Biosocial and bionumerical diversity of variously sized home gardens in Tabasco, Mexico

Hans van der Wal · Frans Bongers

Abstract The evaluation of species and structural diversity of home gardens strongly depends on the methods used. We distinguish the biosocial and the bionumerical method. The first is widely used and takes data of the whole population of trees of home gardens to calculate diversity. The bionumerical method calculates diversity from data of a fixed number of randomly selected trees. We apply both methods to analyze if structural and species diversity varies with home garden size, a theme of considerable conservation interest, and compare results. We inventoried the tree component of a sample of 61 home gardens from rural areas in Tabasco, Mexico, which we assigned to three size categories: small ($\leq$1,000 m^2), medium sized (>1,000 and $\leq$2,000 m^2), and large home gardens (>2,000 m^2). Average species richness and Shannon diversity indices determined by the biosocial method were significantly different among home garden size classes. Average species richness determined by the bionumerical method did not differ among size classes. Both methods showed highest total observed and estimated species richness in the large home gardens, which contain many unique species. Both methods showed similar overall species composition among size classes and highest structural diversity in large home gardens. We conclude that it is important for conservation to maintain large home gardens in local mosaics, and that the biosocial and bionumerical methods are complementary. The bionumerical method allows straight comparison of population diversity within and among systems, but lacks attention for rare and unique species. The biosocial method evaluates how much diversity families custody.

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Introduction

Many households around the world produce goods and services for home consumption, markets and social networks in home gardens. These have been technically defined as agroforestry land-use systems with multipurpose trees and shrubs intimately associated with seasonal and perennial agricultural crops and

livestock, that are situated within the compound of individual houses and under the management of family labor (Fernandes and Nair 1986). Attention has been drawn to the social-ecological nature of such systems, which have properties of both nature and society (Zimmerer 2007). "Home gardens can be treated as a vegetation type, that is, it has physiognomic character and floristic composition. However, the garden is more than a vegetation type; it is a cultural-biological complex that can tell us much about people as they express themselves in the plant world. Each dooryard garden is the identifiable result, subject to examination, of thousands of decisions about plants which a person makes in his own near space" (Kimber 1973, p. 6). Home gardens are eminently social-ecological systems (Soemarwoto and Conway 1991).

Home gardens conserve biodiversity, including agrobiodiversity (Casas et al. 1996; Engels 2002; Albuquerque et al. 2005; Goddard et al. 2009; Abebe et al. 2010). We can distinguish planned diversity, managed to produce goods and services, and associated diversity (Vandermeer et al. 1998). Planned diversity includes tolerated and favored spontaneous useful plants (Blanckaert et al. 2004). Many inventories document the planned species richness of home gardens. Regionally, planned species richness in samples of home gardens ranges from 27 to 602 species; species richness in individual home gardens ranges from 4 to 74 species (Kumar and Nair 2004, p. 139). Associated diversity includes species that spontaneously use the system (Vandermeer et al. 1998). Planned diversity influences associated diversity (Reitsma et al. 2001; Harvey and Gonzalez-Villalobos 2007; Bhagwat et al. 2008). Though a linear correlation of planned and associated diversity does not hold (Lawton et al. 1998; Beukema et al. 2007; Scales and Marsden 2008), as a rule of thumb planned species and structural diversity catalyze associated diversity of vertebrates, arthropods, and non-crop plants (Vandermeer et al. 1998; Hughes et al. 2002; Perfecto and Vandermeer 2008; Chappell and LaValle 2011).

Most studies on planned diversity in home gardens have equated the complete home garden, as it is taken care of and managed by the family (Kimber 1973), with the sampling unit, and have considered all censused plants of this unit to calculate diversity parameters (for example: Rico-Gray et al. 1990; Kehlenbeck et al. 2007). We call this method the "biosocial" method, as results are easily related to social or economic information on the same scale, such as family size and income (Jose and Shanmugaratnam 1993; Kehlenbeck et al. 2007). This informs straightforward about how much diversity families steward, and how families create diversity in response to the available area, economic needs, availability of resources, infrastructure (water), availability of labor, complementarity of the home garden with families' economic activities, marketing possibilities, food requirements, and esthetic values (Kehlenbeck et al. 2007; Goddard et al. 2009). Results obtained by this biosocial method, however, do not allow the strict assessment of ecological aspects, or comparison of these aspects within and across systems, as the method does not account for the influence of population size of plants in home gardens on diversity. In principle, in larger populations more species are expected.

In ecology it is increasingly common to calculate diversity from sample data of fixed numbers of randomly drawn individuals or samples (Gotelli and Colwell 2001), because this allows comparison within and across systems using a same standard. To date, such "bionumerical" methods have not been applied to home gardens. Individual-based rarefaction allows determining species richness among home gardens at a given number of individuals observed in each home garden (Colwell and Coddington 1994; Gotelli and Entsminger 2011). Individuals are randomly selected from the population of trees in each home garden and results are averaged over a user-defined number of runs in the program. Sample-based rarefaction allows estimating total species richness on a regional level for a class of home gardens from abundance data, which may refer to the complete population of plants (biosocial method) or a fixed number of plants (bionumerical method). Structural parameters can also be determined from a fixed number of randomly chosen trees from the populations in home gardens (bionumerical method), or alternatively from all trees found in each of them (biosocial method). Bionumerical methods allow strict comparisons among populations in distinct systems, as well as in home gardens of distinct classes. They allow a population biology view of home garden diversity, while biosocial methods essentially inform about peoples stewardship of diversity in their near space.

The planned species and structural diversity of home gardens is influenced by a series of factors, which includes socio-economic status, culture, taste,

economic strategies, market integration, the availability of natural forests, and agricultural land availability (Rico-Gray et al. 1990; Moreno-Black et al. 1996; Das and Das 2005; Goddard et al. 2009). Home garden size is one of these factors (Rico-Gray et al. 1990; Kumar et al. 1994; Kehlenbeck et al. 2007). In two villages in Yucatan, Mexico, home garden size had correlation coefficients of 0.64 and 0.54 with species richness (Rico-Gray et al. 1990). In Kerala, India, species diversity increased with home garden size (Kumar et al. 1994). A positive correlation is however not ubiquitous (Kumar et al. 1994; Gajaseni and Gajaseni 1999; Kehlenbeck et al. 2007; Galluzzi et al. 2010). Families may respond in various ways to home garden size, in accordance with the complexities of home gardens as social-ecological systems. Networking among owners may lead to mosaics of complementary elements with a certain specialization in distinct products, the mosaic providing a scope of products that cannot be all cultivated in individual home gardens (Harvey and Gonzalez-Villalobos 2007; Imbruce 2007). If producers focus on such networking, the number of common species in individual home gardens will be small, but the mosaic will contain many species. Alternatively, if owners focus on providing themselves with the most common products, home gardens will show repeated narrow selections of species and the mosaic will contain few species. It is therefore currently unknown if small home gardens contribute in a similar way to the conservation of biodiversity in the larger landscape as large home gardens (Goddard et al. 2009). To evaluate this we need to analyze not only the species diversity in home gardens, but also the similarity of species composition among home garden size classes. Knowledge of the relation between home garden size and diversity is of major interest for policies on the conservation of both planned and associated diversity (Sutherland et al. 2006).

Here we use the biosocial and bionumerical method to determine species and structural diversity of home gardens of various sizes in the tropical lowlands of Tabasco, Mexico. Our goals are (1) to compare the results obtained by both methods in the analysis of diversity in home gardens; and (2) to determine if and how home garden size influences home gardens' planned diversity as calculated by both methods. Our hypotheses are that the biosocial and bionumerical method give distinct results on home garden diversity,

and that species and structural diversity calculated by both methods vary with home garden size.

## Methods

Study area and home garden selection

We studied home gardens in the tropical lowlands of Tabasco State in southeastern Mexico. Rainfall is 1,500 mm per year near the coast and 4,000 mm in the mountains. Rains concentrate in the wet season from June to November, and continue moderately from December to March. The dry season is from April to June. Average annual temperature is 25.0 °C in the plains and 24 °C on the low mountain slopes (West et al. 1985). Rural population is distributed over many small villages ("rancherías"). We selected a sample of 61 home gardens in two steps. In the first step we selected a set of 29 villages distributed over the whole territory of the state of Tabasco, along three roughly parallel north–south transects from the Gulf coast to the lower mountain slopes. In the second step we established contact with villagers, and selected one to three home gardens that were actively managed, had an area of more than 100 m^2, and whose owners were willing to let us do the research in their near space. Figure 1 shows the distribution of selected home gardens over the state's territory.

Measurement and observations

We measured the home gardens' precise extensions. During 2009 and 2010 we fully inventoried all individuals of perennial and mostly woody species—hereafter "trees"—with DBH > 2 cm (trees, plantains, palms, cycads, and bamboo). We measured all individuals' total height with a laser rangefinder, diameter at breast height (DBH), and two perpendicular crown diameters. We identified plants by their scientific name in the field. In case of doubt we collected voucher specimens for identification in the herbarium of El Colegio de la Frontera Sur in San Cristobal de las Casas, Chiapas.

Data treatment and analysis

We grouped the home gardens in three size classes, considering practicality of thresholds and the criterion
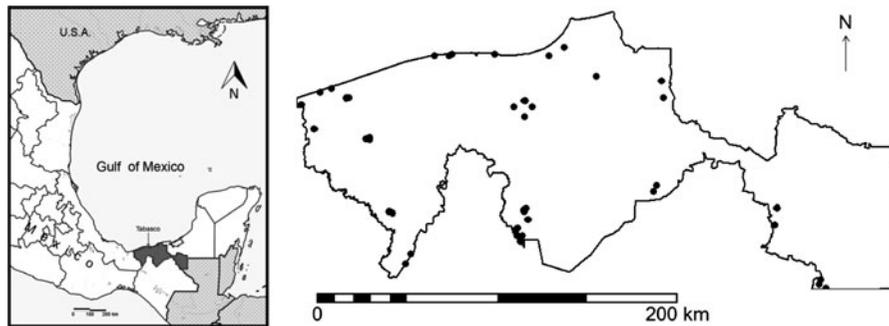
Fig. 1 Geographic location of Tabasco and the distribution of the sample of home gardens over its territory

that each class contain at least 25 % of the total sample: small ($\leq$1,000 m², $n = 16$), medium sized (>1,000 and $\leq$2,000 m², $n = 25$), and large (>2,000 m², $n = 20$), and determined diversity of home gardens in these size classes, using both the biosocial and bionumerical method. We elaborated a species abundance matrix for the biosocial method, including all trees in all home gardens, and used PAST software to determine species richness, Shannon diversity (H') and equitability (Shannon diversity divided by the logarithm of number of taxa) of all home gardens (Hammer et al. 2001). For the bionumerical method we used 1,000 iterations for individual-based rarefaction in ECOSIM (Gotelli and Entsminger 2011) to calculate species richness, H' and equitability of random samples of 50 trees from all home garden with 50 or more individuals. We chose the threshold of 50 individuals to maintain sufficient numbers of home gardens in the three size categories. We tested for differences in diversity parameters among home garden size classes with ANOVA and Tukey's HSD post hoc test, or Tamhane's test if variance was not homogeneous. We used t tests for analysis of differences among the results of both methods.

We estimated total species richness for each size class by both methods, using sample based rarefaction in the program EstimateS Version 8 (Colwell 2006) and the Jackknife 1 estimator. For the biosocial method we considered the complete abundance matrix, and for the bionumerical method we elaborated a new matrix containing species abundance data of a sample of 50 randomly selected trees from home gardens with more than 50 trees, excluding home gardens with less than 50 individuals. We applied analysis of similarity (ANOSIM), available in the PAST package (Hammer et al. 2001), using both

matrices as data inputs, and calculated similarity matrices with Jaccard presence–absence based and Gower abundance based indices. We compared average similarity within and among home garden size classes using t-tests. We counted the number of unique species in each home garden size class and performed χ^2 tests to determine if differences among them were statistically significant.

We determined by both methods average and maximum tree height, as well as the number and basal area of trees in three size classes (<10 m, from 10 to 20 m, and $\geq$20 m) for each home garden. We tested differences among home garden size classes with ANOVA, using post hoc Tukey's HSD or Tamhane's tests. We tested differences among methods with t-tests, or Mann–Whitney U-tests in cases where data were not normally distributed.

Results

We observed 5,501 individuals that belonged to 195 species in the sample of 61 home gardens. Total sampled area was 10.41 ha and average home garden size was 1,707 m². The most frequent species were *Citrus sinensis* Osbeck, *Mangifera indica* L., *Citrus limon* (L.) Osbeck, *Annona murricata* L., *Cocos nucifera* L. and *Tabebuia rosea* DC., all present in more than 40 home gardens. The most abundant species were *Cocos nucifera*, *Citrus sinensis*, *Tabebuia rosea*, *Musa paradisiaca* L., *Glyricidia sepium* (Jacq.) Kunth and *Theobroma cacao* L., which all had more than 200 individuals in the total sample. *Mangifera indica*, *Cocos nucifera*, *Citrus sinensis*, *Cedrela odorata*, *Tabebuia rosea*, *Gliricidia sepium*, *Swietenia macrophylla* King and *Persea americana*

Mill. had highest basal area. A list of tree species in home gardens Tabasco was recently published (Van der Wal et al. 2011).

Biosocial diversity of home gardens in three size classes

Species richness and number of trees were significantly correlated with the extension of home gardens ($r = 0.60, P < 0.001$, and $0.72, P < 0.001$) in the area range of the sampled home gardens from 170 to 5,335 m^2 and varied among home garden size classes ($F = 14.4$, $P < 0.001$, $F = 20.34$, $P < 0.001$, $n = 61$). Biosocial species richness varied between 9 and 54 species in individual home gardens with a median of 22 species. Small home gardens were not as species rich as medium sized and large home gardens (Tamhane's test, $P < 0.05$ and $P < 0.001$), and medium sized home gardens had less species than large home gardens (Tamhane's test, $P < 0.01$). Shannon diversity indices varied from 1.76 to 3.53, with a median of 2.55. H' was smaller in small than in large home gardens (ANOVA, $F = 3.77$, $P < 0.05$; Tukey's HSD test, $P < 0.05$) (Table 1).

Total observed species richness varied among home garden size classes (Fig. 2a). In small home gardens, observed species richness was 88 species, in medium sized home gardens 114 species, and in large home gardens 163 species. Sixty-five species occurred exclusively in large home gardens. Of these, 30 species occurred in only one home garden with only one individual, nine species with two individuals, and nine species with three individuals. Ten species were only found in small home gardens. These occurred in small numbers, and did not represent a specialized production: six out of the ten mentioned species only occurred once with one individual. In medium sized home gardens, eight species occurred in only one home garden with only one individual. The proportion of the number of unique species with one occurrence of total species richness was significantly higher in large home gardens than in small and medium sized home gardens, and equal among the latter two classes (χ^2 tests, $P < 0.01$ and $P = 0.96$). The three home garden size classes had one-third of the total number of species in common.

Analysis of similarity (ANOSIM) on the abundance matrix, with Gower's similarity as a distance measure, showed no significantly different species composition among home garden size classes. The Jaccard index of similarity, calculated from bulked species presence–absence data, was highest among small and medium sized home gardens (0.554, see Fig. 2a). Small and large, and medium sized and large home gardens had lower Jaccard similarity indices of 0.394 and 0.497. Average Jaccard similarity indices among home gardens were highest in medium sized home gardens (0.24, Mann–Whitney U-test, $P < 0.05$). Small home gardens were not more similar among themselves than with medium sized and large home gardens. The abundance based Gower similarity index was generally low, indicating that owners follow their own preferences when they select species (Fig. 2c). Values were higher among large home gardens than among small or medium sized home gardens; and higher in medium sized than in small home gardens (all differences significant with Mann–Whitney's U-test, $P < 0.05$).
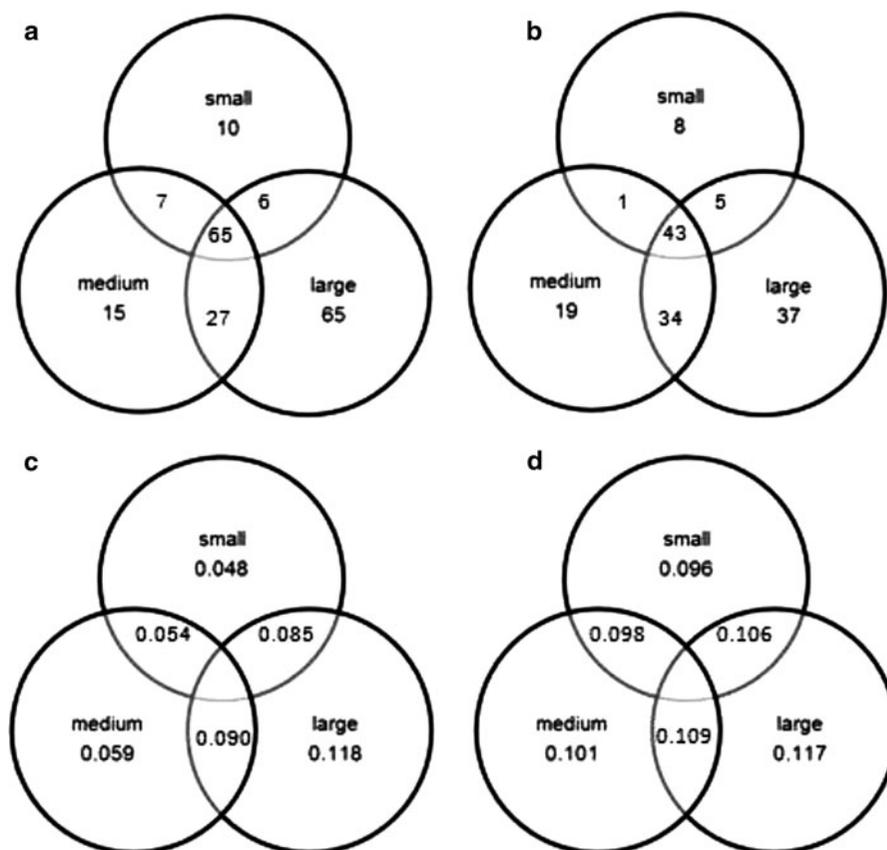
Estimated total species richness in large home gardens in Tabasco was 225 species at 20 sampled home gardens (Fig. 3a). With an equal number of 16

Table 1 Diversity parameters in home garden size classes in Tabasco, Mexico, determined by the biosocial and bionumerical method

Size class	Biosocial method				Bionumerical method			
	n	Richness	Shannon H	Equitability	n	Richness	Shannon H	Equitability
Small	16	17.2[c]	2.39[b]	0.68[a]	6	17.2	2.39	0.65
Medium	25	22.1[b]	2.51[ab]	0.58[b]	21	18.6	2.47	0.66
Large	20	30.9[a]	2.72[a]	0.54[b]	18	19.8	2.54	0.69
All	61	23.7	2.55	0.60	45	18.9	2.49	0.66

n number of home gardens sampled. Means were tested with ANOVA, and post hoc Tukey 's HSD or Tamhane 's tests. Different superscripts in columns indicate significant differences among home garden size classes ($P < 0.05$). Differences among size classes obtained by the bionumerical method were not significant

Fig. 2 Numbers of shared and separately held species and Gower similarity indices among small, medium sized and large home gardens in Tabasco, Mexico. **a** Shared and separately held species, biosocial method; total observed number of species: 195. **b** Shared and separately held species, bionumerical method. Total number of species: 147. **c** Gower similarity indices, biosocial; **d** Gower similarity indices, bionumerical method

sampled home gardens, estimated total species richness was significantly larger in large (211 species) than in small and medium sized home gardens (121 and 132 species). Also observed total species richness was significantly higher in large home gardens than in small and medium sized home gardens (Fig. 3c). Differences in observed and estimated total species richness paralleled differences in sampling area (Fig. 3e). Observed richness increased faster in small home gardens in the low area range than in medium sized and large home gardens, but with a sampled area of 100 ares (1 ha) there was no significant difference in the observed species richness among home garden size classes. Observed species richness was significantly higher in large than in small home gardens with a sampled area of 350 ares (3.5 ha). The total observed species richness of 88 species in small home gardens occurs on 60 % of the area required for finding the same number of species in medium sized and large home gardens (Fig. 3e).

The number of trees in home gardens varied from 19 to 401, with a median of 74. The average number of

trees in large home gardens was 143.1, higher than in small and medium sized home gardens ($F_{2,58} = 13.72$, $P < 0.001$; Tamhane's test, $P < 0.01$). The average number of trees in small home gardens (51.0) was however not significantly different from that observed in medium sized home gardens (75.0 trees) (Tamhane's test, $P = 0.052$). Tree densities varied widely, from 200 to 2,209 per ha. Average density in small home gardens (798.1) was higher than in medium sized (557.7) and large home gardens (489.9) ($F_{2,58} = 5.32$, $P = 0.008$, Tukey's HSD test, $P < 0.05$ and $P < 0.01$). Basal area varied from 5.5 to 31.2 m^2/ha, but was not significantly different among home garden size classes (ANOVA, $F_{2,58} = 0.16$, with $P = 0.856$). Average and maximum height were less in small than in medium sized and large home gardens, whereas basal area per tree was larger in large and medium sized than in small home gardens ($F_{2,58} = 6.39$, $P = 0.003$; Tamhane's test, $P < 0.05$ and $P < 0.001$) (Table 2). The standard deviation of height was significantly less in small than in large home gardens ($F_{2,58} = 6.76$, $P = 0.002$, Tukey's HSD test, $P < 0.01$).
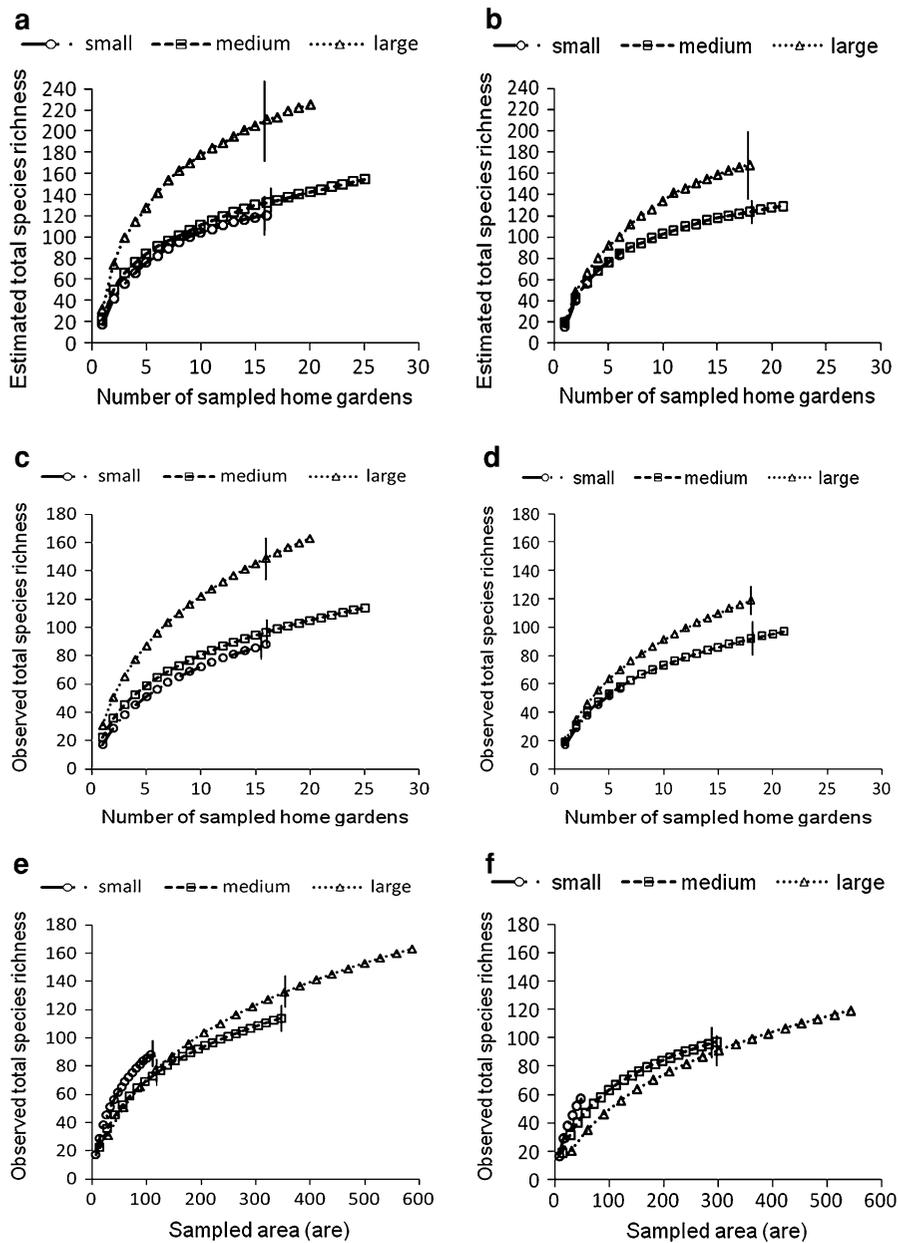
Fig. 3 Observed and estimated biosocial and bionumerical species richness in small, medium sized, and large home gardens in Tabasco, Mexico. Vertical lines indicate 95 % confidence intervals. **a** Total estimated species richness (Jackknife 1), biosocial method; **b** total estimated species richness, bionumerical method; **c** observed species richness, biosocial method; **d** observed species richness, bionumerical method; **e** observed species richness plotted against sampled area, biosocial method, **f** observed species richness plotted against sampled area, bionumerical method

Home garden size classes had distinct distributions of number of trees and basal area over three tree height classes (<10, ≥10 and <20, and ≥20 m (Fig. 4a, c). Differences in the numbers of trees in tree size classes among home garden size classes were significant for

trees < 10 m and trees > 20 m (ANOVA, $F_{58,2} = 7.64$, $P = 0.001$ and $F = 3.10$, $P = 0.05$) (Fig. 4a). There were more trees < 10 m in small than in medium sized and large home gardens (Tukey's HSD test, $P < 0.05$). Trees taller than 20 m were particularly

Table 2 Average structural parameters of trees determined by the biosocial method in home garden size classes in Tabasco, Mexico

Size class	Biosocial method					Bionumerical method				
	n	Height (m)	Maximum height (m)	Basal area (cm^2)	Maximum basal area (cm^2)	n	Height (m)	Maximum height (m)	Basal area (cm^2)	Maximum basal area (cm^2)
Small	16	5.6[b]	14.7[b]	207[b]	1,529[c]	6	5.8[b]	14.3	173[b]	1,234
Medium	25	6.9[a]	18.3[a]	287[a]	2,282[b]	21	6.8[ab]	17.5	283[a]	2,293
Large	20	7.6[a]	20.4[a]	337[a]	5,278[a]	18	7.8[a]	18.7	323[a]	2,948
All	61	6.8	18.0	282	3,067	45	7.1	17.6	284	2,414

Biosocial method: height $F_{2,58} = 8.51$, $P = 0.001$, Tamhane's test $P = 0.004$, <0.001; maximum height $F_{2,58} = 9.45$, $P < 0.001$, Tamhane's test $P < 0.05$; basal area $F_{2,58} = 6.39$, $P = 0.003$, Tamhane's test $P = 0.013$, <0.001; maximum basal area $F_{2,58} = 15.10$, $P < 0.001$, Tamhane's test $P < 0.05$; bionumerical method: height: $F_{2,42} = 3.49$, $P = 0.04$, Tukey HSD, $P = 0.008$; maximum height: $F_{2,42} = 2.60$, $P = 0.086$; basal area: Kruskal–Wallis test, $P < 0.05$, Mann–Whitney's U-test $P < 0.05$; maximum basal area: $F_{2,42} = 2.08$, $P = 0.138$. Different superscripts in columns indicate significant differences among home garden size classes ($P < 0.05$)

scarce in small home gardens. There were more tall trees in large home gardens than in small home gardens (Tamhane's test, $P < 0.05$). In small and medium sized home gardens trees < 10 m had higher basal area than in large home gardens ($F = 9.43$, $P < 0.001$, Tamhane's test, $P = 0.009$ and 0.001). Basal area of tall trees was higher in large home gardens than in small home gardens ($F = 3.27$, $P < 0.05$; Tamhane's test, $P < 0.05$) (Fig. 4c).

Bionumerical diversity of home gardens in three size classes

Bionumerical species richness varied between 11.7 and 29.4, with a median of 18.9. Shannon diversity indices varied from 1.84 to 3.13, with a median of 2.46. Bionumerical species richness and Shannon diversity indices showed no significant correlation with home garden extension (r around 0.1, $P > 0.4$) and were not significantly different among small, medium sized and large home gardens ($F_{2,42} = 1.20$ for species richness and $F_{2,42} = 0.55$ for H') (Table 1).
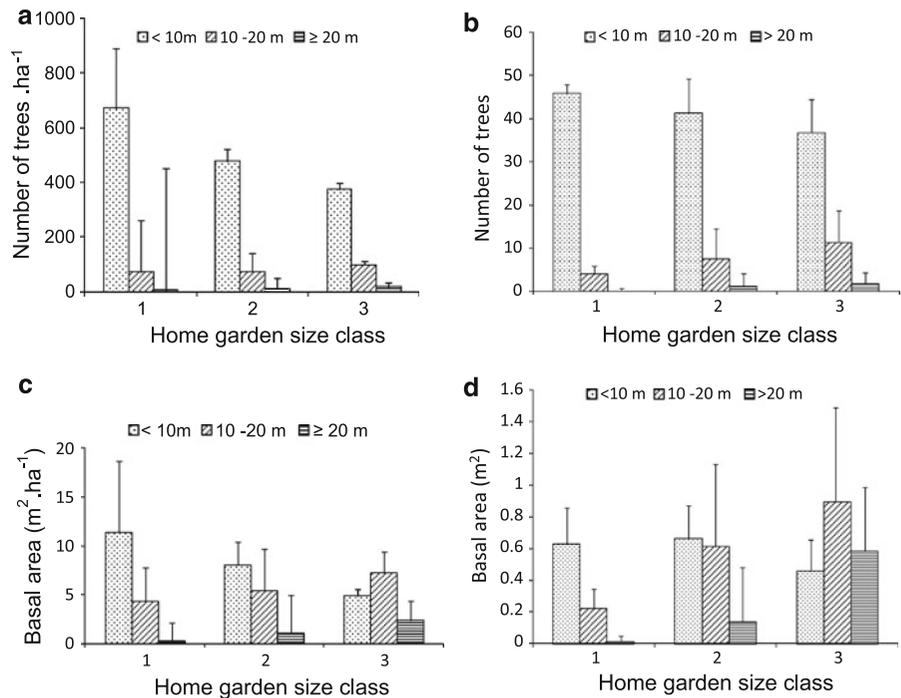
Total observed species richness was highest in large home gardens, with 119 species; in medium sized home gardens we observed 87 species, and 57 species in small home gardens (Fig. 2b). Thirty-seven species occurred exclusively in large home gardens. Of these, 23 species occurred in only one home garden with only one individual, and four species with two and three individuals. Eight species were only found in small home gardens. Three of them only occurred once in one home garden, two twice, and one three times.

Nineteen species were only found in medium sized home gardens, of which eight species occurred only once in one garden. The proportion of unique species with one occurrence was significantly higher in large than in small home gardens (χ^2 test, $P < 0.01$); there was no significant difference among small or large and medium sized home gardens (χ^2 test, $P = 0.15$ and 0.17). Species found exclusively in one home garden did not represent a productive specialization.

Analysis of similarity (ANOSIM) on the abundance matrix, with Gower's distance measure, showed no significantly different species composition among home garden size classes. The Jaccard index of similarity, calculated from bulked species presence–absence data, among small and medium sized home gardens was 0.60 (see also Fig. 2). Small and large, and medium sized and large home gardens had similarity indices of 0.51 and 0.45. Average Jaccard similarity indices within home garden size classes were significantly higher in the medium sized home gardens, than in small and large home gardens (Mann–Whitney U-test, $P < 0.05$). Similarity among pairs of small home gardens was not different from similarity of pairs of small and medium sized or large home gardens. The abundance based Gower similarity index was higher among large home gardens than among small and medium sized home gardens (Fig. 2d) (Mann–Whitney's U-test, $P < 0.05$ for differences). Average similarity within size categories was not distinct from similarity among size categories.

Estimated total species richness in 18 large home gardens (168) was significantly higher than in 18

Fig. 4 Distribution of basal area and number of trees over size classes of trees in small, medium sized and large home gardens in Tabasco, Mexico. **a** and **c**: Biosocial method; **b** and **d**: bionumerical method. **a** Tree density and size; **b** distribution of the number of trees over size classes; **c** basal area distribution over tree size classes; **d** basal area distribution over tree size classes. Biosocial data (**a** and **c**) are extrapolated to hectares. Bionumerical data (**b** and **d**) refer to 50 randomly selected trees. *Whiskers* indicate standard errors

medium sized home gardens (129) (Fig. 3b). Observed total species richness in small, medium sized and large home gardens were similar at low numbers of sampled gardens. Observed species richness was significantly higher in large than in medium sized home gardens with 18 sampled home gardens (Fig. 3d). When we plotted the number of species in the sample of 50 trees against sample area—which does not represent a common species area curve, but a reference line which can only be used for comparing home gardens among classes and with other systems—we found steepest slopes in the low area range in small home gardens. Medium sized home gardens showed higher species richness than large home gardens in the area interval from 0 to 300 ares (3 ha), but the differences were not significant (Fig. 3f). The sample area required to find 60 species in random samples from small home gardens was one-third of that required to find the same number of species in large home gardens.

Trees in small home gardens were smaller than in large home gardens (Table 2). Basal area was distinct among size classes (Kruskall–Wallis test, $P < 0.05$), being smaller in small home gardens than in medium sized and large home gardens (Mann–Whitney's U-test, $P < 0.05$). Maximum height and maximum basal area of trees were not different among home garden size

classes. Standard deviations of average height were less in small than in large home gardens ($F_{2,42} = 4.02$, $P < 0.05$, Tukey's HSD test, $P < 0.05$). Variation coefficients of average height were on average 50 % in small home gardens, and 64 % in medium sized and large home gardens. Few trees (2.7 %) of the total sample of 2,250 trees in the 45 home gardens with more than 50 trees were larger than 20 m, whereas 17.2 % had heights between 10 and 20 m. The distribution of the number of trees and basal area over tree height classes varied among small, medium sized and large home gardens (Fig. 4b, d). Ninety-two percent of the trees in small home gardens were smaller than 10 m (Fig. 4b). Short trees were also the most abundant in medium sized and large home gardens. The average number of short trees was higher in small home gardens than in large home gardens ($F_{2,42} = 4.86, P = 0.026$, Tukey's HSD test, $P < 0.05$). Intermediate trees were more numerous in large than in small home gardens ($F_{2,42} = 4.02$, $P < 0.05$, Tukey's HSD test, $P < 0.05$). Differences in the number of large trees were not significant. The basal area of short trees was larger in medium sized home gardens than in large home gardens ($F_{2,42} = 4.86$, $P < 0.05$, Tukey's HSD test, $P < 0.05$) (Fig. 4d). The basal area of trees of intermediate height in medium sized gardens was similar to that of small trees.

Comparison of the biosocial and bionumerical
diversity assessment

Average species richness and diversity indices deter-
mined by the bionumerical method were significantly
lower than those determined by the biosocial method
(t-test, $P < 0.001$) (Fig. 5a, b). The correlation coef-
ficient among the results of both methods for species
richness was 0.72, and 0.96 for the Shannon diversity
index. Home garden size was significantly correlated
with species richness determined by the biosocial
method ($r = 0.52$, $n = 45$, $P < 0.01$), but not when it
was determined by the bionumerical method
($r = 0.13$, $n = 45$, $P = 0.41$).

The total observed species richness determined by
the bionumerical method was smaller than when it was
determined by the biosocial method (Fig. 3c, d). The
difference was large in large home gardens, and small
in small and medium sized home gardens (Fig. 2a, b).
Total observed biosocial species richness in medium
sized home gardens of 114 reduced to 97 in the random
samples of 50 trees in the bionumerical method
(15 %); in large home gardens it reduced from 163
to 119 (27 %) (Fig. 3c, d). Total estimated species
richness in large home gardens determined by the

bionumerical method was 60 species less than when
determined by the biosocial method, whereas the
difference was only 20 species in medium sized home
gardens (Fig. 3a, b).

There was no difference in bionumerical species
richness and H′ among home garden size classes,
whereas we did find differences by the biosocial
method (Table 3). Differences in species richness and
H′ obtained by the two methods were less in small and
medium sized than in large home gardens (Fig. 5a, b)
(ANOVA, $F = 12.30$ and 11.64, $P < 0.001$; Tamh-
ane's test, $P < 0.01$). Whereas similarity within classes
determined by the biosocial method varied among all
home garden size classes, results of the bionumerical
method showed few differences (Table 3). Observed
and estimated species richness were much lower when
determined by the bionumerical method, but the same
differences among home garden size classes were
detected by both methods (Fig. 3).

The distribution of basal area and number of trees
over tree size classes showed minor differences among
methods (Fig. 4). Average height of trees determined
by both methods was similar, as was basal area per tree
(Table 2). Significant differences among home garden
size classes were observed in average maximum

Fig. 5 Biosocial and
bionumerical species and
structural diversity in small,
medium sized and large
home gardens in Tabasco,
Mexico. a species richness;
b Shannon diversity index;
c basal area; d tree height
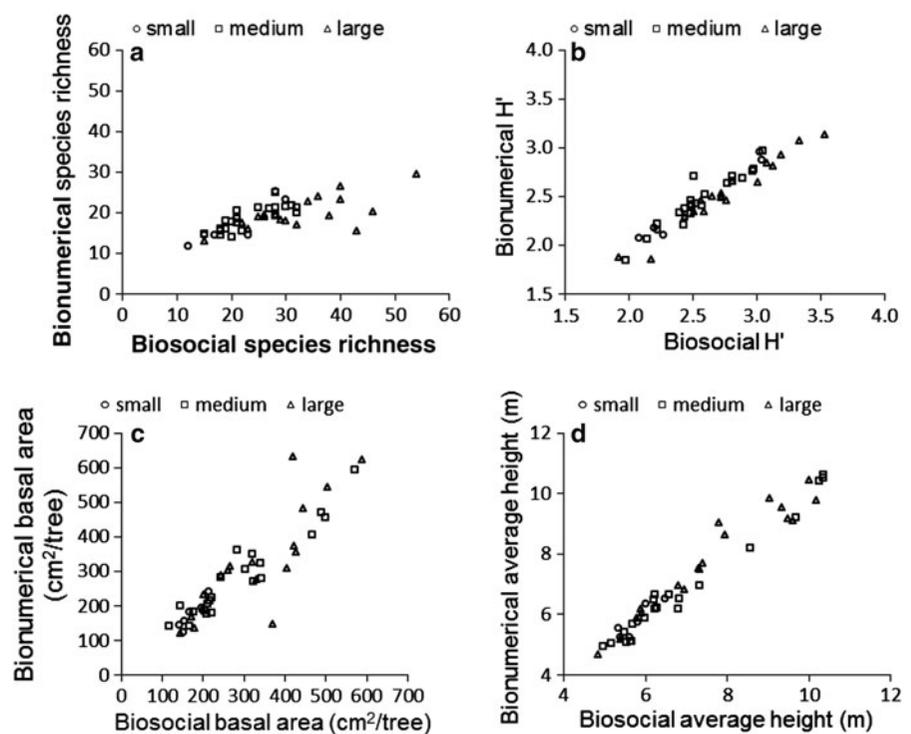
Table 3 Differences among home garden size classes observed by the biosocial and bionumerical method

	Biosocial method	Bionumerical method
Species richness	Small less rich than medium sized and large; and medium sized less rich than large	No differences observed
Shannon diversity index	Small lower diversity index than large	No differences observed
Equitability	Small more equitable than medium sized and large	No differences observed
Similarity indexes within size classes	Different among all classes	Medium sized larger than small and large (Jaccard); large larger than small and medium sized (Gower)
Number of species occurring in only one home garden	Larger in large home gardens than in small and medium sized home gardens	Larger in large than in small home gardens
Estimated and observed richness versus number of sampled home gardens	Larger in large than in medium sized and small home gardens	Larger in large than in medium sized and small home gardens
Observed richness versus sampled area	Near 300 ares sample area higher richness in large home gardens	Near 300 ares sample area similar richness in medium sized and large home gardens
Average tree size, max height, standard deviation, basal area	All variables have smaller values in small than in medium sized and large home gardens	Trees size and its standard deviation is less in small than in large home gardens; basal area less in small than in medium sized and large home gardens
Tree number	Absolute number less in small than in large home gardens. Density higher than in medium sized and large home gardens	Fixed
Distribution of number of trees over tree size classes	More trees < 10 m in small than in medium sized and large	More short trees in small home gardens than in large home gardens; more intermediate trees in large than in small home gardens
Distribution of basal area over tree size classes	Higher basal area of trees < 10 m in small and medium sized than in large home gardens	Higher basal area of trees < 10 m in medium sized than in large home gardens

values of height and biomass per tree determined by the biosocial method. Such differences were not observed when these parameters were determined by the bionumerical method.

Discussion

Tree species richness in our sample of 61 home gardens, determined by the biosocial method, had an average of 23.7 species, and ranged from 9 to 54 species. Total observed tree species richness in home gardens in Tabasco was 195 species. Similar ranges and total observed species richness are found in other regions around the world (Kumar and Nair 2004, p. 139), but these generally include all species, not only the perennial species in our study. This indicates that diversity of home gardens in Tabasco is comparatively high. The values of diversity indices confirm this. The biosocial Shannon species diversity index (H') in home gardens in Tabasco varied from 1.76 to

3.53, with a median of 2.55. Rico-Gray et al. (1990) reported an average H' value of 1.67 of home gardens of varying sizes in two villages in Yucatán, Mexico. Kumar et al. (1994) found average H' values from 1.13 to 3.02 in villages in Kerala, India. Zaldivar et al. (2002) report average Shannon diversity indices of varying numbers and sizes of home gardens for villages in Costa Rica ranging from 1.79 to 2.89. The comparatively high diversity of home gardens in the lowlands of Tabasco, Mexico, may be due to several causes, among which the almost complete deforestation of the state's territory in the second half of the 20th century (forcing people to plant much-needed species in their home gardens), the humid climate and fertile soils, and the human settlement pattern of many small villages may play a role (West et al. 1985).

As expected, we found distinct results of the biosocial and bionumerical methods of determining diversity parameters. In the first place, species richness found is logically smaller with the bionumerical

method than with the biosocial method, as a subsample of the trees in home gardens is considered in the former, and all trees in the latter. Biosocial average species richness and H′ were 23.7 and 2.55, and bionumerical average species richness and H′ were 18.9 and 2.49. The resulting difference in results between methods increases with the population size of trees. Whereas in small home gardens average species richness, H′ and evenness determined by both methods are similar (Mann–Whitney U test, $P > 0.75$), values determined by the bionumerical method are smaller in medium sized and large home gardens (Mann–Whitney U-tests, $P < 0.05$). This is also the case for observed and estimated total diversity. Average structural parameters of trees are similar by both methods (Table 2). This means that if the interest lies in the species diversity that is custodied by families, the biosocial method is preferred, as the bionumerical method underestimates this diversity, particularly in large home gardens. If interested is in structural diversity, the bionumerical method is fine. For comparing ecological aspects among different categories of home gardens or across systems, the common standard of a same number of individuals is most adequate. The choice may make a considerable difference for the conclusions on differences. In our study, the bionumerical method showed fewer differences among home garden size classes than the biosocial method (Table 3). Species and structural diversity determined by the biosocial method were higher in large home gardens than in the small home gardens, whereas species richness and Shannon diversity indices determined by the bionumerical method did not differ among home garden size classes.

Species richness and Shannon diversity indices determined by the biosocial method were lowest in small home gardens and largest in large home gardens, whereas equitability was largest in small home gardens. Home gardens contained the same common species, independently of size class. Limitations of space confined species selections to these most common species in small home gardens, and the number of individuals was distributed more evenly over species than in other size classes. In large home gardens, however, many unique species were grown in between the common species. Large home gardens thus play an important role in conserving these unique species. This may be of great regional importance as well, as Tabasco has extreme levels of deforestation. Our results contrast

with those of Kehlenbeck et al. (2007), who found lowest H′ in villages with the largest home gardens, due to productive specialization in a few abundant crop species. Productive specialization did not play a role in determining diversity in our study area.

Correlation of home garden size and diversity varies between regions. In Yucatan, Mexico, the correlation coefficient of size and species richness was 0.61 (Rico-Gray et al. 1990), and it was as high as 0.80 in Santa Rosa, Peru (data from Padoch and De Jong 1991, our calculus). Correlation was weak in Kerala, India (Kumar et al. 1994). In other cases, there was no significant correlation, or even a negative correlation (Gajaseni and Gajaseni 1999). In India H′ was higher (1.24) in home gardens of intermediate sizes (0.4 ha) than in large (0.72 ha) and small home gardens (0.24 ha) (Peyre et al. 2006). In our sample of home gardens in Tabasco, Mexico, species richness and H′ determined by the biosocial method and home garden extension showed a positive Spearman correlation coefficient of 0.62 ($n = 61$) and 0.31, whereas correlation coefficients in each of the size classes were not significant. Home garden size thus explains 37 % of variation in species richness in the mosaic of home gardens in Tabasco. Size indeed influences diversity and is therefore a factor of interest for policies on diversity conservation in the productive landscape. It is however not the only factor that influences diversity, and there is no universal relation between home garden size and diversity; regional factors and markets, among other factors, modulate such relations. As social-ecological systems, dynamics depend on specific combinations of influencing factors.

Results of the bionumerical method show no differences in species richness and Shannon diversity index among home garden size classes. It can be argued, that this is due to the reduced size of the sample of small home gardens, as we excluded home gardens that had less than 50 trees from analysis (Table 1). Sample size was not decisive, however, as differences in biosocial species richness among home garden classes were significant when the same sample size was used as for the bionumerical method ($F_{2,42} = 9.10$, $P = 0.001$, Tukey's HSD test, $P < 0.01$). Rather, absence of significant differences in diversity determined by the bionumerical method was due to low bionumerical species richness and diversity in medium sized and large home gardens, whereas diversity in small home gardens found by both methods were the same (Table 1).

Random selection of tree from the populations in home gardens favors the occurrence of abundant species in the samples of 50 trees, and not of unique species with one or few individuals. In small gardens, where most of the available trees are selected as their total number of individuals is near 50, there was logically little difference in the results among the two methods. In large home gardens, however, a comparatively small fraction of the total population of trees is selected, and species with few individuals have little chance of being selected. The difference between biosocial and bionumerical species richness is therefore larger in large than in small home gardens (Fig. 5a). As a consequence, we find no significant differences in bionumerical diversity between small and large home gardens. This result nuances the finding that large home gardens are more diverse. They are in a biosocial sense, i.e. referring to the biodiversity that families steward; in an ecological sense, however, diversity of small home gardens is not different from that of large home gardens.

Observed and estimated total species richness were larger in large than in medium sized and small home gardens, and this result was obtained by both methods (Fig. 3a–d). When species richness was plotted against area, small home gardens show a steeper slope in the low area range than medium sized and large home gardens (Fig. 3e–f). However, the increment in the total number of species is likely to diminish if a larger area is observed, as the increments in the low area range are based on common species of which only few fit in small home gardens due to space limitations. If sampled area would increase to a few hectares, total species richness in small home gardens will most likely be lower than in the case of medium sized and large home gardens. As reduced home garden size confines species selection to common abundant species (Fig. 2a), mosaics of only small home gardens will contain low species richness as compared to mosaics that contain home gardens of different size categories (Fig. 3). As indicated in the present study by low similarity indices and focus on common species, species selections in small home gardens may reflect family economic strategies of exchange of products. Our results also show that people who own small home gardens adapt to limited available space by planting more species on the same area than owners of medium sized and large home gardens (Fig. 3e). This is also indicated by the fact that total observed species richness in 16 small and medium sized home

gardens was similar (Fig. 3c), in spite of a 50 % smaller sampled area in the former (Fig. 3e). This confirms earlier findings in the sense that people with small home gardens pack more species per unit area (Kumar and Nair 2004).

Species composition was not different among home garden size classes. This finding was independent of which of both general methods we used. Home gardens of the different size classes had many species in common, and these common species are the most abundant. The analysis of species composition that we used (ANOSIM), as well as other methods, cannot account for little frequent or unique species with few individuals. As they weigh all individuals equally, few individuals of rare species only marginally influence distances in the generated similarity matrixes. The finding that little frequent species make the difference in species composition between large and small home gardens does not contradict overall similarity among size classes. Precisely the difference in species composition among home garden size classes is that rare species occur more in large home gardens.

Height and basal area per tree were smallest in small home gardens, and this result was the same by both methods. Only in large and medium sized home gardens were large trees quantitatively important (Fig. 4). Small home gardens were structurally even and large home gardens diverse. Because of their structural diversity, large home gardens contribute more to the conservation of associated diversity than small home gardens (Vandermeer et al. 1998; Reitsma et al. 2001; Hughes et al. 2002; Beukema et al. 2007; Gordon et al. 2007; Perfecto and Vandermeer 2008; Chappell and LaValle 2011). For this reason, and because of their higher planned diversity, conservation policies should address the persistence of large home gardens in local and regional mosaics.

Low similarity among home gardens indicates that social networking and complementarity of production are important considerations for home garden owners to define species compositions. Diversity of mosaics thus emerges that builds on social relationships. This provides opportunities to further enhance diversity of local or regional home garden mosaics and the surrounding landscape, building on the exchange of planting material among home garden owners (Winkler-Prins and de Souza 2005). It is not desirable that all home gardens have the same species composition. Rather, it is desirable that together they contain a wide

range of species of sufficient population sizes, assuring durability and providing resources for associated diversity. Variation among home gardens in local and regional mosaics and the properties of the aggregate are important elements to consider in regional policies to conserve diversity (Sutherland et al. 2006; Goddard et al. 2009). Our results indicate that variation in home garden size contributes to the properties of the aggregate.

We conclude that the biosocial and bionumerical method highlight distinct types of diversity, and that they result in different values of diversity parameters such as species richness and Shannon diversity index. They are both useful, but for different purposes. The fixed sample size applied in the bionumerical method allows comparison of this diversity with other agroforestry systems and natural vegetation. This cannot be done readily on the basis of biosocial diversity, which indicates how much diversity individual families take care of. Our results further confirm the distinct role that home gardens of distinct sizes may play in regional conservation of (agro)biodiversity. Large home gardens have a crucial role to play to conserve rare species, whereas social networking allows access to and conservation of diversity beyond individual home gardens.

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