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# Species richness increases income in agroforestry systems of eastern Amazonia

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**Abstract** Biodiversity is believed to reduce risks (resistance and resilience against perturbations), to increase productivity via niche expansion, and possibly also to improve resource efficiency via mutually benefic species interactions. Agroforestry has been postulated as an ideal pathway of maintaining or restoring biodiversity in a socioeconomically sustainable manner. This study tests the relevance of agroforestry species diversity and richness on socioeconomic performance in a wide range of agroforestry systems in 38 farms aggregated in four clusters of sites in eastern Amazonia. We cover both commercial and subsistence agroforestry, ranging from simply structured plantations to diverse systems (enriched fallows, multi-strata home gardens), as well as pastures and shifting cultivation for comparisons. We quantify (i) all cultivated species, classifying them economically into species with commercial value, primarily subsistence purpose species or 'non-productive' species, and (ii) socioeconomic system variables (costs, monetary/non-monetary income, degree of satisfaction). Land-use intensity (per-hectare costs and income) was highest in commercial agroforestry and subsistence home gardens, and lowest in enriched fallows and pastures. All agroforestry systems resulted in higher income:cost ratios and greater satisfaction than pastures and shifting cultivation. Net income, non-monetary income and income:cost ratio were maximum in home gardens. Total species richness was negatively related with costs and monetary income, but not with non-monetary income, due to occupation of space by 'non-productive' species (juveniles or species providing ecosystem services). By contrast, productive (combining commercial and subsistence) species richness was positively related with (mainly non-monetary) income, net income and income:cost ratio. According to GLM, both productive species richness and Shannon–Wiener diversity positively affected net income. Future efforts for food security and poverty reduction need to focus more on species-rich agroforestry systems, both in terms of applied research and of extension service programs. Notably, the ubiquitous and successful home gardens merit far more attention.

**Keywords** Babassu pasture · Commercial agroforestry · Fallow enrichment · Home gardens · Non-monetary income · Subsistence farming

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## Introduction

Agroforestry exists on all continents and most biomes (Zomer et al. 2009), in a multitude of systems which vary widely both in terms of their socioeconomic origins and purposes and their botanical composition (Atangana et al. 2014). Systems origins range from traditional indigenous (Diemont and Martin 2009) to 'modern' (Yamada and Gholz 2002), purposes range from subsistence to commercial (Nair 1985), and species richness and diversity from low/simplistic (alley cropping, tree plantation) (Atangana et al. 2014; Nair 2013) to high/complex (Schroth and da Mota 2014; Nair 2013). Consequently, ecological and socioeconomic systems sustainability will likewise vary widely (Atangana et al. 2014).

The multiple relationships between species diversity and agroecosystem functioning are fundamental issues of ecological theory. Expected biodiversity benefits are higher system stability (via increased resistance and resilience i.e., against pests or diseases (Ratnadass et al. 2012) and weather/climate instabilities (Lin 2011), increased resource exploration and productivity via niche expansions (Weiher and Keddy 2001; García-Barrios and Ong 2004), and possibly also increased efficiencies caused by the stimulation of positive species interactions (Cardinale et al. 2002; García-Barrios and Ong 2004). Forms of such relationships, redundancies, and possible diversity thresholds have been hotly debated (Schulze and Mooney 1993; Loreau 2000; Schleuning et al. 2015), and functional diversity can be more relevant than taxonomic diversity (Díaz and Cabido 2001).

From an economic perspective, portfolio diversity bears both advantages and disadvantages (Godsey 2010). Diversity can reduce risks, but also increase management complexity (Altieri et al. 2011). Low diversity and concentration of investments in a few components permits the development of scale effects, both in systems management and in the sale of products (Rosa et al. 2009). Sociologically, diversity of cultures and of species use increase resilience, serve as insurance against unexpected or disruptive events and provide components that facilitate renewal after disturbances of 'socioecological systems' (Berkes et al. 2003; Cabell and Oelofse 2012).

This study tests the hypothesis that species richness and diversity can drive socioeconomic performance of agroforestry systems. We investigate possible relationships of commercial, subsistence and 'non-productive' species on key socioeconomic parameters over a wide range of agroforestry systems in eastern Amazonia. Specifically, we (i) compare simple or complex subsistence or commercial agroforestry systems—among another and with extensive pastures with babassu palms (dominating in area) and slash-and-burn shifting cultivation (sustaining most of rural population); (ii) establish specific relationships between commercial, subsistence, and 'non-productive' species diversity and costs, benefits, profitability, and satisfaction; and (iii) give practical recommendations for agroforestry research and development.

## Methods

### Study region and study sites

Research was conducted in the eastern periphery of Amazonia in four clusters of sites, in the Brazilian states of Maranhão 3°28′S/44°53′W and Pará 2°31′S/48°22′W. Three of the four clusters are located in Maranhao State, the Tomé-Açu cluster of Pará State is approximately 400 km further westward (Fig. 1).

Climate classification according to Köppen is *Aw* and *Ami* (Alvares et al. 2013), varying slightly between clusters (2100 mm annual rainfall in the Maranhão clusters and 2300 mm in Tomé-Açu, 5 vs. 4 months hydric deficit). All soils are acid and nutrient-poor upland soils, classified as sandy loam Oxisols. Vegetation is predominantly extensive pastures or secondary forests. Frequent slash-and-burning has drastically increased dominance of the babassu palm (*Attalea speciosa* Mart., Arecaceae), covering an estimated 100,000 ha in Maranhão alone (Porro 2005).

### Agroforestry systems

Research was conducted with 38 families (owners and careholders of farms, consisting of farmer, wife, and the children living there): 27 families/sites with agroforestry systems, three with babassu pastures, and eight with slash-and-burn shifting cultivation. We classify land-use systems according to their socioeconomic finalities in three classes ('commercial', 'mixed', and 'subsistence'), as proposed by Nair (1993), and we distinguish three types of subsistence agroforestry. All land-use systems have three or more site replications, but not all systems occurred in all

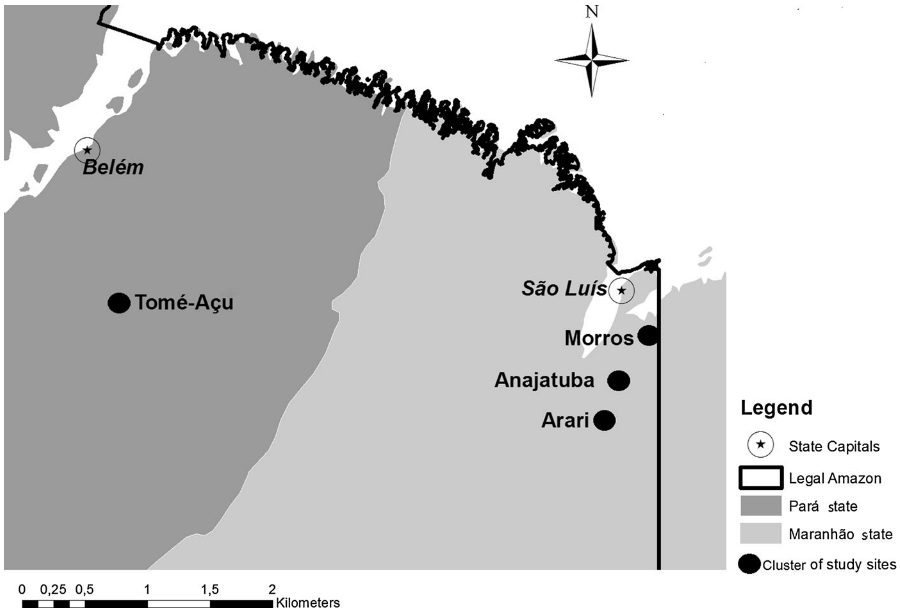


**Fig. 1** Clusters of study sites

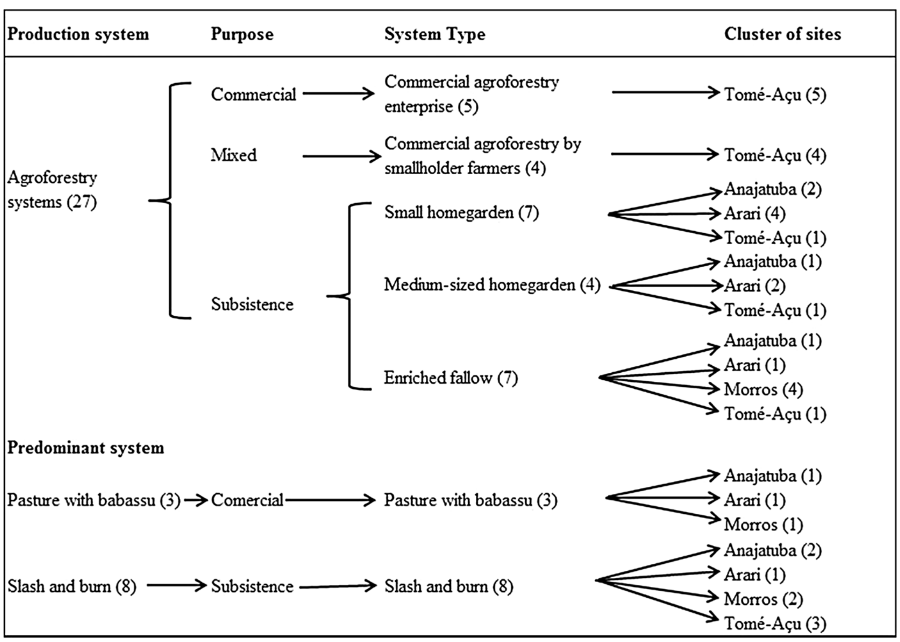


**Fig. 2** Agroforestry systems, classifications, and their aggregation in site clusters. Values in *brackets* give the number of sites

clusters (Fig. 2). At site selection, we strived to maintain a high level of within-system structural homogeneity, though species composition did vary regionally and between clusters of sites.

### *Commercial agroforestry plantations*

The main products of these regularly spaced agroforestry plantations are coconut (*Cocos nucifera*), acai (*Euterpe oleracea*), cacao (*Theobroma cacao*), cupuassu (*Theobroma grandiflorum*), and black pepper (*Piper nigrum*). We directly compare two types of commercial agroforestry plantations that are ecologically similar but differ socioeconomically by distinguishing into:

(a) Purely commercial operations: *Commercial agroforestry enterprise (CAE)* Large-scale plantations mainly by the pioneer Japanese immigrants (Yamada and Gholz 2002); and
(b) Mixed systems: *Commercial agroforestry by smallholder farmers (CASF)* Inspired by the Japanese agroforestry plantations, but owned by smallholder farmers. These plantations differ from the commercial large-scale operations in the inclusion of additional subsistence species such as acai, banana (*Musa* spp.) and pupunha (*Bactris gasipaes*).

### *Subsistence agroforestry*

*Home gardens* Multistrata agroforestry systems surround the houses, providing vital shade and omnipresent throughout our region. Dominant overstory trees are cupuassu, acai, cacao, banana, mango (*Mangifera indica*), and jackfruit (*Artocarpus integrifolia*), understory fruticulture and small domestic animals are further important components.

We distinguish home gardens according to their size into:

(a) Small home garden (SH): home garden <1 ha.
(b) Medium-sized home garden (MH): home garden >1 ha.

*Enriched fallow (EF)* This agroforestry system is established by enrichment plantings of fruit and timber in the understory of old secondary forests. The degree of human control over vegetation structure and species composition is far lower than in all other systems covered by our study. Fallow enrichment developed independently in various site clusters by isolated initiatives of innovative farmers partly was initiated (and thereafter abandoned) by a local NGO. Enrichment plantings are an ecologically valuable option for income generation in otherwise 'unproductive' forest reserves required by law. In our study, secondary forest age ranged from 6 to >30 years and enrichment planting age was 3–12 years. Banana, acai, and bacuri (*Platonia insignis*) are the most important enrichment species.

We compare these agroforestry systems with the region's two predominant land-use systems, which likewise constitute agroforestry in the wider sense (silvopastoral pastures with babassu and sequential agroforestry shifting cultivation):

*Pasture with babassu (PB)* Extensive pastures predominate throughout most of the Amazonian arc of deforestation, with brachiaria grass and stocking rates of typically <1 Nelore cattle $ha^{-1}$ (Sarmento et al. 2010). A conspicuous feature is the babassu palms growing within these pastures, providing shade for the cattle, and a source for babassu nut extractivism (not quantified in this study).

*Slash-and-burn shifting cultivation (SB)* In terms of area, this age-old production system is far less important than the pastures (i.e., low percentages of active fields), but this system sustains 74.4 % of the region's rural population (MDA 2011). We investigate the socioeconomic variables of the cultivation phase, and do not attempt to quantify the biodiversity nor the extraction of timber and non-timber products during the fallow phase. As secondary forest regrowth in our study region typically is young and strongly degraded (consequence of repeated slash-and-burn cycles and the shortening fallow phases), extractivism (some medicinal plants, nectar and pollen for bees, sometimes charcoal production) is likely to be only of minor relevance.

## Biodiversity

We identified and quantified all planted agroforestry species and all spontaneously occurring species ≥5 cm diameter at breast height (i.e., dbh at 1.30 m), in the case of cacao and cupuassu ≥5 cm diameter at 30 cm height, and also, because of its prominent economical relevance, black pepper. The inventory was conducted in one circular sampling unit per site with 50 m diameter (1963 $m^2$) in all agroforestry systems without regular spacing (Richards 1996; Brown 2002; Soto-Pinto et al. 2009). Given their regular spacing and low mid-scale spatial variability, we preferred a differing sampling scheme in the regularly spaced commercial agroforestry plantations (both CAE and CASF) with three 25 × 25-m quadrants per site (1875 $m^2$). This scheme has previously been successfully used by Kato (2009) and Somarriba et al. (2013) in similar plantations. We subsequently corrected for the slightly different sampling sizes. We discarded large boarder zones to neighboring vegetation.

In a first step, the identification of agroforestry species counted on the help of the farmers who indicated the cultivated plants and gave them associating local names, which were subsequently transformed into scientific nomenclature. In all doubtful cases, taxonomic classification was based on subsequent analysis in the herbarium of Maranhão State University, following the *Angiosperm Phylogeny Group* III classification system (Angiosperm Phylogeny Group III 2009).

We calculate (i) species richness (number of species in sampling area), and (ii) diversity indices of Simpson and Shannon–Wiener and equitability index of Pielou (Magurran 1988), based on species' abundance and frequency shares and using FITOPAC software (Shepherd and Fitopac shell 2009).

We classified all agroforestry species into (1) commercial species (market production), (2) subsistence species (mainly auto-consumption, small quantities are also sold), and (3) 'non-productive' (species without immediate productive value but often exerting important ecosystem-services such as shade, organic-matter cycling/soil-cover or nectar/pollen for bees, medicinal), as well as juvenile plants.

## Socioeconomic variables

We collected all socioeconomic variables via semi-structured interviews with open questions (Sibelet and Smektala 1999). We classified costs and income as follows:

*Monetary income*

Value of commercialized production (on-farm prices). We do not include timber as future income source.

*Non-monetary income*

Value of non-commercialized production that would have been obtained if the farmer had sold production instead of consuming it (on-farm prices).

Total costs Costs for maintenance and harvest operations, comprising external inputs and (own-family or hired) labor. Original installation costs are not considered.

*Net income*

Sum of monetary and non-monetary income minus total costs.

*Income:cost ratio*

An indicator of economic efficiency (das Chagas Oliveira et al. 2013).

Estimates of costs, wages, and income were obtained using the prices reigning in each county in 2012. We subsequently extrapolated the values of our sampling sites to per-hectare estimates.

We estimated the degree of satisfaction via auto-evaluation of life quality of the farmers and wives (Veenhoven 1994, 2007), combining aspects of work routine in the different land-use systems, comfort, food availability and quality, and leisure aspects. Farmers classified their satisfaction utilizing the following numerical scale:

8–10: Very satisfied
6–8: Satisfied
4–6: Indifferent
2–4: Dissatisfied
0–2: Very dissatisfied

## Statistics

We verified normality of distribution of all data via Shapiro–Wilk and Lilliefor's tests against normality, and checked for homogeneity of variance with Levene's test (Crawley 2007). We compared the different agroforestry systems via one-way ANOVA and post hoc Spjøtfoll–Stoline test (Tukey for unequal replication numbers; Spjøtvoll and Stoline 1973), and analyzed relationships between biodiversity and socioeconomic variables via linear and logarithmic regressions. We identified and eliminated two outlier values. Our experimental setup is unbalanced, due to the non-occurrence of some systems in some clusters of sites. We believe this is not a serious problem, because of (i) small regional edaphic differences (chap. 2.1), and (ii) lacking statistical differences of all biodiversity and socioeconomic variables between the three Maranhão and the Tomé-Açu clusters of sites, both in home gardens (small and medium-sized combined) and in slash-and-burn shifting cultivation systems. We also investigate the impact of total and productive species richness and diversity and of the type of agroforestry system on costs and income via generalized linear modeling (GLM). All analyses involving species diversity exclude our two 'control' systems (pastures with babassu containing only one species, and slash-and-burn shifting cultivation without data on the fallow phase). Statistical analyses were conducted with STATISTICA 8.0 (StatSoft 2007). In order to gain a better overview of all variables and agroforestry systems under investigation, we also conducted a principal component analysis using INFOSTAT software (Di Rienzo et al. 2012).

## Results

### Species composition and systems management

We identified, in the 27 agroforestry sites, a total of 83 species, distributed in 73 genera and 34 plant families. Details on taxonomy, use, and origin of the overall ten most abundant species of this study are given in Annex 1.

Figure 3 explores between-system differences in the relative abundances of the principal agroforestry species, and large and systematic differences turn apparent.

### Commercial agroforestry enterprise

Species-poor plantations, cocoa, banana and black pepper combine 90 % of all plants. Contrary to the other two, the main finality of banana is in its ecosystem services (rapid shade, organic matter). The main management activities are understory clearing and periodic prunings, fertilizer and pesticide applications, and cocoa processing. This system relies exclusively on hired labor and amply applies external inputs.

In direct comparison, commercial agroforestry by smallholder farmers was slightly more diverse, five species combine 93 % of all plants. Production of cocoa and black pepper is completely commercialized, whereas açai, banana, and cupuassu serve both for auto-consumption and the market. Next to understory clearing and periodic prunings, cocoa and cupuassu fruit processing is important, relying almost exclusively on family labor, though additional labor is hired for black pepper harvesting. Contrary to

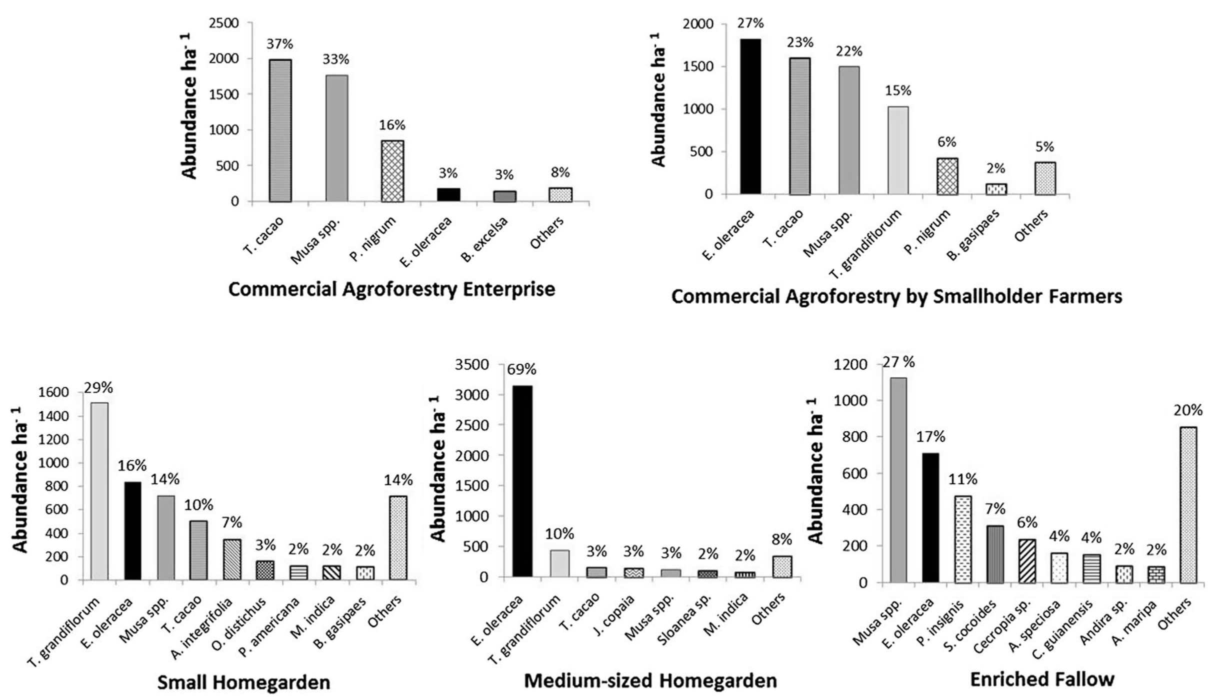


**Fig. 3** The most abundant species in eastern Amazonian agroforestry systems

commercial agroforestry enterprises, there is no use of external inputs (fertilizers or pesticides).

### Small (<1 ha) home gardens

Surrounding the houses and typically inherited from the preceding generation(s). Five species (cupuassu, açai, banana, jackfruit, and cocoa) combine 76 % of all plants. Almost all production is for home consumption, though excess cupuassu and açai also are sold to local markets. The main management activities are periodic pruning conducted exclusively by family labor; no use of external inputs. Female labor predominates in cupuassu fruit processing.

### Medium-sized (>1 ha) home gardens

Often developed around initial natural clusters of açai palms close to springs, and subsequently systematically enriched and enlarged. Açai and cupuassu combine 79 % of all plants. The main management activities are periodic prunings conducted exclusively by family labor; no use of external inputs.

### Enriched fallow

The most important enrichment species are banana açai and bacurí, combining 55 % of all plants. Most of the remainder are spontaneously occurring species of the secondary forest overstory, which furnishes ecosystem services such as shade, organic matter/litter, wildlife feed (*Cecropia* sp.), or nectar and pollen for bees (*Andira* sp.). The multi-use babassu palm provides charcoal, palm oil, construction material, and feed for (rodent) wildlife. The main management activities are periodic understory clearing and shade regulation, using exclusively family labor and no external inputs.

### Species richness and diversity

Table 1 shows the key biodiversity indicators of our agroforestry systems. We exclude pastures with babassu (with merely one woody species, the babassu palm) and slash-and-burn shifting cultivation (no data on fallow phase) from this analysis. Within agroforestry systems, species richness and Shannon diversity are highest in enriched fallows and small home gardens, and lowest in commercial agroforestry enterprises. Dominance (Simpson) is lowest in small home gardens, equitability (Pielou) does not differ between systems.

### Socioeconomic profile of agroforestry species

Of the total of 83 species, 4 % were exclusively commercial, 23 % served both auto-consumption and commercial purposes, and 73 % 'non-productive' species were maintained because of the ecosystem services they provided, were juveniles or medicinal plants. Species composition differed markedly between systems (Table 2).

Total species number was similar in enriched fallows and small home gardens, but home gardens had a much higher quantity of productive species.

### Costs and benefits, net income

The only two systems with significant costs caused by external inputs (fertilizers and pesticides) and by hired labor were the two exclusively commercial systems, commercial agroforestry enterprises and pastures with

**Table 1** Total species richness and biodiversity indicators in agroforestry systems of eastern Amazonia

| Agroforestry system | *N* | Number of species per plot (1963 $m^2$)[a] | Shannon–Wiener | Simpson | Pielou |
|---|---|---|---|---|---|
| Commercial agroforestry enterprise | 5 | 4.40 ± 0.69b | 0.73 ± 0.11b | 0.66 ± 0.05a | 0.54 ± 0.04a |
| Commercial agroforestry by smallholder farmers | 4 | 7.50 ± 1.19ab | 0.98 ± 0.13ab | 0.50 ± 0.09ab | 0.51 ± 0.08a |
| Small home garden | 7 | 12.14 ± 1.78a | 1.70 ± 0.02a | 0.26 ± 0.04b | 0.68 ± 0.05a |
| Medium-sized home garden | 4 | 10.00 ± 3.10ab | 1.08 ± 0.10ab | 0.49 ± 0.04ab | 0.51 ± 0.05a |
| Enriched fallow | 7 | 12.57 ± 1.60a | 1.54 ± 0.25a | 0.37 ± 0.10ab | 0.60 ± 0.08a |

Means ± SE, absence of common letters within the same column indicates significant between—system differences (monospecific pastures with babassu not included in statistical analysis), *n* number of sites

[a] Values obtained in regularly spaced agroforestry plantations corrected for their 4.5 % smaller sampling size

**Table 2** Species number and their socioeconomic profile in agroforestry systems of eastern Amazonia (means ± SE)

| Species profile | Agroforestry system | | | | |
|---|---|---|---|---|---|
| | CAE | CASF | SH | MH | EF |
| Commercial | 2.2 (±0.2) | 1.3 (±0.5) | 0 | 0 | 0 |
| Auto-consumption and commercial | 0.0 | 3.0 (±0.9) | 7.7 (±0.9) | 4.8 (±0.3) | 3.0 (±0.3) |
| Non-productive (juveniles and ecosystem services) | 1.6 (±0.6) | 2.5 (±1.0) | 4.3 (±1.2) | 5.3 (±3.1) | 9.6 (±1.7) |
| All species | 4.20 ± 0.66 | 7.50 ± 1.19 | 12.14 ± 1.78 | 10.00 ± 3.10 | 12.57 ± 1.60 |

*CAE* Commercial agroforestry enterprise, *CASF* commercial agroforestry by smallholder farmers, *SH* small home garden, *MH* medium-sized home garden, *EF* enriched fallow

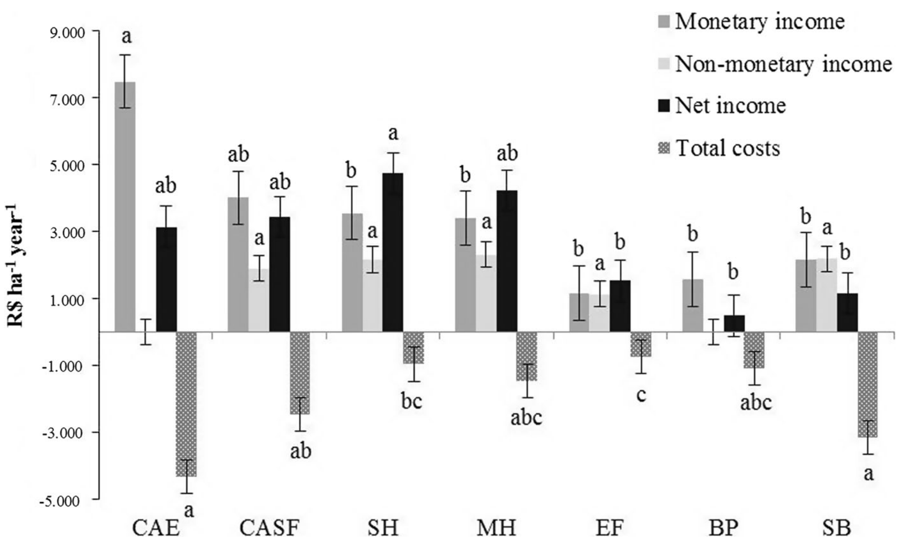


**Fig. 4** Total costs, monetary and non-monetary benefits, and net income generated in agroforestry and predominating land-use systems of eastern Amazonia (means ± SE). *CAE* Commercial agroforestry enterprise, *CASF* commercial agroforestry by smallholder farmers, *SH* small home garden, *MH* medium-sized home garden, *EF* enriched fallow, *PB* pasture with babassu, *SB* slash-and-burn shifting cultivation. Absence of *common letters* indicates significant difference between systems

babassu. In the commercial agroforestry enterprise plantations, external inputs summed 36 % and hired labor 64 % of total costs. In all other agroforestry systems, costs were caused exclusively by proper (family) labor.

Figure 4 exhibits large differences between systems in monetary and non-monetary benefits and net income. As to be expected, monetary income and costs are highest in commercial agroforestry enterprises. Costs are also high in slash-and-burn shifting cultivation. Both costs and returns are far lower (i.e., more extensive land use) both in enriched fallows and in pastures with babassu. Net per-hectare income is highest in home gardens (due to low costs and high non-monetary income), and lowest in the extensive pastures with babassu and in slash-and-burn shifting cultivation.

Based on the minimum wage of R$622.00 in 2012, small and medium-sized home gardens annually generated 7.47 and 6.77 minimum wages per hectare respectively, whereas pastures with babassu and slash-and-burn shifting cultivation generated only 0.77 and 1.85 minimum wages per hectare respectively, the other systems were intermediate between these two extremes (CAE, 5.02, CASF, 5.48, EF, 2.43).

Figure 5 compares the income:cost ratios as a measure of the 'socioeconomic efficiency.' Efficiency is highest in home gardens (especially in the small ones), and lowest in commercial agroforestry plantations (both enterprise and smallholder farmer ventures), the enriched fallows, and especially in the predominating pastures with babassu and slash-and-burn shifting cultivation land-use systems.

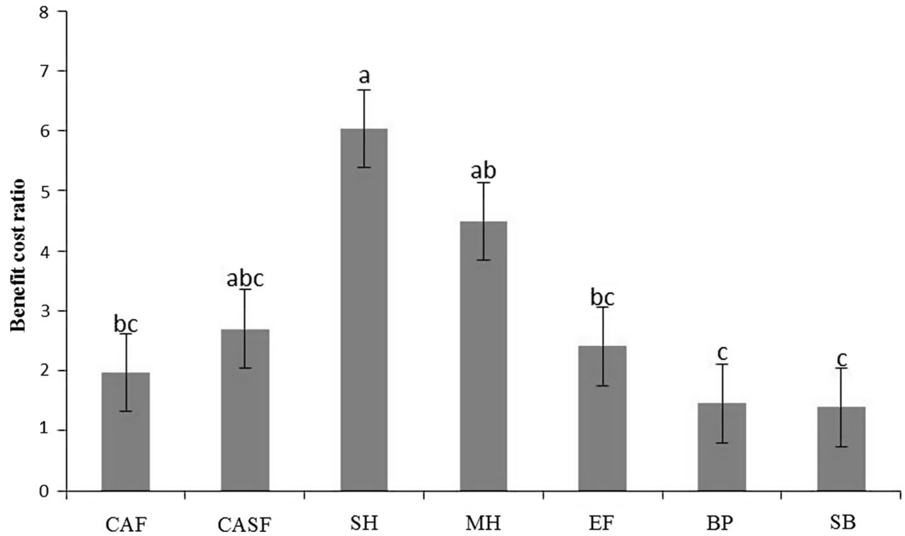


**Fig. 5** Income-to-cost ratio of agroforestry and of predominating land-use systems of eastern Amazonia (means ± SE). *CAE* Commercial agroforestry enterprise, *CASF* commercial agroforestry by smallholder farmers, *SH* small home garden, *MH* medium-sized home garden, *EF* enriched fallow, *PB* pasture with babassu, *SB* slash-and-burn shifting cultivation. Absence of *common letters* indicates significant difference between systems

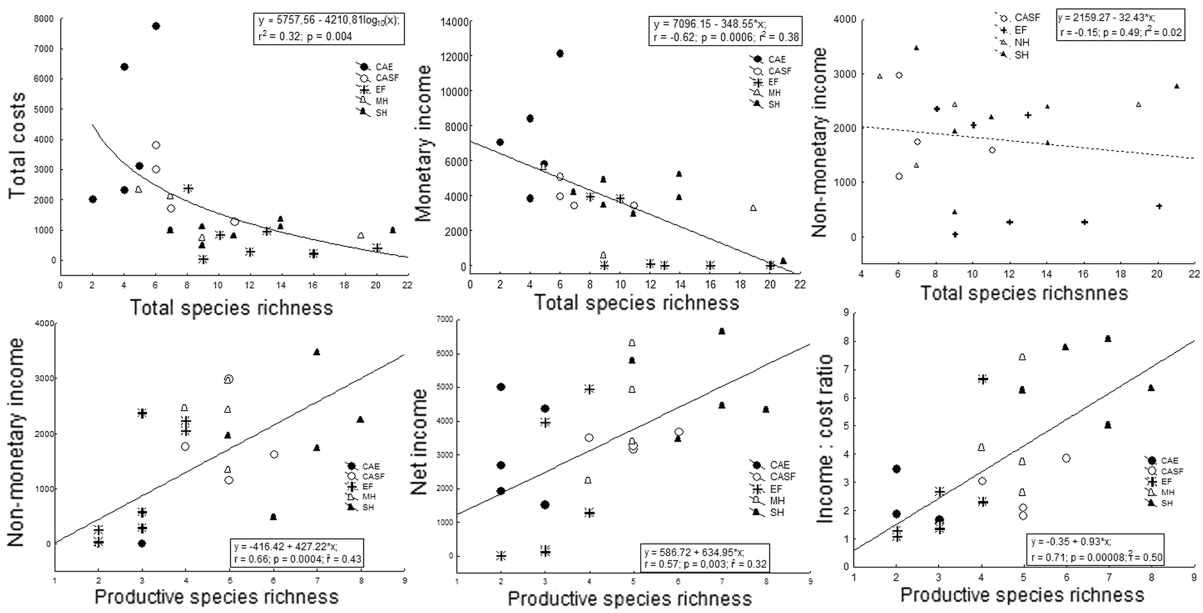


**Fig. 6** Negative impact of total agroforestry species richness on total costs, monetary and (excluding purely commercial agroforestry enterprises) non-monetary income (*top*), and positive impact of productive species richness on non-monetary income, net income, and income:cost ratio (*bottom*) in eastern Amazonian agroforestry systems

## Impacts of species richness and diversity on costs, benefits, and income

Figure 6 explores the relationships between total agroforestry species richness and costs and income (top), and between productive (i.e., commercial and auto-consumption) species richness and non-monetary income, net-income and income:cost ratio (bottom). Relationships were non-linear in some cases. Relationships with Shannon–Wiener diversity were similar though less expressive and significant, whereas there were no relationships with Simpson dominance or Pielou equitability (data not shown).

Total species richness was negatively related both with costs and with monetary (but not with non-monetary) income, presumably a consequence of

**Table 3** Impacts of species richness and diversity and of agroforestry system on net income, for all species (top) and for productive (commercial and auto-consumption) species (bottom)

| | SS | *df* | MS | *F* | *p* value |
|---|---|---|---|---|---|
| Intercept | 2,207,159 | 1 | 2,207,159 | 1.210 | 0.285 |
| Species richness | 138,380 | 1 | 138,380 | 0.076 | 0.786 |
| Shannon diversity | 1,248,133 | 1 | 1,248,133 | 0.685 | 0.418 |
| Simpson diversity | 2404 | 1 | 2404 | 0.001 | 0.971 |
| Agroforestry system | 46,476,381 | 4 | 11,619,095 | 6.374 | **0.002** |
| Error | 34,636,260 | 19 | 1,822,961 | | |
| | SS | *df* | MS | *F* | *p* value |
| Intercept | 13,773,557 | 1 | 13,773,557 | 6.526 | 0.019 |
| Species richness | 9,856,415 | 1 | 9,856,415 | 4.670 | **0.045** |
| Shannon diversity | 9,220,406 | 1 | 9,220,406 | 4.368 | **0.050** |
| Simpson diversity | 3,918,752 | 1 | 3,918,752 | 1.857 | 0.189 |
| Agroforestry system | 22,022,129 | 4 | 5,505,532 | 2.608 | **0.068** |
| Error | 40,102,858 | 19 | 2,110,677 | | |

Significant or near-significant *p* values are highlighted in *bold*

occupying space with non-productive 'other' species. By contrast, non-monetary income, net income and the income:cost ratio were positively related with productive species richness.

Table 3 depicts the joint impacts of total and of productive (commercial and auto-consumption) species richness and diversity and of the categorical variable 'agroforestry system' on net income, as identified by generalized linear modeling (GLM). When considering all species, neither species richness or diversity affected net income, whereas limiting our analysis to the productive species, both species richness and diversity turn important predictors of net income.

GLM based on total species consistently indicated 'agroforestry system' as predictors of costs, monetary and non-monetary income, and failed to do so for species richness and diversity. The only exception to this is in the significant effects both of species richness and Shannon–Wiener diversity on profitability (the income-cost ratio), presumably the outcome of the higher profitability of home gardens relative to plantation agroforests (data not shown). GLM limited to productive species likewise consistently identified significant effects of 'agroforestry system' on costs, monetary and non-monetary income, but failed to do so for species richness or diversity (data not shown).

### Multivariate correlations between biodiversity and monetary variables

The first two axes of principal component analysis accounted for 88.0 % of total variation (Fig. 7). Axis-1 (70.0 % of variation) identifies systems with high and low diversity, and axis-2 (18.0 % of variation) is largely income-related. Whereas commercial agroforestry enterprises constitute the species-poor extreme of axis-1, small home gardens and enriched fallows are on the diverse other end. The main difference in axis-2 coincides with the latter two systems, reflecting economic differences caused by the contrasting predominance of 'productive' versus 'non-productive' species.

### Satisfaction

The degree of satisfaction was systematically higher in all agroforestry systems than in the two predominating land-use systems, pasture with babassu and slash-and-burn shifting cultivation (Fig. 8). All farmer families of all types of agroforestry systems were 'very satisfied', satisfaction was maximum in commercial agroforestry enterprises and near-maximum in the home gardens.

## Discussion

Taxonomic and/or functional diversity are known to be key for the functioning and stability of (agro) ecosystems (Schulze and Mooney 1993; Loreau 2000; Schleuning et al. 2015). Relative to tree or crop monocultures, multi-species agroforests could have higher productivity (niche expansion, improved resource exploitation; Cannell et al. 1996; Schroth

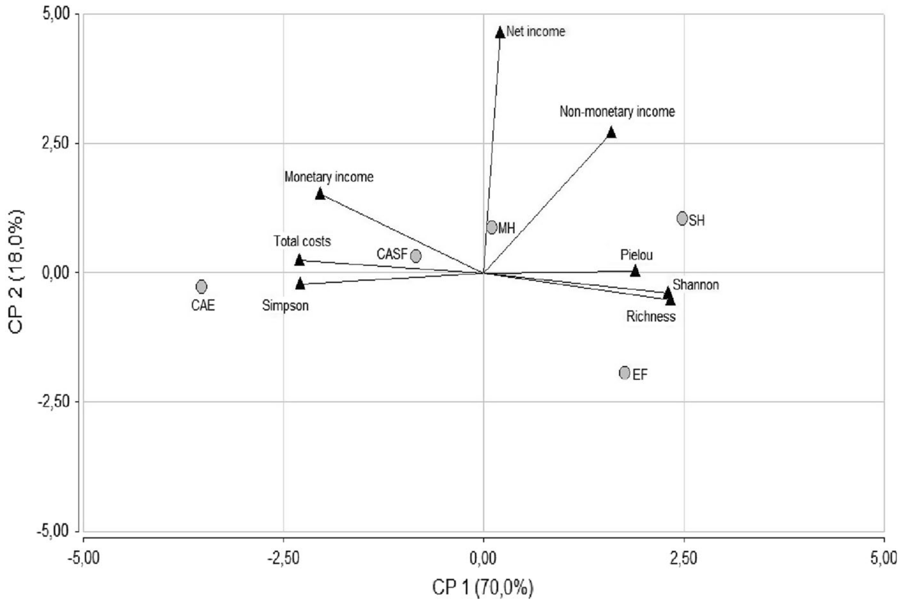


**Fig. 7** Principal component analysis of tree diversity and income variables over five agroforestry systems (27 sites) in eastern Amazonia (*CAE* commercial agroforestry enterprise, *CASF* commercial agroforestry by smallholder farmers, *SH* small home garden, *MH* medium-sized home garden, *EF* enriched fallow). The first two axes of PCA accounted for 88 % of total variation

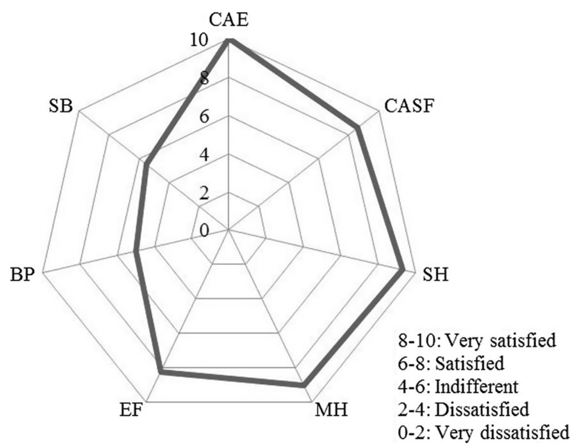


**Fig. 8** Degree of satisfaction of farmers in the different land-use systems of eastern Amazonia. *CAE* Commercial agroforestry enterprise, *CASF* commercial agroforestry by smallholder farmers, *SH* small home garden, *MH* medium-sized home garden, *EF* enriched fallow, *PB* pasture with babassu, *SB* slash-and-burn shifting cultivation

et al. 2001), and higher stability (resistance against and resilience following disturbances), though species' identity and functional traits strongly affect such relationships (Díaz and Cabido 2001). From a market perspective, product diversity reduces market risks (vulnerability against price fluctuations) (Faye et al. 2011; Vallejo et al. 2015), but likewise reduces scale effects and increases marketing costs (Souza et al. 2011). Our study establishes positive linear relationships between productive species richness and both monetary and non-monetary income and income:cost ratios over a wide range of agroforestry systems (see Fig. 6). According to GLM, productive (but not total) species richness strongly affected net income.

Species-poor commercial agroforestry plantations have both the highest costs and the highest (monetary) returns. On the other end are low-intensity and (total) species-rich enriched fallows. Lower intensity is caused by the occupation of space and light capture by 'non-productive' species (Steffan-Dewenter et al. 2007; Godsey 2010; Clough et al. 2011), which reduce both the costs and monetary (but not non-monetary) income. Next to the 'species of the future' (still unproductive juveniles), this category is composed of plants renown for the ecosystem services they provide (shade, $N_2$ fixation, organic matter cycling) (Jose 2009; Godsey 2010). Taking only the productive species (which generate commercial and/or non-monetary auto-consumption benefits), agroforestry species richness and diversity are positively related with non-monetary income, net income, and, most expressed of all, the income:cost ratio (i.e., efficiency). The strong relationships with net income and income:cost ratio point to efficiency increase, possibly generated by synergies between agroforestry species (García-Barrios and Ong 2004).

Next to the above-mentioned positive ecological biodiversity effects, two further—socioeconomic—benefits of agroforestry species diversity are important: (i) a better temporal distribution of labor demands and income generation, and (ii) reduced (financial and non-financial) risks. Whereas overall labor availability as the main input factor in subsistence smallholder systems is high, peak labor demands during planting operations and subsequently during weeding and harvest are limiting factors in traditional slash-and-burn shifting cultivation (Metzger 2002). Income in food and other products is likewise very unevenly distributed, with critically low-income phases during dry season and at onset of rainy season (Huss-Ashmore and Goodman 1988). Tree and palm crops in agroforestry can reduce seasonality (a crucial issue in poverty alleviation), both in labor requirements and in income generation, this effect could increase with agroforestry species diversity.

Even though profitability (i.e., the income:cost ratio) is lowest in commercial agroforestry enterprise plantations, the average ratio of almost 2 (1.97) nevertheless is a sound investment. Yamada and Gholz (2002) confirm the efficiency of this system developed by Japanese immigrants in southern Pará State, with returns generated by 10–20 ha agroforestry plantations equivalent to those of 400–1200 ha pasture. The income:cost ratio is 36.7 % higher (2.70) in commercial agroforestry by smallholder farmers, which in turn contains 87.5 % more productive species relative to pure commercial operations. Future financial returns in both commercial agroforestry systems are bound to increase in both systems, due to the timber species overstory (not considered in our study).

We underestimate total income generation in pastures with babassu as we omit babassu nut extractivism for palm oil and charcoal production. We do this from the farmer's perspective, as this income is generated by non-farm actors (the babassu nut-cracker women), and is sporadic and geographically unpredictable. This is because of a legal singularity in Maranhão State, which guarantees free access and exploitation of babassu nuts on all private lands (the 'Free Babassu' law). Manual babassu nut cracking still provides a vital income source for the rural poor especially during dry season (Porro et al. 2004), for some 300,000 families in Maranhão State alone (Almeida et al. 2001). However, (almost exclusively female) labor is tough, involves health risks and generates very marginal income, well below the poverty line. Thanks to the advent of new income opportunities (migration to urban areas, government programs), babassu extractivism is declining, with a 9.7 % reduction of oil production between 2006 and 2010 (IBGE 2010). The 'silvopastoral' babassu pastures not only are by far the least productive system, they also have the lowest biodiversity (one single 'forestry' species). Carbon stocks of these sites are likewise much lower (Muchavisoy 2013). This confirms the low socioeconomic and ecological efficiency of extensive pastures, which only are profitable because of the unequal land distribution/low land prices, connected scale effects and high labor efficiency, and (mainly in the past) direct and indirect government subsidies (Porro et al. 2004).

Our other control, slash-and-burn shifting cultivation, is stricken by a sustainability crisis. Estimates of the socioeconomic importance of slash-and-burn shifting cultivation are scarce, old, and insecure. This form of land use is believed to sustain some 300–500 million people worldwide (Brady 1996). Whereas non-degraded fallows can maintain considerable biodiversity (Padoch and Pinedo-Vasquez 2010), this is not the case in our study region, where increasing land-use pressure and reduced fallow periods (in our study region only 2–5 years) cause continuous degradation, reduced productive potential and yields, lower resilience, and a widespread increase in rural poverty, confirming trends of many other parts of the humid tropics (Styger et al. 2007; Lawrence et al. 2010). There is a large intensification potential via technological efficiency increases (Pascual 2005), next to understory enrichment plantings in older fallows (as investigated in this study), main intensification pathways are in ecological enrichment of young regrowth with fast-growing legume trees (Koutika et al. 2005) and/or fire-free land preparation (Denich et al. 2004), or alternatively slash-and-char land preparation (McHenry 2009).

We investigate only the agricultural phase of shifting cultivation, which explains the higher per-hectare income generation (intensity) relative to extensive pastures with babassu. We did not quantify income-generation via extractivism of useful species during the fallow phase. As our secondary forests are severely degraded and species-poor, this income source is likely very small. Our results indicate a low profitability of shifting cultivation, as both per-hectare net income and income:cost ratio are significantly higher in all agroforestry systems.

Our study identifies home-garden agroforestry as the most efficient and promising of all land-use systems, top performing both in net benefits per area (averages of small and mid-sized home gardens generate R$ 4532 $ha^{-1}$ or 7.3 minimum monthly wages (of R$ R$ 622 in census year 2012) and in profitability (income:cost ratio of 5.5). Coincidentally, we encountered maximum agroforestry biodiversity in the small home gardens (1.7 ± 0.02 Shannon diversity index and 12.1 ± 1.8 species richness/plot) which is intermediate relative to Shannon diversity reported in other studies ranging from 1.00 (home gardens in the northern periphery of Amazonia; da Semedo and Barbosa 2007) to 2.21 and 2.30 in home gardens of neighboring Pará State and in urban home gardens in Paraná State of southern Brazil (Gomes 2010; Vieira et al. 2012). Home gardens developed independently in many cultures throughout the world, especially in the humid tropics. Even though they still are definitely under-researched (Nair 2001) and have never been part of systematic agronomic improvement efforts (Kumar 2006), these systems persist to the modern day and constitute a remarkable success story both in ecological and socioeconomic terms (Peyre et al. 2006; Galluzzi et al. 2010). Our results point to three key socioeconomic features for rural poverty reduction efforts destined to those with no money and little land: low costs/zero external inputs, maximum profitability (income:cost ratio) and high (mainly non-monetary) per-hectare income generation. Home gardens generate high-quality products for auto-consumption, the degree of satisfaction of their farmers is near maximum.

## Conclusions

(i) Agroforestry species diversity reduces costs and increases (especially non-monetary) income and profitability. This is important both from theoretical and practical perspectives.

(ii) All agroforestry systems are more sustainable than extensive pastures with babassu and slash-and-burn shifting cultivation, the two predominating land-use systems throughout Amazonia. This reiterates the notion that agroforestry can provide a solution to the socioecological sustainability crisis in the tropics.

(iii) Farmer's satisfaction is maximum both in commercial agroforestry plantations and in the home gardens, which form the two most intense forms of agroforestry, and which at the same time are the extreme ends in terms of their economic and biodiversity settings.

(iv) Traditional species-rich home gardens outperform all other systems in terms of net income per area, profitability, and non-monetary income, providing the explanation for their pan-tropical success and persistence to date. Home gardens have so far been left on the sidelines of applied agronomic research and extension efforts in Brazil and worldwide. Future investments into home-garden agroforestry would be highly efficient for poverty reduction and nutritional security in eastern Amazonia and throughout the tropics. Investment is needed both in bidirectional research (e.g., selection/introduction of productive species, optimized management of organic matter and nutrient cycling in joint trials with local communities), and in subsequent extension efforts (formation of home garden expertise in extension services and training programs, specialized rural credit lines, certification efforts etc.).

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## Annex 1

See Table 4.

**Table 4** The ten most abundant agroforestry species: shares in total abundance (over all sites), uses and origins

| Common name | Scientific name | Family | Abundance (%) | Commercial classification | Main uses | Origin[a] |
|---|---|---|---|---|---|---|
| Açaí | *Euterpe oleracea* Mart. | Arecaceae | 25.9 | AC | Food | Native |
| Banana | *Musa* spp. | Musaceae | 20.2 | AC | Food, shade, organic matter | Exotic |
| Cocoa | *Theobroma cacao* L. | Malvaceae | 16.4 | CO | Food, organic matter | Native |
| Cupuassu | *Theobroma grandiflorum* (Wild. ex Spreng.) K. Schum. | | 11.6 | AC | Food, organic matter | Native |
| Black pepper | *Piper nigrum* L. | Piperaceae | 4.9 | CO | Food | Exotic |
| Bacuri | *Platonia insignis* Mart | Clusiaceae | 2.3 | AC | Food | Native |
| Jaca | *Artocarpus integrifolia* L. | Moraceae | 1.4 | AC | Food timber | Exotic |
| Cecropia | *Cecropia* sp. | Urticaceae | 1.3 | NP | Food, fauna shade medicinal | Native |
| Pati | *Syagrus cocoides* Mart. | Arecaceae | 1.2 | NP | Food, fauna | Native |
| Mango | *Mangifera indica* L. | Anacardiaceae | 1 | AC | Food | Exotic |
| Others | | | 13.7 | | – | – |

*CO* Commercial, *AC* mainly auto-consumption, *NP* non-productive (providing ecosystem services, juveniles or medicinal use)

[a] We consider as 'native' species all species originating in Amazonia or the Cerrado forests, or introduced into the region before the year 1500

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