The Role of Agroforestry Systems in promoting healthy Diets: Insights from an Agricultural Frontier in Mexico

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Contents

Introduction Agroforestry systems are increasingly recognized for their potential to alleviate the adverse effects of deforestation in tropical landscapes while ensuring food security, carbon sequestration, nutrient cycling, biodiversity conservation, and integral provisioning services. However, limited attention has been given to understanding the impact that a diverse range of agroforestry systems can have on diets and fruit consumption. In this research we aim to shed light on the species composition of different agroforestry systems and their potential impact in promoting sustainable diets.

Methods Settled in the context of a fragmented, tropical agricultural frontier, we sampled across three communities and four categories of land-use. Species composition and vegetation parameters of 89 agricultural fields and 40 Home gardens (HG) were assessed using transect sampling and complete inventories, respectively. Based on intended purpose, the agricultural fields are discerned as maize fields (M), pastures (P), and newly planted agroforestry plots in accordance with the federal "*Sembrando Vida*"-program (SV). Alongside the plot-based sampling, a complete, daily dietary journal was filled out by 33 households to whom these fields pertain over a study period of 14 days.

Beyond describing differences in species composition and fruit tree abundance and -diversity across four land-uses, a general linear model is constructed to probe for relationships between the fruit species richness present on farmer's fields and their fruit consumption.

Results Throughout the four categories of land-use, I found 284 species belonging to 68 genera. Rarefaction consistently determines home gardens to be highest in regard to overall species diversity and a subset of fruit species diversity, followed by *SV*, P and M in descending order. Fruit tree density and percentage of fruit trees likewise descend accordingly. Using ordination techniques, species composition is found to be markedly different between HG and the rest, with some overlap between P and *SV* fields. Indicator species analysis finds a majority of fruit trees to be closely associated with HG.

Out of three different response variables tested, one generalized linear model found a significantly positive effect between the rarefied fruit species richness of agricultural fields other than HG and the fruit species consumed by that household. Fruit consumption expressed in portions and frequency were not explained by fruit tree species richness in neither HG nor the pooled fruit tree species richness of agricultural fields.

Discussion Limitations arise as the uneven sampling methodology employed in HG and the other land uses might cause an underestimation of the relative importance of the other land uses in regard to the provisioning of fruits from fruit trees.

1. Introduction

1.1 The complexity of tropical deforestation

Tropical forests play a paramount role in the global carbon cycle, acting as sinks in sequestering carbon from the atmosphere and storing it in aboveground biomass like no other ecosystem (*Pan et al.,* 2013; *Feliciano et al.,* 2018; *Suarez, D.*, 2021). 15 of the 25 identified hotspots for biodiversity conservation fall within tropical forests, as they boast an unparalleled wealth of endemic plant and animal species (*Myers et al.,* 2000).

The graveness of the problem is centered around the loss of ecosystem functioning at all scales (*Laurance, W.,* 1999). Climate regulation and water cycling are impaired, leading to uneven rainfall patterns amidst temperature extremes (*Lawrence et al.,* 2022; *Brandon, K.,* 2015). Fragmentation of forests leads to increased erosion and lowered flood amelioration. It is also causing the loss of connectivity between habitats, lowering the range and survival rates for seed dispersing animal populations (*Marsh, L.,* 2003).

Despite conservation efforts, tropical regions see ongoing and wide-scale deforestation due to complex land-use change dynamics (*Walker, R.,* 1993; *Geist & Lambin,* 2001; *Seymour & Harris,* 2019) with expected adverse effects on climate change mitigation, agricultural productivity, and biodiversity at large (*Vaca et al.,* 2012; *Lawrence & Vandecar*, 2015).

But the problem of tropical deforestation is not easily addressed, as the dynamics at play differ in each case. Geist and Lambin (2001) identified the proximate and underlying causes of deforestation in 152 case studies and found that deforestation is usually the result of a combination of factors. In 96% of the cases, however, agricultural expansion was identified to be the leading cause of deforestation, often paired with another driver.

Currently, conservation of tropical forests focusses on limiting the expansion of commercial agriculture for export markets and by promoting environmental stewardship and agency of local communities (*Rudel et al.,* 2009). But as economic incentives to pursue profitable activities like cattle ranching persist over those that are not, forest recovery is at risk (*Barbier et al.,* 2009).

1.2 Land-use change in the Lacandon rainforest

Described as a "*human-modified tropical landscape*" (*Arroyo-Rodríguez* et al. 2017; *Wies et al.,* 2021) or, highlighting its historical expansionism, a "*tropical agricultural frontier*" (*Carr, D.*, 2004), the larger region once covered by the Lacandon rainforest, in the southeastern Mexican state of Chiapas, lends itself as a case study for the aforementioned deforestation dynamics. Here, the establishment of the *Montes Azules* biosphere reserve in 1978 created a boundary to separate and spare a protected part of 331,200 hectares from expanding settlements and economic activity, now limited to the *Marques-de-Comillas* (*MdC*) and *Benemerito-de-las-Americas* regions situated southeast of the reserve. The settlements in the thinly populated region of *MdC* are formally organized as 37 "*Ejidos",* and their development since the arrival of the first settlers in the 1970's has coincided with a large-scale conversion of old-growth forests to agricultural land-uses such as maize fields for subsistence, pastures for cattle ranching and commercial plantations of oil palm or rubber (*Berget et al.,* 2021).

These far-reaching, anthropogenic changes have caused merely 37% of the original old-growth forest to remain in the two settled regions, and deforestation rates are outweighing annual regrowth (*Lohbeck et al.,* 2022). While the initial settlement between 1960 and 1985 saw wide scale clearing of the forests of southern Mexico, Bray and Klepeis (2005) find that this expansionism resulted in a multitude of possible pathways for secondary forest recovery and its extent. As farmers move away from shifting cultivation, vegetation is left thriving on abandoned fields, turning into secondary forest (*Lohbeck et al.,* 2022).

1.3 Agroforestry of present Marques de Comillas

Ubiquitous to tropical countries, home gardens form the backbone of social life in the communities of *MdC*. They are defined as a type of agroforestry, boast with a variety of carefully managed, multi-strata plants in the immediate surroundings of rural houses and provide the households that maintain them with a myriad of uses (*Aguilar-Støen* et al., 2009; *Eyzaguirre & Linares,* 2004; *Ordóñez Díaz*, 2018). Their value for food security is explained by their high productivity and diversity of edible plants (*Castañeda-Navarrete*, *J*. 2021; *Galhena et al.,* 2013; *Aguilar-Støen* et al., 2009; *Eyzaguirre & Linares* 2004; *Galluzzi* et al., 2010).

The different land-use categories outside of the communities make up the wider landscape mosaic in *MdC* and can each be regarded as a type of agroforestry system. Trees grow abundantly outside of forest patches on former and present agricultural fields, amounting to 11% of the total area (*Lohbeck* et al., 2022). Live fences around pastures, the occasional trees within them, riparian borders, and vegetation surrounding maize fields constitute examples.

Conservation efforts within the region are impacted by a multitude of tailored subsidy programs for farmers, launched over the last 30 years. With a recent addition that subsidizes the conversion of abandoned plots to a planned agroforestry system, recipients are to replant 2.5 hectares with a selection of timber and fruit-trees. The aim of the "*Sembrando Vida*" - program (sowing life) is to "reactivate the countryside" whilst relieving pressure from remaining forest. The program intends to increase forest cover, diversify livelihoods, enhance food security, and enrich diets with a diversity of locally produced fruit (*Pedraza López, J.,* 2020; *Avalos et al.,* 2020). Many households in *MdC* continue to benefit from such subsidies, and shape their lands according to them (*Berget, C.,* 2022).

1.4 Human nutrition in Mexico

At the same time, worldwide efforts are made to transition to a diet that is healthy and climate-proof. Studies show that marginalized populations in Latin America, the Caribbean, Western Asia and many African regions are most at risk to suffer from malnutrition, putting rural food security on top of the agenda (*FAO, IFAD, UNICEF WFP, WHO,* 2022).

Over decades, nutritional assessments in Mexico find marked contrasts between the rural and urban populations, the social classes, genders, and in relation to ethnicity (*Castellanos-Gutiérrez et al.,* 2021; *Backstrand et al.,* 1997; *Kaiser* & *Dewey,* 1991). Studies find an overconsumption of red meat, processed-, and sugary foods, and point out a lack of fruit and vegetables in the diet (*Castellanos-Gutiérrez et al.,* 2021; *Hervert-Hernández et al.,* 2011). These trends have led to the rise of food-related non-communicable diseases and obesity (*Riviera et al.,* 2002; *Romieu et al.,* 1997).

Given the environmental and health impacts of diets high in red meat (*Gonzaléz et al.,* 2020; *Clark et al.,* 2019), coming adaptations to the Mexican government's *Dietary Guidelines* ("*guias alimentarias*") are advised to take aspects of sustainability into account (*Castellanos-Gutiérrez et al.,* 2021). This is supported by an assessment that currently finds only 10,2% of the Mexican population to follow a sustainable diet, while another study shows that attaining a healthy and sustainable diet is not necessarily linked to higher costs, as the price of vegetables and fruits relative to staple foods is lower in the Mexican context, than in high-income countries (*Curi-Quinto et al.,* 2022; *Batis et al.,* 2021).

Increasing the variety of fruits and vegetables produced and consumed locally is therefore deemed as a straightforward way to boost healthy and sustainable diets in rural areas (*Hervert-Hernández et al.,* 2011; *McMullin et al.,* 2019).

1.7 Problem statement

For the most part, remote regions rely on food provisioning from local production but with a shift towards export agriculture, the variety and amounts of foods derived from subsistence agriculture may decrease (*Novotny et al.,* 2021). If increasing the fruit consumption of rural populations is needed to overcome malnutrition and ensure a healthy diet, the diversity and abundance of fruit trees present in subsistence farming are assumed to take on a pivoting role.

A variety of fruit trees needs to be managed so as to ensure a year-round provisioning of fruits (*McMullin et al.,* 2019). However, the extent to which existing agroforestry systems in *MdC* are suited to provide edible fruits from fruit trees remains to be studied.

Whether the presence of fruit-producing trees actually impacts the diets of smallholder farmers remains to be investigated. To date, no dietary assessment has been conducted in *MdC,* albeit the insights that this could provide on the importance of subsistence agriculture for fruit provisioning in the region, while highlighting the land-uses that contribute most to this end.

Existing studies of the region focus on the species diversity of remaining forest fragments rather than the trees present on agricultural fields (*Wies et al.,* 2021; *Navarrete-Segueda et al.,* 2017; *Hernández-Ruedas et al.,* 2014). Two exceptions look at tree density and species composition of pastures in the state of *Veracruz* and the coastal plains of Chiapas but don't investigate the importance of fruit trees (*Villanueva-Partida et al.,* 2016; *Otero-Arnaiz et al.,* 2006). There exists a wealth of studies on the tree-diversity of topical home gardens of Latin America, and these lend themselves for comparison (*Alcudia Aguilar et al.,* 2018; *Serrano-Ysunza et al.,* 2018; *Rayol et al.,* 2019; *Galluzzi et al.,* 2010). None of these studies have directly investigated the link between on-field tree diversity and fruit consumption, with one notable exception (*Castañeda-Navarrete,* 2021).

1.8 Study objective and research questions

The objectives of this research are twofold:

- to investigate how the different agroforestry systems relate to the provisioning of fruits, measured on-field as fruit tree abundance and -diversity and
- to discern the effect that the presence and abundance of fruit trees has on the local diet.

Further insights gained about the differences in tree density, stand-basal areas, and species compositions may allow for conclusions about the relative importance of each studied land-use category for reforestation efforts.

This thesis therefore aims to characterize edible-fruit-tree species and diversity across four different land-uses as well as assess the extent to which this affects household fruit consumption. This multidisciplinary approach will provide further insights into the relative importance of each managed land-use category in promoting a healthy diet reflected in fruit consumption.

This investigation is to answer the following research questions:

1. How do species composition, fruit tree diversity and -abundance differ between the 4 land-use categories?

While much of the preceding literature highlights the importance of home gardens for provisioning of fruits in the tropical smallholder context, the implications of the newly launched *Sembrando Vida* program for the same end remain to be examined. I expect to find marked differences in species composition, most fruit trees and -species in home gardens and *Sembrando Vida*-fields, less in maize fields and pastures.

2. To what extent is the household's fruit consumption reflected in the fruit species richness present on farms?

I expect those households with a higher fruit consumption, expressed in quantity, frequency, and diversity, to have more fruit trees and -species overall. The importance of home gardens for provisioning of fruits is expected to explain marked differences in fruit consumption between households that have home gardens that are species rich and those that are poor.

2. Methodology

2.1 Study sites and sample plot selection

Spanning a surface area of 909.3 km², the municipal region of *Marqués De Comillas* is situated at an altitude of 176-222m above sea-level between the Guatemalan borders of Mexico's south-eastern state of Chiapas and the protected *Montes Azules* national park. The tropical climate showcases a mean annual precipitation of 3000mm and annual mean temperature of 24°C. The dry period, defined as less than 100mm rainfall per month lasts from February to April (*van Breugel et al*., 2006).

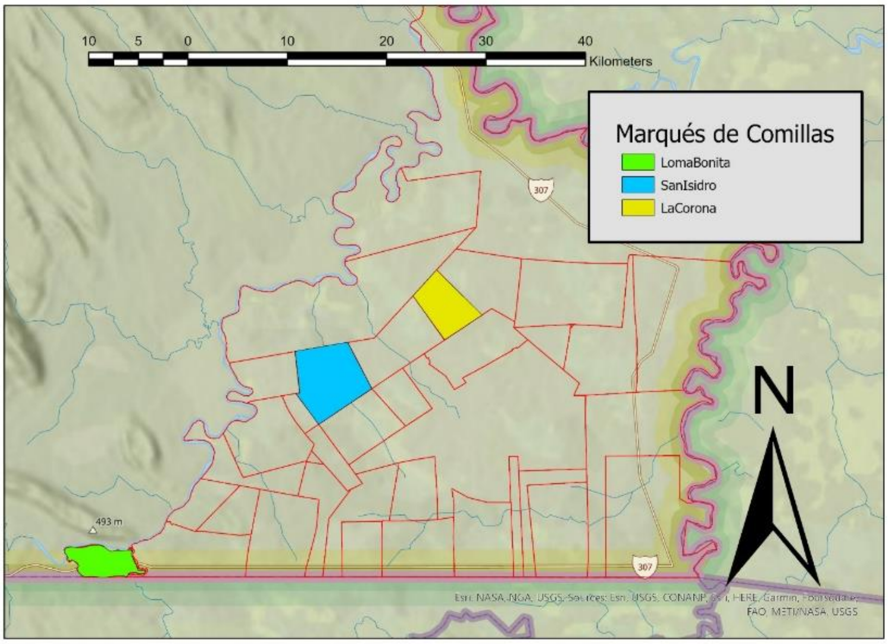

Figure 1: Map of the Marqués de Comillas and Benemerito de las Americas regions with the three study locations

MdC is characterized by a landscape-mosaic of different land-uses, as farmers in the region have adopted different livelihood strategies, mainly based around arable subsistence farming, and raising livestock (1).

Field work took place between July and October of 2022, on the fields pertaining to a selection of 45 households across three communities in *MdC*: *La Corona, San Isidro,* and *Loma Bonita (Figure 1).* The communities and their households were chosen in prior research conducted by Dr. Monica Borda-Niño and Dr. Natsuho Fujisawa Endo. The selection of the three communities was based on their "physical and cultural heterogeneity" (*Borda-Niño et al.,* work in progress). The physical variations are based on soil types, topology, distance to primary forests and rivers while ethnicity and place of origin of the settlers make for socio-cultural differences. These factors are thought to explain variation in structure and taxonomic composition of home gardens, the object of interest of their research. The households were approached at random within each community.

We went to the same households of the preceding visit a day prior to sampling and asked to accompany the farmer on their field visit. We asked which kinds of land-uses were present in the fields and tried to sample at least one field of every land use managed by the farmer. We only sampled fields that are currently in use and destined for agricultural production of goods that may also be consumed by the producing household. Hence excluding commercial plantations of oil palm and rubber. The following categories of land-use were sampled during our visit:

- The traditional *Milpa* cropping system for self-subsistence. These fields are cropped with a rotation of maize (*Zea maiz*), squash (*Cucurbita sp.)*, and beans (*Phaseolus vulgaris*). Nearly all households manage at least one such field.
- *Sembrando Vida* – fields, have recently been planted with timber- and fruit trees. Sometimes they are intercropped with maize between the tree rows. The products of this land-use category are not intended to be traded on the market in big quantities, but rather to remain within the community of the household.
- Cattle pastures. Fields that have been cleared and fenced in order for cows to graze on them. Some trees would remain on these fields or regrow from the seedbank. Especially edible fruit trees, trees with a big canopy for shade, and those growing around the perimeter (live fences) are retained or tolerated to grow.

Ethical considerations before and during the sampling period

Field work was announced to each community's leadership, and sampling was conducted only after receiving oral permission of each landowner. We took due precautions during sampling and while staying in the communities, so as to avoid causing disturbance to the people, animals, and plants. The study, with the insights gained from it, seeks to contribute to the betterment of agricultural policies in stimulating healthy diets, to the benefit of the rural populations of Mexico.

2.2 Tree inventories

To assess species composition of pastures, maize fields and *Sembrando Vida* – fields, I laid 4 meter wide transect lines, spanning between two diagonally opposite corners of each field. Species, genus, and diameter breast height (DBH) of every woody perennial encountered within the transects that had a DBH > 2.5 cm was noted.

The majority of tree species were identified on-site by their colloquial name. In case of doubts, local taxonomists were provided with a sample and pictures of the tree in question. If the taxonomists couldn't be consulted the same day, the sample of the tree was marked, photographed, and pressed in between layers of newspapers and sheets of carton before being left to dry.

Upon arrival at the field, one of its corners was marked using a handheld GPS-device (*Garmin GPSmap 64sx*) and approached from the diagonally opposite end. In case the corner was visible or unmissable due to a high tree or similar landmark behind it, this step was omitted. Multiple waypoints marked along the transect aided in navigating a straight transect line. Field surface area measurements relied on satellite imagery.

In all pastures, field boundaries were obvious due to fencing. Maize fields sometimes lacked this feature and so either the farmer marked the end of their field for us or the transect line was extended until vegetation became impassable. If the pastures were subdivided into multiple divisions, all divisions were measured, and the fields were treated as one. Field sizes of sampled plots were calculated using the logged GPS coordinates of field corners and visual assessment of the field's perimeter in *ArcGisPro*.

In the case of home gardens, 40 inventories of every woody perennial were carried out between February and March of 2022 by Dr. Monica Borda-Niño. Each plant with a diameter at breast height (DBH) > 2.5cm was assessed, noting growth type (*liana, shrub, tree, palm*-tree); taxonomic family and species.

There is an overlap between the households whose fields I sampled, that also had their home garden assessed in the prior field visit. This overlap amounts to 30 (of the 40 assessed home gardens) as in some cases, no agricultural fields were under cultivation beside the home garden.

Adding Home Gardens, the dataset comprises full inventories and transects of 129 fields across three regions (Table 1).

Land Use	La Corona	San Isidro	Loma Bonita	Overall
Pasture	11	11	13	35
Maize Field	8	7	9	24
Sembrando Vida	11	11	8	30
Home Garden	14	12	14	40
Total n	**44**	**41**	**44**	**129**

Table 1: number of sampled plots per land use and region

Maps of the sampled plots are attached in the appendix (*appendix* 6.1).

2.3 Fruit consumption

Data on dietary diversity of 33 households was collected by Dr. Natsuho Fujisawa-Endo and processed in my analysis. The participating households were asked to keep a diary for 9 days describing every consumed dish, its ingredients, and the source of the ingredient. The aim was to oversee the diversity of foods consumed and to identify their source, not to quantify caloric or nutritional intake. Therefore, intakes were recorded as portions without weighing or standardizing. Food intakes of any and every household member were reported by the eldest woman of the household. I received a filtered dataset on the fruit consumption of each of the approached households in the three communities.

The dataset distinguishes three variables in relation to fruit consumption of any and every member of the household:

- The total number of different fruit species that were consumed.
- The total counts of fruits consumed, without discerning between species. The number results from reported incidences of fruit consumption, as a snack or as ingredients to a meal.
- The number of days in which fruits were consumed (between 0 and 9 days).

The data collection of Dr. Natsuho Fujisawa-Endo discerns between the origin of the consumed item: whether it is bought, gifted by neighbors, or derived from the households' fields or home garden. For this analysis, only consumption of fruit that was derived from the farm's own fields was considered.

2.4 Edible and non-edible tree species

Recorded tree-, shrub-, and palm-species were categorized into edible- and non-edible, meaning that they bear fruit that is fit or unfit for human consumption. This is based on a collection of datasets compiled by *Segura et al.* (2018). In this context, the terms "fruit trees" or "fruit species", encompass the entirety of individuals or species that produce fruit that is edible and also generally consumed by the local population.

2.5 Quantification of species diversity

Species richness is assessed by counts of species per plot. As the study plots differ in size, rarefaction of the observed species richness to a common sampling effort needs to precede comparison, as observed species richness generally increases with greater sampling effort (*Chao et al.,* 2014).

The widely used *Shannon-Weiner* index was quantified using R's "*vegan"* – package. Shannon's index of diversity is also a measure of species evenness, as it considers the relative abundances of species (*Magurran*, *A.,* 1988):

Shannon-Weiner Index of Diversity: $H' = -\sum p_i \ln p_i$

where p_i represents the proportion of individuals found belonging to Species *i*.

The index can be transformed and displayed as effective number of species by calculating the exponent of *H´*, becoming a measure of species richness. I calculated *H'* using each species' summed basal area per plot, accounting for the greater biological significance of species represented in bigger individuals.

I quantified Shannon's exponent based on the summed relative basal area that each species covers of the total area covered by all trees in a given field.

Rarefaction curves were plotted using the *"iNEXT"*-package in *R*, discerning between land-uses for a subset of only the fruit species and for all species. This was done for species richness and species evenness. These were compared at common sampling efforts of 5000 and 2500 individuals.

2.6 Statistical methods

I answered my first research question (*How do species composition, fruit tree diversity and -abundance differ between the 4 land-use categories?*) in four steps:

1. Rarefied diversity indices were compared between the land uses. Using a nested design, I pooled the rarefied fruit species richness of all other land-uses within a farm and compared it to the level of fruit tree diversity of the farm's Home Garden. The Wilcoxon-signed rank test for paired data was used.
2. The land use with the highest fruit tree abundance was determined by testing the fruit tree density per hectare using a Kruskall-Wallis's test with *post-hoc* Dunn's test.
3. Species compositions were compared by means of a NMDS-plot (*Holland, S.,* 2008), using the "*ggplot2"* – package. A dissimilarity matrix was created using the "*vegdist*" function of the "*vegan"* package. Smaller ellipses represent high similarity in species composition between plots. A permutational multivariate analysis of variance (PERMANOVA) with 999 permutations was used to test for statistical significance of the visual differences in species composition's clusters using the "*adonis2*" function from the "*vegan*" package (*Anderson,* 2005).
4. Indicator species analysis (*Dufrene & Legendre,* 1997) is employed to test the relationship between specific species' abundance and the type of land-use management. For this, the R-package "*indicspecies"* is used. Indicator analysis assigns an indicator value to each species based on its relative abundance or occurrences throughout sites with predetermined grouping that results from environmental factors or treatment. The square root of the indicator value is the test statistic that is used in permutational testing to assure the significance of an association (*De Cáceres,* 2023).

To answer the second research question (*To what extent is the household's fruit consumption reflected in the fruit species richness present on farms?*), I constructed and compared three generalized linear mixed models (GLMM) to test the effect of fruit tree abundance and diversity on consumption variables.

The predictor variables are the rarefied fruit species richness of home gardens and that of fields besides the home garden. The response variables are derived from the dietary assessment (2.3). There are three response variables that I am testing:

1. As a measure of quantity, fruit consumption is assessed in portions.
2. As a measure of diversity, the dietary journal discerns between unique fruit species that have been consumed.

3. Finally, as a measure of frequency, the dataset lists the number of days that fruits appeared in the daily journal.

Differences in biophysical and socio-cultural characteristics between the three sampled regions may affect the number of fruit trees and -species present on the fields, as well as preferences in diet. I therefore include region as a potential random effect in the models.

Model selection

When plotting these response variables against the predictors (rarefied fruit species richness in home gardens and rarefied fruit species richness on other fields), no combination showed linear relationship, and therefore the choice of using a generalized linear mixed model (GLMM) was made.

Family and link function

Choice of family distribution was informed by the nature of each outcome variable. The Poisson family was chosen for the amount of fruit species consumed and the frequency of fruit consumption with a log link function as they constitute counts. The total amount of fruit consumed tested significantly positive for overdispersion, in which case the negative binomial family is suited.

To test for a potential random of the region, the goodness of fit of models including or excluding the random term is assessed using the Akaike-Information-criterion (*Akaike,* 1998).

3. Results

3.1 Overall species richness, abundant and rare species

In 129 fields, a total of 5838 individual trees were assessed. 3673 of these were measured in home gardens (n = 40), 1101 in *Sembrando Vida* fields (n = 30), 200 in Maize fields (n = 24), and 711 in Pastures (n = 35). Across home gardens, pastures, maize- and *Sembrando Vida* -fields, we found 283 different tree and palm species belonging to 66 families. 84 species produced fruit that is considered edible for humans. Of all the trees assessed, 195 could only be discerned to genus level, and were kept in the analysis as "[*genus*] *spp."*. Individual trees that could not be identified were excluded from the analysis. This reduction resulted in a dataset counting 5675 observations.

Over all three regions, the three most common species found in home gardens were the leguminous multi-purpose tree *Gliricidia sepium* (*Fabaceae*, n = 370), closely followed by *Musa spp.* (*Musaceae,* n = 327) and *Erythrina cf. americana* (*Fabaceae*, n = 242). In pastures, the most abundant were *Blepharidium guatemalense* (*Rubiaceae,* n = 122); *Vernonia Patens* (*Asteraceae,* n = 77); and *Byrsonima Crassifolia* (*Malpighiaceae*, n = 41*).* In maize fields the most encountered species was the palm-tree, *Sabal mauritiiformis* (*Arecaceae,* n = 34), followed by *Musa spp.* (*Musaceae,* n = 28) and *Gliricidia sepium* (*Leguminosae,* n = 12). In *Sembrando Vida* plantations, the two most planted trees are intended for timber supply: *Cedrela odorata* (*Meliaceae,* n = 135) and *Swietenia macrophylla* (*Meliaceae,* n = 120), while the third most abundant species was again *Musa spp.* (*Musaceae,* n = 102).

The assessment counts 84 singletons (species occurring only once) and 39 doubletons (species occurring twice). 198 species are represented by fewer than 10 individuals.

3.2 Differences in species diversity

Comparing extrapolated species richness between the land-uses (*figures* 2-5), home gardens stand out as the most species rich. Overall species richness (*figure* 2) of home gardens lies at (S_{5000} = 238.3), followed by pastures (S_{5000} = 137.3); *Sembrando Vida* -(S_{5000} = 118.5); and maize - fields (S_{5000} = 53). Species evenness, expressed through Shannon's exponent (*figure 3*), was highest in home gardens (H_{5000} = 53.6); and lesser in pastures (H_{5000} = 40.6); *Sembrando Vida-* (H_{5000} = 34.5); and maize - fields (H_{5000} = 26.4).

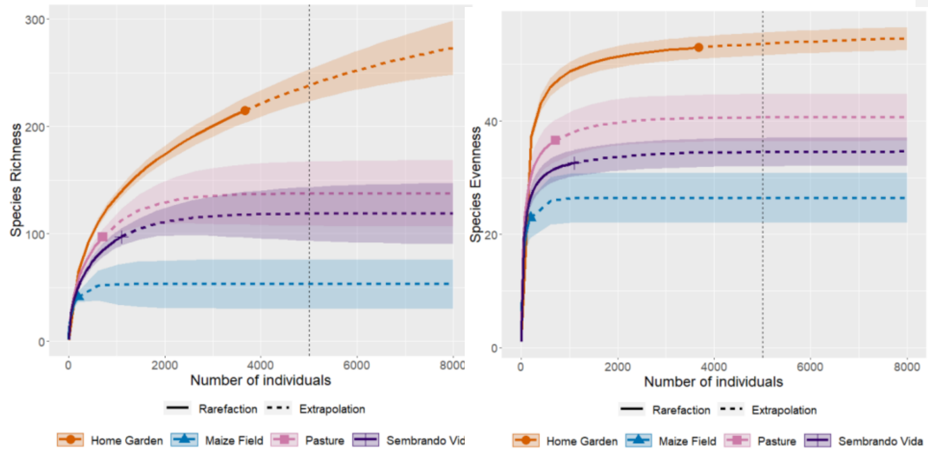

Figure 2 & 3: Extrapolated Species Richness (left) and Extrapolated Shannon's Exponent (right) across land-uses.

Figure 4 depicts how, at a sample size of 2500 individuals, most fruit tree species would be encountered in home gardens (SF_{2500} = 77.3); followed by *Sembrando Vida* (SF_{2500} = 41.3); pastures (SF_{2500} = 38.4); and maize fields (SF_{2500} = 19). Fruit tree species evenness across the land-uses is arranged in the same descending order (*figure 5*): home gardens (HF_{2500} = 26.4): *Sembrando Vida* (HF_{2500} = 15.3); pastures (HF_{2500} = 13.9); and maize fields (HF_{2500} = 10).

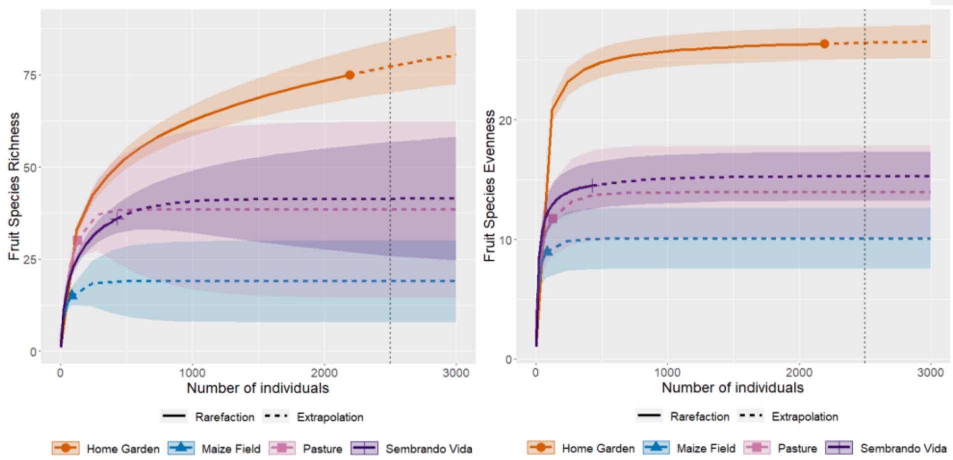

Figure 4 & 5: Extrapolated Species Richness (left) and Extrapolated Shannon's Exponent (right) of fruit-tree across land-uses.

The rarefaction curve for overall species richness of home gardens does not reach its asymptote at the cut-off point of 5000 individuals, and nearly does so for a sample of 2500 individuals in the subset, suggesting that the actual species richness is even higher for home gardens.

Home gardens contain the highest diversity of fruit tree species consistently throughout the three sampled regions (Wilcoxon-signed rank test, p = 1.639e-06).

3.3 Differences in fruit tree abundance

The average amount of fruit trees, calculated as the sum of fruit trees per farm divided by the number of farms, lies at 52.8 in home gardens; 10.4 in *Sembrando Vida* - fields; 3 in maize fields; and 2.49 in pastures. In terms of the percentage of trees that produced edible fruits, home gardens contained the most (60.4%); followed by *Sembrando Vida* - (33.8%); maize - fields (33.3%); and pastures (10%).

A table and two boxplots give oversight over the distributions of these variables in *appendix 6.2*.

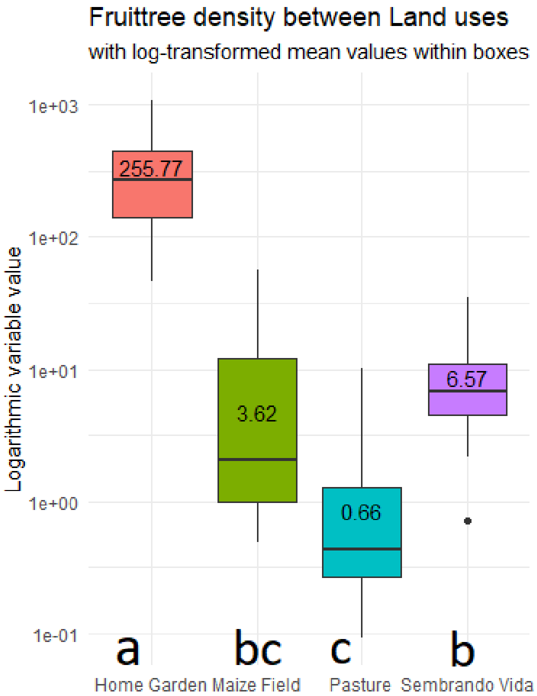

Figure 6: Differences in fruit tree density per ha between the land use categories, logarithmic scale.

In order to account for differences in the sampled field's sizes, the fruit tree density was calculated per hectare (*Appendix Table 1*). Home gardens have the highest fruit-tree density of 343 individuals per hectare when compared to other land-uses (8.24 in *Sembrando Vida*; 6.03 in maize fields; and 0.822 in pastures), that are statistically significant (Kruskal-Wallis, χ^2 = 97.322 p < 2.2e-16).

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This result is displayed in a boxplot with logarithmic adjustment to the data (*figure 6*). Lower case letters show which groups differed significantly from one another (post-hoc *Dunn's* test).

3.4 Species composition across land uses

Clustering of fields due to similar species composition within the generated NMDS-plot (*figure 8*) becomes apparent for Home Gardens and *Sembrando Vida* fields and less so for Pastures. Maize fields on the other hand, don't cluster together but spread across both axes, as a result of a higher dissimilarity in species composition between individual sampled fields. Given the highly diverse context, the probability of encountering a similar species composition decreases with the size of the subsamples and so the spread is an effect of the low number of individuals registered in Maize fields.

As a goodness-of-fit measure, the stress value of 0.21 ranks just above the intermediate range 0.0-0.2, indicating that the distances between the points displayed in the NMDS-plot sufficiently represent the dissimilarity of samples.

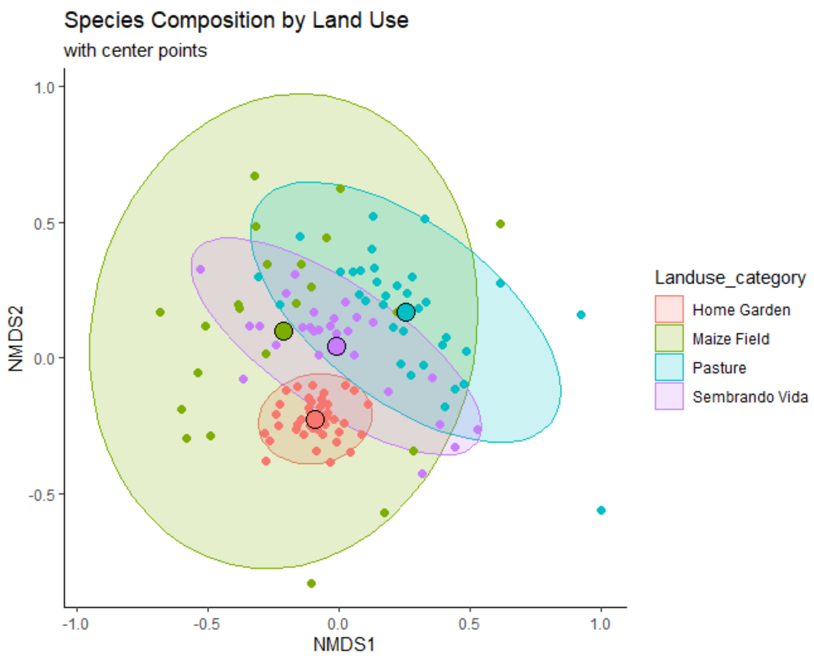


Figure 8: NMDS-plot of species compositions of the sampled land-uses

Results of the PERMANOVA show a p-value of 0.001, indicating a significant difference in species compositions between the land-uses. The R^2-value for the residuals lies at 0.648, meaning that about 35% of the variation in species compositions is explained by inherent differences of the land-use category. The R^2-value for residuals is lowered to 0.57 after exclusion of the highly heterogeneous Maize Fields.

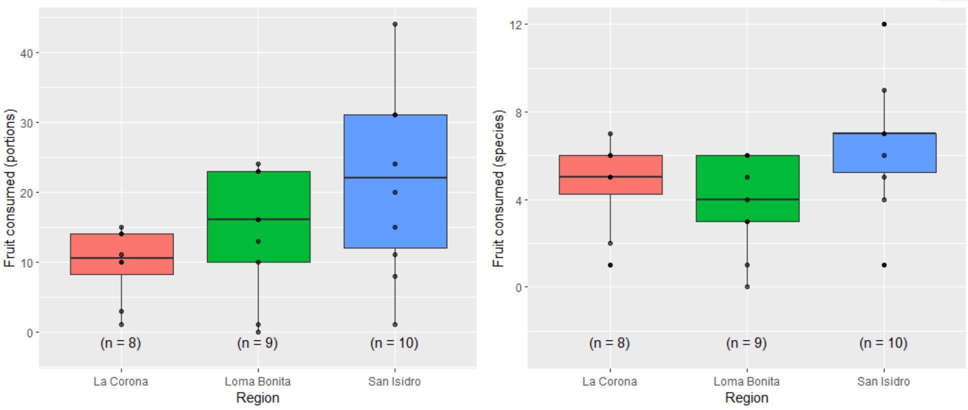
3.5 Indicator species analysis

Out of the 283 species, the analysis discerns 62 to be indicative of a land-use and 16 for a combination of land-uses. These are listed in the *appendix tables* 2 & 3 (*Appendix* 6.3). For home gardens, the ratio between edible and non-edible indicator species the ratio is highest as from the 50 indicator species discerned, 27 belong to the edible group. For *Sembrando Vida* - fields, 2 of the 7 indicator species are edible, in Pastures, none of the 6 indicator species are edible. No species are associated to maize fields alone, but there are species that are associated with a combination of maize fields and another land-use. In all three cases, the species are edible.

3.6 Model outcomes: linking fruit trees and diets

I found a positive effect of the pooled fruit species richness of agricultural fields (p = 0.002) on the amount of fruit species consumed during the study period. Surprisingly, there was no effect of the fruit species richness of home gardens on the amount of fruit species consumed. This means that the number of fruit species consumed during the study period was not affected by higher species richness within home gardens but was rather affected by the number of fruit species present within the agricultural fields.

Fruit species richness, both of home gardens and other land uses pooled, did not exert a significant effect neither on the number of fruit portions nor the frequency of fruit consumption during the study period. Exclusion of the random effect of region did not alter these outcomes in all cases. The following graphs show the distribution of the three response variables across the sampled communities.



Figures 9 & 10: Boxplots showing distributions of the response variables across the sampled communities.

Tables containing the statistical parameters of each of the three constructed models are represented in the appendix (*6.4 Model Outcomes*).

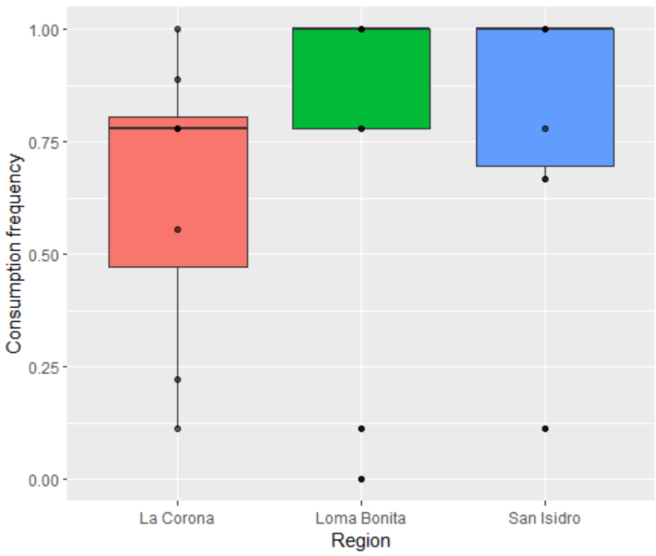


Figure 11: Frequency of fruit consumption

4. Discussion

The present study assesses the relative importance of each of the most prevalent agricultural land-uses within the region of *Marques de Comillas* for the provisioning of fruit to rural populations.

Based on the results, the hypothesis of expecting highest species diversity and most fruit provisioning trees in home gardens is accepted. This finding aligns with those of a plethora of previous studies on home garden biodiversity and its food provisioning potential (*Alcudia-Aguilar et al.,* 2018; *Rayol et al.,* 2019; *Eyzaguirre & Linares,* 2004; *Castañeda-Navarrete, J.,* 2021; *Serrano-Ysunza et al.,* 2018; *Galhena et al.,* 2013). Home gardens stand out as the most diverse, in both overall species richness and fruit tree species richness, but against my expectation, variation in HG fruit species richness did not significantly affect any of the proxies used to quantify fruit consumption.

While *Sembrando Vida* – fields contain second to most fruit trees measured in density and percentage, their main function lies in providing timber (3.1, appendix table 4, also *Ramírez-Jaramillo et al.,* 2021). *Sembrando-Vida* – fields have been initiated between 2019 and 2022 and the fruit trees on them have barely reached a stage of producing fruit. They have yet to provide substantially to the household's diet. *Sembrando Vida's* impact on improving rural diets remains an interesting question for future studies.

The fruits consumed during the study period could have been derived therefore from the home garden, the pastures, or the maize fields. The fruit species richness of other agricultural fields was indeed found to be a significant predictor for the amount of different fruit species consumed during the study period. But the model only probes for a relationship between on-field species richness and consumption and is less concerned with the origin of the consumed fruit. The wider literature on traditional agricultural practices in tropical areas describes present agroforestry systems in relation to their potential for subsistence. Persisting since pre-Columbian times (*Bray & Klepeis*, 2005), the *milpa* system consists of small-scale forest clearing for shifting cultivation of primarily maize, beans, and squash. Its impact on fruit consumption appears negligible at first, but Soto-Pinto et al. (2022) highlight that a variety of fruits is derived from these systems.

In two of the three communities, most households consumed fruit that was derived from their fields on a daily basis, constituting further evidence of a good provisioning of subsistence agriculture including home gardens (*Fernandez & Méndez*, 2018). The studied agroforestry systems are all recognized for their capability of provisioning of fruit (*Soto-Pinto et al.,* 2022).

The sampled fields subjected to the *Sembrando Vida* program present a markedly higher tree density than the other land-uses, equaling that of home gardens. Their value for reforestation, however, depends on a broader set of variables like scale, future management, native over commercial species, and can be drastically improved by linking remaining fragments of forest (*Cunningham et al.,* 2015). As the two most abundant species encountered in my assessment are used for timber production, mainly economic gains for managing households can be expected (*Ramírez-Jaramillo et al.,* 2021), in line with the stated goals of the program. The long-term provisioning benefits derived from these fields depend on continued commitment of the farmers, as the subsidy is planned to cease financial support for the farmers that implemented the scheme (*Gómez-Rodriguez et al.,* 2023).

Unequal cluster densities of the sampled fields within the NMDS plot represent the level of similarity of species composition between fields, but also emerge as patterns of sample size. While home gardens cluster together tightly in the ordination space, maize fields don't exhibit such a property. This effect is due to both the low number of sampled trees within maize fields and a high variability of species encountered across them. For the tight clustering of home gardens, I offer two possible explanations: due to the relatively small size of home gardens and their high density within the community, unsupervised seed dispersal between gardens is promoted, leading to increased regeneration and retention of the same species. Then, seed and plant exchanges within communities are common and constitute the second major factor.

Sembrando-Vida – fields have a more uniform species composition than pastures and exhibit tighter clustering. This may be due to the same origin of planting material for these fields: community-run nurseries that focus on a given set of species. In contrast, trees on pastures are either remnants of old-growth forests or naturally regenerating resprouts that stem from a highly diverse pool of species. In either case, they are tolerated by the farmer for a variety of reasons (*Vallejo et al.,* 2015; *Moore et al.,* 2020) with implications for regenerative and conservation potential of these fields (*Chomba et al.,* 2020; *Villanueva-Partida et al.,* 2016). Overlap between the clusters of *Sembrando Vida* – fields and pastures, speaks for the selection and retainment of similar tree species in either land-use. It indicates that in both land-uses, the same set of useful species are planted or purposefully retained. Overall, the purposeful retention of trees in tropical agroforestry systems also aims at the provisioning of fruit for consumption (*Vallejo et al.,* 2015), alongside a multitude of other provisioning services (*Navarrete-Segueda et al.,* 2017).

Socio-economic and -cultural factors play a big role in food choice (*Chen & Antonelli*, 2020). Personal preference of store-bought foods might then override the effect of a high fruit species richness within one's fields and be responsible for a low consumption of fruits albeit their abundance. The present diversity is in any case deemed as a precondition for securing healthier diets now and in the future (*Hervert-Hernández et al*., 2011).

Limitations of this study

Due to differences in the sampling methodology between the complete inventories of home gardens and the transect sampling of the other land uses, the actual fruit species richness and abundance must be underestimated, as entire vegetation clusters and the rare species within them have been missed during sampling. The differences in sample size between the land-uses are accounted for by rarefying to common sample sizes, but they do impact the amount of indicator species that are detected. This explains the high amount of indicator species found for home gardens.

Consumption patterns change throughout the year as different tree species provide fruit at different times of the year. This seasonality is potentially the main limiting factor in the attempt to adequately relate fruit consumption with on-field tree diversity. Furthermore, my analysis falls short of capturing the heterogeneity of households and livelihood strategies that might impact fruit consumption at a greater magnitude than on-field diversity could. For example, notable differences between the households that adopt a commercialist livelihood strategy versus those prioritizing subsistence exist in relation to self-sufficiency, food security, and dietary preferences (*Alayón-Gamboa* & *Gurri-García,* 2008).

Recommendations

In order to better assess the importance of home gardens against other land-uses for the consumption of fruits and capture the effect of seasonality, I propose a longitudinal approach for future studies. This entails a dietary assessment at different times of the year, such as the one conducted by Locke et al. (2009). Better yet would be participatory research that involves questions around fruit consumption, the trees present on the interviewed people's fields and the seasonal aspect.

The conceptualization of land-use policies, that aim to support and improve healthy diets through provisioning of fruits from fruit trees, can benefit from the insights gained from the present assessment. Future research can investigate the role that the *Sembrando Vida* program plays in this context and how livelihood strategies relate to self-sufficiency, as they evolve in the background of developing tropical agricultural frontiers.

5. Conclusion

In the shape of a biodiversity study, this research aimed to identify the land-use with the highest fruit tree abundance and diversity. Based on a quantitative assessment employing rarefaction and ordination techniques, the species composition of home gardens is confirmed to rank highest in fruit trees and fruit tree species. The results of this assessment fall in line with a multitude of studies that emphasize the contribution of home gardens to household food security in tropical regions, the novelty lies in the comparison with other fields managed by the same household.

In the shape of a dietary assessment, I tried to link results of the former approach to inform about the impact that a higher tree diversity has on the consumption of fruit to the unexpected result that agricultural fruit tree diversity may play a bigger role than that of home gardens.

To better understand the implications of this, future studies should consider a way to assess year-round fruit consumption, to isolate the effect of the season on fruit ripeness and availability. Ideally, such research employs methods of participatory research that includes the people’s perspective on fruit consumption.

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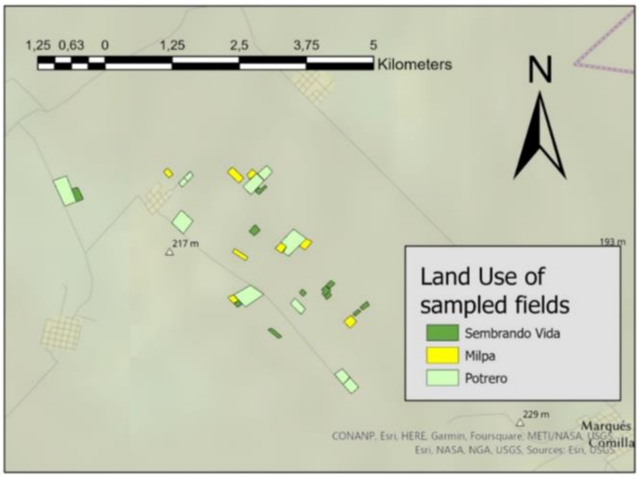
Field Code Changed

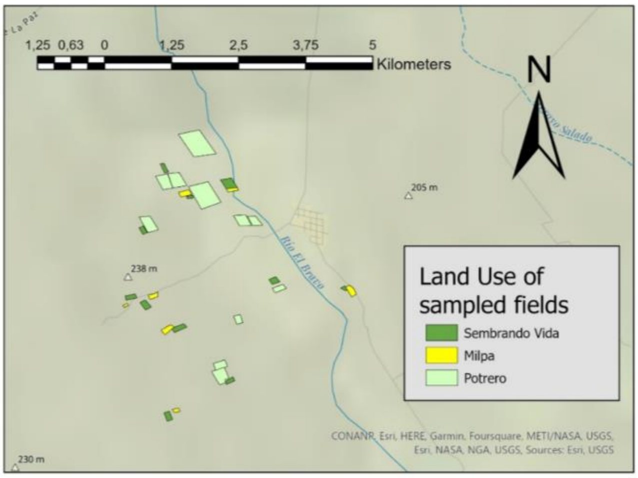
6. Appendix

6.1 Maps of the communities and study plots

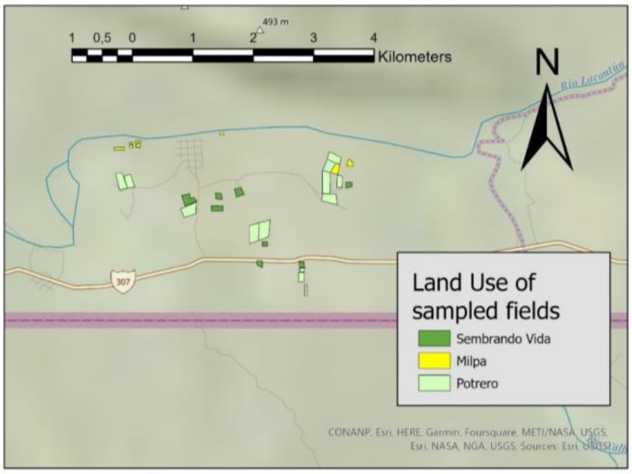
Across three communities, we sampled 89 fields belonging to 43 landowners. Among the fields there are 3 different land-use categories: pastures = “**Potreros”** (n = 35), maize fields = “**Milpa”** (n = 24), and ***Sembrando Vida***-fields (n = 30).



Appendix Figure 1: map of the sampled fields in La Corona



Appendix Figure 2: map of the sampled fields in San Isidro

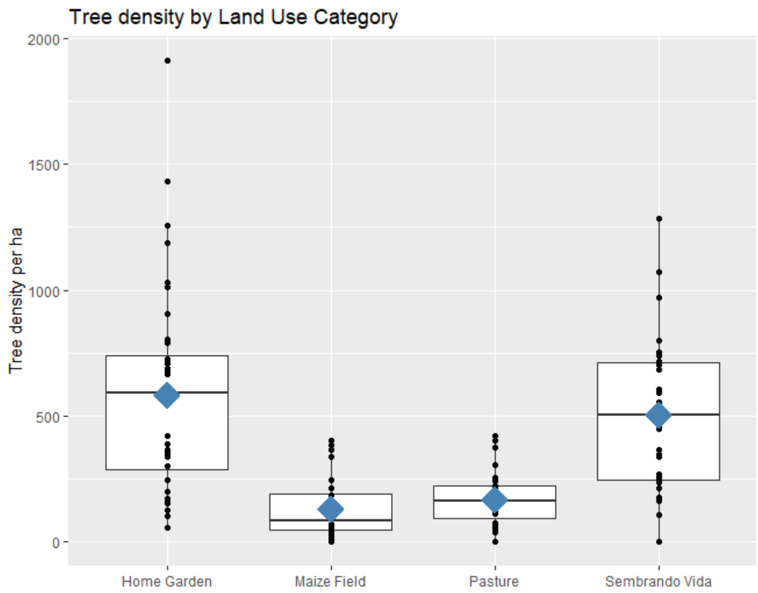


Appendix Figure 3: Map of the sampled fields in Loma Bonita

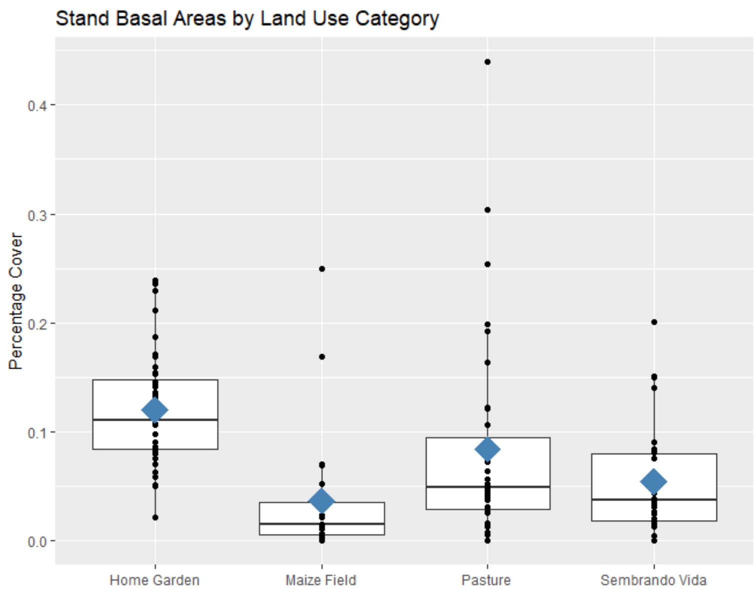
6.2 Distributions of Tree density and Stand Basal Area across land uses

	Home Garden (N=40)	Maize Field (N=24)	Pasture (N=35)	Sembrando Vida (N=30)	Overall (N=129)
Number of Fruit Trees					
Mean (SD)	52.8 (30.7)	3.00 (4.97)	2.49 (4.32)	10.4 (7.60)	20.0 (28.4)
Median [Min, Max]	52.5 [10.0, 154]	1.00 [0, 22.0]	1.00 [0, 20.0]	8.00 [0, 34.0]	8.00 [0, 154]
Percentage of Fruit Trees					
Mean (SD)	0.604 (0.185)	0.333 (0.402)	0.0998 (0.152)	0.338 (0.245)	0.355 (0.311)
Median [Min, Max]	0.613 [0.253, 0.953]	0.167 [0, 1.00]	0.0333 [0, 0.556]	0.251 [0, 0.818]	0.308 [0, 1.00]
Tree Density per hectare					
Mean (SD)	582 (402)	132 (126)	169 (103)	505 (311)	368 (342)
Median [Min, Max]	591 [57.1, 1910]	85.6 [0, 401]	161 [0, 420]	506 [0, 1290]	244 [0, 1910]
Fruit Tree Density per hectare					
Mean (SD)	343 (256)	6.03 (12.9)	0.822 (1.97)	8.24 (7.45)	110 (211)
Median [Min, Max]	270 [46.6, 1090]	0.837 [0, 56.3]	0.142 [0, 10.1]	5.74 [0, 35.2]	5.26 [0, 1090]

Appendix Table 1: Fruit tree abundance, -percentage, and - density across land-uses.



Appendix Figure 4: Tree density per hectare of the measured fields across land uses.



Appendix Figure 5: Percentage cover, based on summed tree basal areas and divided by the fields' size across the land uses.

6.3 Indicator species lists

Group	Species	Common Name	Edibility	Statistic	P.value	Code
Home Gardens	*Annona muricata*	Guanabana	1	0.907	0.005	**
	Mangifera indica	Mango	1	0.904	0.005	**
	Cocos nucifera	Coco	1	0.901	0.005	**
	Citrus x reticulata	Mandarina	1	0.88	0.005	**
	Gliricidia sepium	Cocohite	0	0.819	0.005	**
	Erythrina cf americana	Colorín	0	0.775	0.005	**
	Inga paterna	Vainillo	0	0.766	0.005	**
	Citrus x aurantium	Naranjo amargo	1	0.758	0.005	**
	Citrus x limon	Límon	1	0.672	0.005	**
	Manilkara zapota	Chicosapote, Mamey	1	0.643	0.005	**
	Theobroma cacao	Cacao	1	0.633	0.005	**
	Melicoccus spp.	Mamón	0	0.632	0.005	**
	Nephelium lappaceum	Rambutan	1	0.629	0.005	**
	Inga vera	Guatopillo	1	0.616	0.005	**
	Dracaena fragrans	Palo de agua	0	0.548	0.005	**
	Piper auritum	Hoja santa / de momo	1	0.548	0.005	**
	Eugenia capuli	Capulincillo	1	0.526	0.005	**
	Tamarindus indica	Tamarindo	1	0.526	0.005	**
	Annona reticulata	Chirimoya	1	0.524	0.005	**
	Spathodea campanulata	Tulipán	0	0.524	0.005	**
	Cordia alliodora	Bojón	0	0.521	0.005	**
	Leucaena leucocephala	Guajé	0	0.514	0.005	**
	Diospyros spp.	Kaki	1	0.5	0.005	**
	Spondias purpurea	Jobo	1	0.496	0.01	**
	Muntingia calabura	Capulín	1	0.489	0.005	**
	Luehea speciosa	Papachote	0	0.484	0.005	**
	Annona purpurea	Manirote	1	0.474	0.005	**
	Bauhinia divaricata	Pata de cabra / vaca	0	0.474	0.005	**
	Hibiscus rosasinensis	Flor de jamaica	1	0.474	0.005	**
	Tecoma stans	Árbol de San Pedro	0	0.474	0.01	**
	Parmentiera aculeata	Pepino	1	0.466	0.01	**
	Cnidoscolus multilobus	Mala mujer	1	0.447	0.01	**
	Ficus benjamina	Matapalo	0	0.418	0.005	**
	Lonchocarpus rugosus	Mata Buey	0	0.418	0.005	**
	Senna hayesiana	Barajo	0	0.418	0.01	**
	Terminalia catappa	Almendro	1	0.418	0.005	**
	Cinnamonum verum	Canela	1	0.4	0.005	**
	Cassia fistula	Guanacaste	0	0.387	0.005	**
	Calycophyllum candidissim	Madroño	0	0.387	0.015	*
	Artocarpus altilis	Fruta de pan	1	0.361	0.02	*
	Delonix regia	Flamboyán	0	0.354	0.01	**
	Guazuma ulmifolia	Guácima	0	0.354	0.01	**
	Plumeria rubra	Franchipán	0	0.354	0.005	**
	Callophyllum brasilense	Barí	0	0.337	0.045	*
	Averrhoa carambola	Carambola	1	0.316	0.04	*
	Brugmansia arborea	Trompetero	0	0.316	0.035	*
	Ficus cotinifolia	Amate	0	0.316	0.02	*
	Trichilia havanensis	*unknown*	0	0.316	0.035	*
	Trophis spp.	Lechillo	1	0.316	0.03	*
	Significance Codes	0 '***'; 0.001 '**'; 0.01 '*'; 0.05 '.'; 0.1 '				
	Edibility:	*0 = No*	*1 = Yes*			

Appendix Table 2: Indicator Species of home gardens

Group	Species	Common Name	Edibility	Statistic	P.Value	Code
Pastures	*Vernonia patens*	Bordon de vieja	0	0.542	0.005	**
	Coccoloba cozumelensis	Carnero	0	0.506	0.005	**
	Nectandra ambigens	Aguacatillo	0	0.411	0.01	**
	Virola koschnyi	Crementin	0	0.342	0.035	*
	Dalbergia glaura	Mataguai	0	0.297	0.03	*
	Platimicium yucatanum	Granadillo	0	0.297	0.03	*
Sembrando Vida						
	Swietenia macrophylla	Caoba	0	0.677	0.005	**
	Albizia leucocalyx	Guacibán	0	0.57	0.01	**
	Citrus x sinensis	Naranja	1	0.455	0.005	**
	Cojoba arborea	Frijolillo	0	0.411	0.01	**
	Solanum chrysotrichum	*unknown*	1	0.328	0.02	*
	Pachira aquatica	Palo de agua	0	0.284	0.045	*
	Zuelania guidonia	Volador	0	0.284	0.05	*
Pastures and Sembrando Vida						
	Blepharidium guatemalen	Popistle	0	0.658	0.005	**
	Schizolobium parahyba	Falso guanacaste	0	0.482	0.005	**
	Vatairea lundellii	Amargoso	0	0.407	0.03	*
	Zanthoxylum rhoifolium	Tachuelillo	0	0.38	0.045	*
	Inga pavoniana	Guamo	0	0.356	0.05	*
Pastures and Home Gardens						
	Byrsonima crassifolia	Nancé	1	0.66	0.005	**
	Psidium guajava	Guayava	1	0.613	0.005	**
Maize- and Sembrando Vida fields						
	Attalea butyracea	Coroso	1	0.446	0.025	*
	Manihot esculenta	Yuca	1	0.364	0.02	*
Sembrando Vida and Home Gardens						
	Cedrela odorata	Cedro	0	0.795	0.005	**
	Musa sp	Banana	1	0.758	0.005	**
	Bixea oreallana	Achiote	1	0.584	0.005	**
	Persea cf americana	Aguacate	1	0.469	0.035	*
Pastures, Sembrando Vida, Home Gardens						
	Tabebuia rosea	Maculís	0	0.665	0.015	*
	Bursera simaruba	Mulato	0	0.575	0.005	**
Maize-, Sembrando Vida Fields, Home Gardens						
	Carica papaya	Papaya	1	0.406	0.02	*
Significance codes:		0 ‘***’; 0.001 ‘**’; 0.01 ‘*’; 0.05 ‘.’; 0.1 ‘				
Edibility:	0 = No	1 = Yes				

Appendix Table 3: Indicator Species of other land-uses

6.4 Model Outcomes

	Fruit_Species_consumed		
Predictors	*Incidence Rate Ratios*	*CI*	*p*
(Intercept)	4.37	2.34 – 8.03	**<0.001**
RFruitSpecies Garden	1.00	0.99 – 1.02	0.584
RFruitSpecies other	1.03	1.01 – 1.05	**0.002**
Ejido	0.89	0.72 – 1.11	0.302
Observations	27		
R^2 Nagelkerke	0.378		

Appendix Figure 7: Model of Fruit Species Consumed

	Fruit_Portions_consumed		
Predictors	*Incidence Rate Ratios*	*CI*	*p*
(Intercept)	8.28	2.90 – 24.13	**<0.001**
RFruitSpecies Garden	1.00	0.98 – 1.03	0.813
RFruitSpecies other	1.03	1.00 – 1.07	0.086
Ejido	1.14	0.76 – 1.69	0.489
Observations	27		
R^2 Nagelkerke	0.193		

Appendix Figure 8: Model of Fruit Portions Consumed

	Frequency_of_Fruit_consumption		
Predictors	*Incidence Rate Ratios*	*CI*	*p*
(Intercept)	4.74	2.77 – 8.00	**<0.001**
RFruitSpecies Garden	1.01	0.99 – 1.02	0.360
RFruitSpecies other	1.01	0.99 – 1.03	0.290
Ejido	1.06	0.88 – 1.28	0.513
Observations	27		
R^2 Nagelkerke	0.093		

Appendix Figure 9: Model of Fruit consumption frequency: