmin | mg $kg^{-1}$ $wk^{-1}$ | 0.15 | | 0.11 | | 0.12 | | 0.269 |
| Cmic | µg $g^{-1}$ | 545 | a | 312 | b | 195 | b | 0.009 |
| $CO_2$ | mg $kg^{-1}$ $day^{-1}$ | 1088 | | 867 | | 815 | | 0.060 |
| qMic | % | 12.8 | | 12.7 | | 12.6 | | 0.360 |
| qMet | mg $C–CO_2$ $mg^{-1}$ Cmic $day^{-1}$ × 100 | 0.78 | | 1.37 | | 1.37 | | 0.072 |

Numbers followed by the same letters are not significantly different between systems according to the Bonferroni "*t*" test. *Codes*: (1) Available phosphorus, (2) potassium, (3) calcium, (4) magnesium, (5) aluminium, (6) potential acidity, (7) cation exchange capacity, (8) base saturation, (9) aluminium saturation, (10) total organic carbon, (11) total nitrogen, (12) nitrogen mineralization, (13) microbial biomass carbon, (14) carbon dioxide evolution, (15) microbial quotient, (16) metabolic quotient.

Our results thus demonstrate the potential of AF systems to contribute to the conservation of tree species diversity in tropical rainforest landscapes such as the Zona da Mata. As part of the 62% of native tree species that were not found in AF systems might represent a source of useful tree species for agroforestry systems. An important future challenge is therefore to source local ethnobotanic knowledge, and generate new knowledge on tree characteristics to optimize the use of trees in AF systems (e.g. to verify compatibility with intercropping).

The use of native trees in coffee AFs is not common elsewhere in Brazil. Instead, exotic leguminous trees and/or marketable timber trees are preferred (Jaramillo-Botero et al., 2007; Vieira et al., 2007). In local agroforests in Kigezi Highlands in Rwanda most (69%) cultivated tree species were also exotic (Boffa et al., 2009). In contrast, in coffee agroforestry systems in Guatemala, on average 70 native tree species per hectare were surveyed (Rice, 2008). In other Latin American countries such as Honduras, El Salvador, and Peru, native *Inga* spp. were found to dominate the agroforestry systems and most shade canopies included a mixture of three to six of these tree species (Schroth et al., 2004). Unfortunately, to our best knowledge, quantitative data on tree species composition in AF systems in Brazil is lacking. The results of our study show a much greater $\gamma$-diversity than $\alpha$-diversity in AFs. Hence, different choices of farmers probably increase habitat diversity, which is important for conservation of the diversity of both trees and other groups of fauna and flora (Schulze et al., 2004; Philpott et al., 2008; Cassano et al., 2009). Bhagwat et al. (2008) found that the more complex AF systems in their studies had on average 60% greater species richness of birds, bats, herptiles, insects, macrofungi, mammals, plants, and trees than the forests.

### 4.2. Agroforestry for adaptation to climate change

The average annual temperature for sun coffee, agroforestry system, and reference forest was 22, 20, and 19 °C, respectively, which falls within the range of the optimum temperature for *C. arabica*, which is between 18 and 23 °C (Camargo, 1985). On a daily basis, however, the maximum temperature registered in SC reached maxima up to 38 °C. Exposing coffee plants continuously to extreme temperatures higher than 30 °C can cause a reduction in the coffee production due to depressed growth and occurrence of abnormalities such as yellowing of leaves (DaMatta, 2004; DaMatta and Ramalho, 2006). The difference between the mean daily maximum temperature in SC and the average in AF and RF was approximately 6 °C. This result fully supports our third hypothesis that AF would moderate extremes of high temperature, thereby creating a more adequate microclimate for coffee production than full-sun coffee. Some studies emphasized the negative influence of high temperatures on coffee quality and production. For instance, Muschler (2001) observed that coffee fruit weight and bean size under shade systems in Costa Rica were on average 50% higher than in unshaded coffee systems. All three farmers (A1, A2 and D1) reported that the coffee from AF acquired high beverage (better quality) that guarantees a better price than the coffee harvested in SC.

Morton (2007) reported that climate change will affect smallholder farmers and indigenous communities in particular. Our results indicate that agroforestry provides temperature regulation as an ecosystem service, thereby offering an adaptation strategy for small coffee growers in response to global warming, in line with previous studies (Beer et al., 1997). Agroforestry could significantly reduce the risk of loss of coffee production in Minas Gerais state, which is predicted to be as high as 92% by 2050 if the climate warms up with 5.8 °C (Assad et al., 2004), in Minas Gerais and other coffee growing regions such as the higher elevation regions of the southeast of São Paulo state (Junior et al., 2006).

### 4.3. Local strategies for the use of tree resources and its effects on soil quality

Agroforestry management in Zona da Mata is not a traditional practice and farmers learn and improve their systems by exchanging their main findings. Tree species diversity in the individual AF plots is determined by different underlying factors related to farm features, physiographic conditions, local knowledge on tree species traits and soil fertility management, and farmer preferences. Our third hypothesis was that chemical and biological soil characteristics are improved under AF as compared to sun coffee system and these improvements are related to leaf litter quality. We found only partial evidence for this hypothesis. The AF in location A1 was established at a degraded plot. The choice of tree species by the farmer was functional in selecting N-fixing species that improve soil fertility. In location A2, the AF was located on a very steep slope (>70%), legally characterized as a Permanently Protected Area (BRASIL, 2006). At this position the soil was severely degraded by erosion, requiring an efficient and rapid topsoil recovery. The main tree species selected were *P. americana* (class IV, dominant in AFA2) in combination with *A. sellowiana* (class II). The farmer motivated his choice by reporting that *P. americana* is a deeper rooting species, that produces a large amount of relatively slowly decomposing litter that will contribute to an increased soil cover, whereas the leaves of *A. sellowiana*, a tree species that does not need pruning, are decomposed much faster and contribute to soil fertility. As a result, soil erosion was controlled (personal observation). In location D1, AF was introduced in a degraded pasture where already some secondary tree species were present. The farmer's decision was aiming at a high diversity of tree species to produce a variety of residue qualities to improve soil protection. The AFD1 farmer achieved this goal by selecting trees belonging to class II (*A. sellowiana*), class III (*C. ferruginea*, *L. grandiflora*, *Z. tuberculosa*) and class IV (*P. americana* and *P. gonoacantha*). The wood providing *P. gonoacantha* (class IV) can provide additional benefits for erosion control due to its slow decomposition. Furthermore, e.g. *C. urucurana* and *Z. tuberculosa* (class III) were used for wood production only, but can according to the residue category classification system of Palm et al. (2001) also be mixed to facilitate nutrient release.

Hence, most of the actual uses of the trees found in the three AF systems studied did not entirely correspond with the function of the categories of residue quality according to the classification of Palm et al. (2001). The farmers selected trees based on multiple criteria and trade-offs, whereas the Palm classification looks at a limited set of criteria such as decomposability and nutrient supply while ignoring market value, management requirements, seed availability, and compatibility with other plants, such as coffee. A previous study reported on the main criteria and indicators of farmers for selecting trees to use in the agroforestry coffee systems in Zona da Mata, including the compatibility with coffee plants (e.g., no competition and negative phytosanitary interactions), the amount of biomass produced, the labour needed to manage the trees, and diversification of the production (Souza et al., 2010). A multi-criteria decision support system would be needed for the farmers to enhance their options and improve their selection. Moreover, to further improve the residue category classification system of Palm et al. (2001), we propose to base the classification of leaf material on characteristics of freshly fallen litter and not on fresh leaves.

We found significant differences in soil characteristics between reference forest and both coffee systems, but not between AF and sun coffee system. However, there is a clear trend in soil quality of AF being closer to RF than SC (Table 4), suggesting that soil quality in AFs is improving more than in SC. Differences in soil conditions between RF and the two coffee systems were related to organic matter content and soil microbial activity (higher TOC, Cmic, soil respiration and Nmin). H + Al was only higher in RF in

the 10–20 cm soil layer, with a similar, but not significant trend in the 0–10 cm layer. Such differences, which were also found in other studies (Sena et al., 2002; Macedo et al., 2008), might be explained by higher inputs of organic matter and less soil disturbance in RF, and inorganic fertilizer application in AF/SC.

AF did not result in higher soil carbon contents than SC despite the higher litter returns in AF. In contrast, Youkhana and Idol (2009) found differences in soil C and N already 3 years after conversion from SC to AF. The lack of such effect in our study may be explained by the fact that the experimental plots in ZM were highly degraded at the start of the experiments and may need relatively long time or high OM inputs before soil improvement can be detected. There may still be room for improvement of the soil quality in the AF systems, e.g. through enhanced organic matter returns and reduced soil disturbance. However, more research is needed to improve our knowledge of the management of residue quality and their effects on soil C dynamics and soil nutrient cycling as essential to support ecosystem services in tropical AF, such as erosion control, carbon sequestration and soil structure maintenance.

Coffee production in AF can be as high as in SC, as was proven at two of three studied farms, and also of a better quality that led to an enhanced price on sales. Again the large variability across farms suggests that there is scope for improvement, e.g. through further farmer-to-farmer knowledge exchange.

## 5. Conclusions

Our comparison between reference forest fragments, agroforestry coffee and sun coffee revealed that:

- Agroforestry can support the conservation of native trees.
- Agroforestry systems can moderate high temperature extremes to the extent that agroforestry coffee production, unlike sun coffee, is resistant to expected near-future temperature increases resulting from climate change.
- Some soil quality parameters (total organic carbon, microbial carbon, soil respiration and nitrogen mineralization) showed higher values in reference forest fragments compared to agroforestry and sun coffee systems, and there was a trend towards improved soil quality in AF relative to SC.
- The selection of trees in agroforestry systems was based on multiple criteria and trade-offs, Local and scientific knowledge on native tree species and multi-criteria decision support systems would increase farmers' options to further enhance ecosystem services provided by agroforestry systems.

Based on the successful examples of agroforestry coffee systems, our study has shown the potential of agroforestry systems to reconcile coffee production with biodiversity conservation under climate change and to contribute to some regulating and supporting ecosystem services. We see much scope for better design of these systems, based on increased ecological literacy through continued participative work among scientists and stakeholders.

## Acknowledgements

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## Appendix A.

See Table A.1.

**Table A.1**
Species of native and exotic trees used in agroforestry systems and found in the forest fragments, Zona da Mata, Minas Gerais, Brazilian Rainforest.

| # | Family/specie | Common name | Agroforests[a] | Fragments[b] |
|---|---|---|---|---|
| ANACARDIACEAE | | | | |
| 1 | *Mangifera indica* L. | Manga | D1, A3, A4, A5, A7 | |
| 2 | *Schinus terebentifolius* Raddi | Aroeira-do-sertão | A1, A4 | 1 |
| 3 | *Tapirira guianensis* Aubl. | Pau-pombo | | 1, 2 |
| 4 | *Tapirira obtusa* (Benth.) JD.Mitch | Pau-pombo | | 1 |
| ANNONACEAE | | | | |
| 5 | *Annona cacans* Warm. | Araticum-cagão | | 2 |
| 6 | *Annona muricata* | | D1 | |
| 7 | *Annona squamosa* L. | | D1, A6 | |
| 8 | *Ephedranthus* sp. | | | 1 |
| 9 | *Guatteria mexiae* R. & Fr. | Pindaíba | | 1 |
| 10 | *Guatteria sellowiana* Schltdl. | Pimenteira | | 1 |
| 11 | *Guatteria villosissima* A.St.-Hil. | Araticum-peludo | | 2 |
| 12 | *Rollinia dolabripetala* A. St.-Hil. | Articum/Araticum | A1, A3 | 1 |
| 13 | *Rollinia laurifolia* Schltdl. | Araticum-bravo | | 2 |
| 14 | *Rollinia sericea* (R.E.Fr.) R.E.Fr. | Araticum-mirim | | 2 |
| 15 | *Xylopia sericea* A.St.-Hil. | Pimenteira | | 2 |
| APOCYNACEAE | | | | |
| 16 | *Aspidosperma* sp. | Peroba/Tambu | D1 | |
| 17 | *Himatanthus phagedaenicus* (Mart.) | Sucuúba | | 2 |
| 18 | *Peschiera laeta* Miers | | | 2 |
| AQUIFOLIACEAE | | | | |
| 19 | *Ilex breviscuspis* Reissek | | | 1 |
| 20 | *Ilex* L. | | | 1 |
| 21 | *Ilex theezans* Mar | | | 1 |
| ARAUCARIACEAE | | | | |
| 22 | *Aracucaria angustifolia* (Bertol.) Kuntze | Pinheiro | A3 | |
| ARECACEAE | | | | |
| 23 | *Syagrus romanzoffiana* (Cham.) | Coco-babão/Jerivá | A5 | 2 |
| ASTERACEAE | | | | |
| 24 | *Baccharis* sp. | | | 2 |
| 25 | *Eupatorium angulicaule* Sch.Bip. | | | 1 |
| 26 | *Eremanthus erythropappus* (DC.) McLeish | Candeia-miúda | A2, A4 | 1 |
| 27 | *Gochnatia polymorpha* (Less.) Cabr. | Cambará | | 1 |
| 28 | *Piptocarpha oblonga* Baker | | | 1 |
| 29 | *Piptocarpha sellowii* (Sch. Bip) Baker | | | 1 |
| 30 | *Vernonia densiflora* Gardner | Pau-de-fumo | | 1 |
| 31 | *Vernonia diffusa* Less. | Vassourão-preto | | 2 |
| 32 | *Vernonia polyanthes* Less. | | D1 | 1 |
| BIGNONIACEAE | | | | |
| 33 | *Adenocalymma subsessilifolium* DC. | | | 1 |
| 34 | *Cybistax antisyphilitica* Mart. | Pente-de-macaco | | 1 |
| 35 | *Jacaranda macrantha* Cham. | Carobinha/Caroba | A1, A2 | 1, 2 |
| 36 | *Jacaranda microcalyx* A.H.Gentry | | | 1 |
| 37 | *Sparattosperma leucanthum* K. Schum. | Cinco-folhas | | 2 |
| 38 | *Tabebuia chrysotricha* (Mart. Ex DC.) Standl. | Ipê-mulato | A3, A4, A6 | 1 |
| 39 | *Tabebuia serratifolia* | Ipê-amarelo | D1 | |
| 40 | *Zeyheria tuberculosa* | Ipê-preto | D1 | |

Table A.1 (*Continued*)

| # | Family/specie | Common name | Agroforests[a] | Fragments[b] |
|---|---|---|---|---|
| BIXACEAE | | | | |
| 41 | *Bixa orellana* L. | Urucum | A5 | |
| BORAGINACEAE | | | | |
| 42 | *Cordia ecalyculata* Vell. | Poragaba | | 2 |
| 43 | *Cordia sellowiana* Cham. | Chá-de-bugre | | 1, 2 |
| 44 | *Cordia alliodora* (Ruiz and Pav.) Oken. | | | 1 |
| 45 | *Cordia* sp. | | | 2 |
| CANNABACEAE | | | | |
| 46 | *Trema micrantha* (L.) Blume | Crindiúva/Candiúva | D1 | 1, 2 |
| CARICACEAE | | | | |
| 47 | *Carica papaya* L. | Mamão | A1, A3, A4, A6, A7 | |
| CHRYSOBALANACEAE | | | | |
| 48 | *Hirtella hebeclada* Moric. | Azeitona-da-mata | | 2 |
| 49 | *Hirtella selloana* Hook. | | | 2 |
| CLETHRACEAE | | | | |
| 50 | *Clethra scabra* Pers. | | | 1, 2 |
| CLUSIACEAE | | | | |
| 51 | *Vismia brasiliensis* Choisy | Ruão | | 1 |
| CUNONIACEAE | | | | |
| 52 | *Lamanonia ternata* Vell. | Três-folhas | | 1, 2 |
| ELAEOCARPACEAE | | | | |
| 53 | *Sloanea monosperma* Vell. | Sapopeba | | 2 |
| ERYTHROXYLACEAE | | | | |
| 54 | *Erythroxylum pelleterianum* A.St.-Hil. | Cocão | | 2 |
| EUPHORBIACEAE | | | | |
| 55 | *Alchornea triplinervia* Müll. | Irucurana | | 2 |
| 56 | *Croton urucurana* Baill. | Sangra-d'água | A3 | 1 |
| 57 | *Hieronyma alchorneoides* | Licurana | | 2 |
| 58 | *Joannesia princeps* Vell. | Cutieira | A5 | |
| 59 | *Mabea fistulifera* Mart. | Canudo-de-pito | A5 | |
| 60 | *Manihot dulcis* Baill. | Maniçoba | | 2 |
| 61 | *Maprounea guianensis* Aubl. | Carambola-da-mata | | 2 |
| 62 | *Ricinus communis* (L.) Mull. Arg. | Mamona | A1, A3, A5, A7 | |
| 63 | *Pera* sp. | Pera | | 1 |
| 64 | *Sapium glandulatum* (Vell.) Pax | Leiteiro | | 2 |
| 65 | *Sapium* sp. | Leiteira | D1 | |
| FLACOURTIACEAE | | | | |
| 66 | *Carpotroche brasiliensis* Endl. | Canudo-de-pito | | 2 |
| 67 | *Casearia decandra* Jacq. | Café-do-mato | | 2 |
| 68 | *Casearia ulmifolia* Cambess. | Cafezinho | | 2 |
| 69 | *Xylosma prockia* (Turcz.) Turcz. | Espinho-de-judeu | | 2 |
| GUTTIFERAE | | | | |
| 70 | *Kielmeyera* sp. | | | 2 |
| 71 | *Rheedia gardneriana* Planch. and Triana | Bacupari | | 2 |
| 72 | *Vismia martiana* Rechb. f. | Ruão | | 2 |

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|---|---|---|---|---|
| LABIATAE | | | | |
| 73 | *Hyptis cana* Pohl ex Benth. | Hortelã-do-campo | | 2 |
| LACISTEMACEAE | | | | |
| 74 | Lacistema pubescens Mart. | | | 2 |
| LAMIACEAE | | | | |
| 75 | Vitex montevidensis Cham. | Maria-preta | D1, A5, A6 | |
| LAURACEAE | | | | |
| 76 | Endicheria glomerata Mez | | | 1 |
| 77 | Lauraceae sp. | Canela | | 2 |
| 78 | Nectandra lanceolata Nees and Mart. ex Nees | Canela-amarela | A3 | 2 |
| 79 | *Nectandra opositifolia* Nees. | Canela | | 1 |
| 80 | *Nectandra rigida* Nees | Canela | | 2 |
| 81 | *Ocotea corymbosa* Mez | Canela-fedida | | 1,2 |
| 82 | *Ocotea dicaricata* (Nees.) Mez | Canela | | 1 |
| 83 | *Ocotea dispersa* Mez | Canelinha | | 2 |
| 84 | *Ocotea spixiana* (Nees.) Mez | Canela | | 2 |
| 85 | *Ocotea odorifera* (Vell.) Rohwer | Canela-sassafrás | | 1 |
| 86 | *Persea microneura* Meisn. | | | 1 |
| 87 | *Persea americana* Mill. | Abacate | D1, A2, A3, A4, A5, A6, A7 | |
| LEG. CAESALPINIOIDEAE | | | | |
| 88 | *Apuleia leiocarpa* J.F. Macbr. | Garapa | A6, A7 | 1, 2 |
| 89 | *Caesalpinia echinata* Lam. | Pau-brasil | D1, A3, A7 | |
| 90 | *C. ferruginea* (Schrader) Schrader ex DC | Cássia | A1, A2, A4 | 1 |
| 91 | *Copaifera langsdorffii* Desf. | Copaíba/Pau-d'óleo | A3, A7 | |
| 92 | *Hymenaea courbaril* L. | Jatobá | A3, A7 | |
| 93 | *Peltophorum dubium* Taub. | Farinha-seca | | 2 |
| 94 | *Pterogyne nitens* Tul. | Aroeira-do-sertão | A3, A7 | |
| 95 | *Schizolobium parahyba* (Vell.) S.F. Blake | Guapuruvu/Breu | A3, A5 | |
| 96 | *Sclerolobium friburguense* Harms | | | 1 |
| 97 | *Sclerolobium rugosum* Mart. ex Benth. | | | 1 |
| 98 | *Senna* sp. | Fedegoso | D1 | |
| 99 | *Senna alata* | Fedegoso-miúdo | A7 | |
| 100 | *Senna macranthera* (DC. ex Collad.) Irwin and Barneby | Fedegoso | A1, D1, A2, A3, A5, A4, A7 | 1, 2 |
| 101 | *Senna multijuga* (Rich.) H.S. Irwin and Barneby | Farinha-seca | A3, A5 | 1 |
| 102 | *Tachigali paratyensis* (Vell.) H.C.Lima | | | 1 |
| LEG. MIMOSOIDEAE | | | | |
| 103 | *Abarema obovata* (Benth.) Barneby and J.W. Grimes | | | 1 |
| 104 | *Albizia polycephala* (Benth.) Killip ex Record | Farinha-seca | A7 | |
| 105 | *Anadenanthera peregrina* (L.) Speg. | Angico-vermelho | A3, A5 | |
| 106 | *Anadenanthera colubrina* (Vell.) Brenan | Angico-branco | | 2 |
| 107 | *Enterolobium contortisiliquum* (Vell.) Morong | Orelha-de-negro | A4, A6 | 2 |
| 108 | *Inga cylindrica* (Vell.) Mart | Ingá | A4, A6 | 1, 2 |
| 109 | *Inga edulis* Mart. | Ingá-de-metro | A1, A2, A5, A6, A7 | |
| 110 | *Inga leptantha* Benth. | Ingá | | 1 |
| 111 | *Inga sessilis* (Vell.) Mart. | Ingá-ferradura | A1, D1, A4 | 1 |
| 112 | *Inga striata* Benth. | Ingá | | 1 |
| 113 | *Inga subnuda* (Benth). T.D. Penn. | Ingá-serra/Angá | A1, D1, A3, A4, A5, A7 | |
| 114 | *Inga vera* Willd. | Ingá/Angá | | 2 |
| 115 | *Leucaena leucocephala* (La.) de Wit | Leucena | A3, A4, A6, A7 | |
| 116 | *P. gonoacantha* (Mart.) J.F. Macbr. | Pau-jacaré/Jacaré | A1, A2, A3, A4, A6, A7 | 1, 2 |
| 117 | *Plathymenia foliolosa* Benth. | Vinhático | | 2 |
| 118 | *Pseudopiptadenia contorta* (DC.) G.P. Lewis and M.P. Lima | Angico-amarelo | A5, A6 | 2 |
| 119 | *Stryphnodendron guianense* Benth. | | | 2 |

Table A.1 (*Continued*)

| # | Family/specie | Common name | Agroforests[a] | Fragments[b] |
|---|---|---|---|---|
| LEG. PAPILIONOIDEAE | | | | |
| 120 | *Andira fraxinifolia* Benth. | Angelim | | 2 |
| 121 | *Andira surinamensis* (Bondt) Splitg. ex Pulle | Angelim-doce | A3, A5, A6 | 1 |
| 122 | *Dalbergia foliolosa* Benth. | | | 1 |
| 123 | *Dalbergia nigra* Allemao ex Benth. | Jacaraná-caviúna | A1, A3, A5, A7 | 1, 2 |
| 124 | *Dalbergia variabilis* Vogel | Jacarandá | | 2 |
| 125 | *Erythrina speciosa* Andrews | Sumaúma | A3, A7 | |
| 126 | *E. verna* Vell. | Mulungu/Pau-abóbora | D1, A3, A7 | |
| 127 | *Flemingia macrophyla* | Flemigia | A7 | |
| 128 | *Hymenolobium janeirense* var. stipulatum (N.F. Mattos) Lima | | | 1 |
| 129 | *Indigofera suffruticosa* | | A7 | |
| 130 | *Machaerium acutifolium* Vogel | | | 1 |
| 131 | *Machaerium brasiliense* Vogel | Sangue-de-gato | A3, A4, A5, A6 | 1, 2 |
| 132 | *Machaerium hirtum* (Vell.) Stellfeld | | A3, A7 | 1 |
| 133 | *Machaerium nyctitans* (Vell.) Benth. | | A1, A2, A4, A7 | 1 |
| 134 | *Machaerium stiptatum* Vogel | Marmelim | A3, A7 | |
| 135 | *Machaerium* sp. | | A2 | 2 |
| 136 | *Platymiscium pubescens* Micheli | | | 2 |
| 137 | *Platypodium elegans* Vogel | | A1, A4, A5, A6, A7 | |
| 138 | *Swartzia pilulifera* Benth. | | | 1, 2 |
| 139 | *Swartzia* sp. | | | 2 |
| MALPIGHIACEAE | | | | |
| 140 | *Malpighia emarginata* Sessé e Moc. Ec Dc | Acerola | D1, A3 | |
| 141 | *Byrsonima sericea* DC. | Massaranduva | | 1 |
| 142 | *Byrsonima* sp. | | | 1 |
| MALVACEAE | | | | |
| 143 | *Bombax marginatum* K. Schum. | | A3,A4,A5,A6 | |
| 144 | *Luehea grandiflora* | Açoita-cavalo | D1 | 2 |
| 145 | *Luehea divaricata* Mar | Açoita-cavalo | A2,A5,A7 | |
| MELASTOMATACEAE | | | | |
| 146 | *Miconia cubatanensis* Hoehne | | | 2 |
| 147 | *Miconia sellowiana* Naudin | Jacatirão | | 2 |
| 148 | *Miconia latecrenata* (DC) Naudin | Quaresminha | | 1 |
| 149 | *Miconia pyrifolia* Naud. | Quaresminha | | 1 |
| 150 | *Miconia urophylla* DC. | | | 2 |
| 151 | *Tibouchina granulosa* Cogn. | Quaresma | A1,A4 | 1 |
| MELIACEAE | | | | |
| 152 | *Cedrela fissilis* Vell. | Cedro-nativo | D1,A3 | |
| 153 | *Cabralea canjerana* (Vell.) Mart. | Canjerana | | 2 |
| 154 | *Guarea kunthiana* A.Juss. | Andirobarana | | 2 |
| 155 | *Trichilia lepidota* Mart. | | | 2 |
| MONIMIACEAE | | | | |
| 156 | *Siparuna guianensis* Aubl. | Folha-santa | | 2 |
| 157 | *Siparuna reginae* A.DC. | | | 2 |
| MORACEAE | | | | |
| 158 | *Artocarpus heterophyllus* Lam. | Jaca | A3 | |
| 159 | *Brosimum glaziovii* Taub. | | | 2 |
| 160 | *Ficus arpazusa* Casar. | | | 1 |
| 161 | *Ficus guaranitica* Chodat | Figeuria-branca | | 2 |
| 162 | *Maclura tinctoria* D.Don ex Steud. | Amoreira | | 2 |
| 163 | *Morus nigra* L. | Amora-preta | A1 | |
| 164 | *Sorocea bomplandii* (Baill.) Bürger, Lanj. and Boer | Folha-de-serra | | 2 |

| | | | | |
|---|---|---|---|---|
| MORINGACEAE | | | | |
| 165 | *Moringa oleifera* Lam. | Muringa | A3 | |
| | MUSACEAE | | | |
| 166 | *Musa paradisiaca* L. | Banana | A1,D1,A2,A3,A4,A5,A6,A7 | |
| MYRSINACEAE | | | | |
| 167 | *Rapanea ferruginea* (Ruiz et Pavon) Mez | Pororoca | | 1 |
| MYRTACEAE | | | | |
| 168 | *Eucalyptus* sp. | Eucalipto | A6 | |
| 169 | *Eugenia leptoclada* Berg | | | 2 |
| 170 | *Eugenia uniflora* L. | Pitanga | A3,A5 | |
| 171 | *Eugenia* sp. | Pitanga | | 2 |
| 172 | *Gomidesia* sp. | | | 1 |
| 173 | *Myrcia fallax* DC. | Jambo-vermelho | | 1,2 |
| 174 | *Myrcia formosiana* DC. | | | 1 |
| 175 | *Myrcia rostrata* DC. | Jambinho | | 1 |
| 176 | *Myrcia* sp. | Jambo | | 2 |
| 177 | *Psidium cattleyanum* Sabine | Araçá-do-mato | | 2 |
| 178 | *Psidium guajava* L. | Goiaba | A1,A4,A5,A6 | |
| 179 | *Psidium rufum* D.C | Araça | | 1 |
| 180 | *Syzygium jambos* (L.) Alston | Jambo | A3 | |
| NYCTAGINACEAE | | | | |
| 181 | *Guapira opposita* (Vell.) Reitz | Maria-mole | | 2 |
| OCHNACEAE | | | | |
| 182 | *Ouratea castanaefolia* Engl. | | | 1 |
| PALMAE | | | | |
| 183 | *Euterpe edulis* Mart. | Palmito | D1,A4,A7 | |
| PROTEACEAE | | | | |
| 184 | *Euplassa organensis* (Gardner) I. M. Johnst. | Carne-de-vaca | | 1 |
| 185 | *Roupala montana* Aubl. | | | 1 |
| QUINACEAE | | | | |
| 186 | *Lacunaria* sp. | | | 1 |
| RHAMANACEAE | | | | |
| 187 | *Colubrina glandulosa* Var. Reitzii | Sobrasil | A1 | |
| 188 | *Hovenia dulcis* Thunb. | Uva-do-japão | A3 | |
| ROSACEAE | | | | |
| 189 | *Eriobotrya japonica* (Thunb.) Lindl. | Ameixa-amarela | D1,A2,A3 | |
| 190 | *Prunus persica* (L.) Batsch | Pêssego | A7 | |
| RUBIACEAE | | | | |
| 191 | *Alibertia* sp. | | | 2 |
| 192 | *Amaioua guianensis* Aubl. | Carvoeiro | | 1,2 |
| 193 | *Bathysa nicholsonii* K. Schum. | | | 2 |
| 194 | *Guettarda viburnoides* Cham. and Schltdl. | Angélica | | 1,2 |
| 195 | *Randia armata* DC. | Limorana | | 2 |
| 196 | *Rubiaceae* sp. | | | 2 |

Table A.1 (*Continued*)

| # | Family/specie | Common name | Agroforests[a] | Fragments[b] |
|---|---|---|---|---|
| RUTACEAE | | | | |
| 197 | *Citrus limon* (L.) Burm. F. | Limão | A1,D1,A4,A5 | |
| 198 | *Citrus reticulata* Blanco | Pocã/mexerica | A3 | |
| 199 | *Citrus sinensis* L. Osbeck | Laranja | D1,A3 | |
| 200 | *Dictyoloma vandellianum* A.Juss. | Sabugueiro-do-mato | | 1,2 |
| 201 | *Hortia arborea* Engl. | Paratudo | | 1 |
| 202 | *Zanthoxylum rhoifolium* Lam. | Maminha-de-porca | A1,A7 | 1,2 |
| SALICACEAE | | | | |
| 203 | *Casearia arborea* (Rich.) Urb. | | | 1,2 |
| SAPINDACEAE | | | | |
| 204 | *Allophylus edulis* (A.St.-Hil.) Radlk. ex Warm. | Vacunzeiro | | 2 |
| 205 | *Allophylus petiolulatus* Radlk. ex W.Muell. | Casca-solta | | 2 |
| 206 | *Allophylus sericeus* Radlk. | Três-folhas | | 2 |
| 207 | *Cupania* sp. | | D1 | |
| 209 | *Cupania vernalis* Cambess. | Pau-de-cantil | | 2 |
| 209 | *Litchi chinensis* Sonn. | Lichia | A3 | 2 |
| 210 | *Matayba elaeagnoides* Radlk. | Camboatá | | 2 |
| SAPOTACEAE | | | | |
| 211 | *Chrysophyllum gonocarpum* (Mart. and Eckl.) Engl. | Guatambu-sapo | | 2 |
| SIMAROUBACEAE | | | | |
| 212 | *Simarouba amara* Aubl. | | | 1 |
| SOLANACEAE | | | | |
| 213 | *Cestrum sendtnerianum* Mart. ex Sendtn. | Coerana | | 2 |
| 214 | *Solanum cernuum* Vell. | Panacéia | A7 | 2 |
| 215 | *Solanum cinnamomeum* Sendtn | | | 1 |
| 216 | *Solanum cladotrichum* Dunal | | | 1 |
| 217 | *Solanum leptostachys* Dunal | | | 1 |
| 218 | *Solanum pseudoquina* A. St. Hil. | Jessiana | | 1 |
| 219 | *Solanum leucodendron* Sendtn. | Adrago | | 2 |
| 220 | *Solanum mauritianum* Scop. | Capoeira-branca | A1,D1,A2,A4,A5,A6,A7 | 2 |
| 221 | *Solanum robustum* H.Wendl. | | | 2 |
| 222 | *Solanum swartzianum* Roem. and Schult. | | | 1,2 |
| THEACEAE | | | | |
| 223 | *Gordonia semiserrata* (Nees.) Spreng. | Ameixa | | 1 |
| TILIACEAE | | | | |
| 224 | *Triumfetta semitriloba* Jacq. | Carrapichão | | 2 |
| URTICACEAE | | | | |
| 225 | *Cecropia glaziovi* Snethl. | Embaúba | A1, A2, A3, A4 | 1, 2 |
| 226 | *Cecropia hololeuca* Miq. | Embaúba-formiga | | 1, 2 |
| VERBENACEAE | | | | |
| 227 | *Aegiphila sellowiana* Cham. | Papagaio/Capoeirão | D1, A2, A4, A6 | 2, 1 |
| 228 | *Hyptidendron asperrimum* (Spreng.) R. M. Harley | Maria-mole | | 1 |
| 229 | *Vitex sellowiana* Cham. | Tarumã | | 1, 2 |
| VOCHYSIACEAE | | | | |
| 230 | *Qualea cryptantha* Mart. | | | 1 |
| 231 | *Callisthene major* Mart. | | | 1 |

[a] Agroforests: AF1, AF2 (located in Araponga) and AFD1 (located in Divino) are in the selected farms; and AFA4–AFA7 are neighboring agroforests in Araponga.

[b] Total species found in reference forest fragments: 1: Araponga (RFA8 + RFA9), 2: Viçosa (RFV1 + RFV2).

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