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Higher agrobiodiversity is associated with improved dietary diversity, but not child anthropometric status, of Mayan Achí people of Guatemala

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Abstract
Objective: Child undernutrition remains one of the greatest challenges for public health nutrition in rural areas in developing countries. Interventions aiming to increase and conserve agrobiodiversity seem to be promising alternatives to improve child nutrition. However, the existing literature on these interventions is not conclusive about their effectiveness in combating child undernutrition. We tested the hypothesis that 'higher agrobiodiversity is associated with greater dietary diversity and better anthropometric status' in rural Guatemala.
Design/Setting/Subjects: In the summer of 2016, we conducted a cross-sectional study with a sample of 154 children (6–60 months). We conducted dietary recalls and structured interviews, measured children's weight and height, and visited food production systems (*Milpas*, home gardens, coffee plantations). Crop species richness, nutritional functional diversity, dietary diversity scores and anthropometric status were calculated.
Results: Higher food self-sufficiency, nutritional functional diversity and dietary diversity scores were positively correlated with higher crop and animal species richness. Contrarily, remoteness to the local market was negatively correlated with dietary diversity scores. However, higher dietary diversity scores were not correlated with better child anthropometric status. Better child anthropometric status was positively correlated with improved sanitary conditions and maternal education; and negatively correlated with large household size and frequent child morbidity.
Conclusions: Agricultural diversification could diversify diets, increase nutrient availability and improve child anthropometry. However, these interventions need to be accompanied by sanitation improvements, family planning, nutritional education and women's empowerment to strengthen their positive effect on diet and nutrition.

Keywords
Agrobiodiversity
Dietary diversity
Child nutrition
Nutrition-sensitive agriculture
Home gardens
Child morbidity

Child undernutrition remains one of the greatest challenges for public health nutrition in rural areas in developing countries. Stunting, which affects one out of four of the world's children under 5 years old[1], is about 1·5 times higher in rural areas than in urban areas[2]. In Guatemala, 46 % of children under 5 years are stunted, but it can reach up to 70 % in the poorest rural regions[3]. Agricultural interventions have been a common approach to improve food security[4,5] and, consequently, child nutrition. However, some of these interventions have had detrimental effects on the environment and human health[6,7]. Their intensive use of natural resources and chemical inputs have polluted, degraded and disturbed terrestrial ecosystems, reducing their resilience and sustainability. Also, their narrow focus on a limited range of starchy crops (e.g. wheat, rice, maize)[8–10] might have contributed to decreased agrobiodiversity[11,12] and increased micronutrient deficiencies[13,14]. Consequently, there is an urgent need for environmentally sustainable, nutrition-sensitive alternatives to these agricultural interventions.

In this regard, interventions focused on conservation and sustainable use of agrobiodiversity ‡ seem to be promising

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‡ In the present paper, we use the FAO's definition of 'agrobiodiversity', which comprises the variety of domesticated and wild plants and animals that is used for food and that supports agroecosystems[110].

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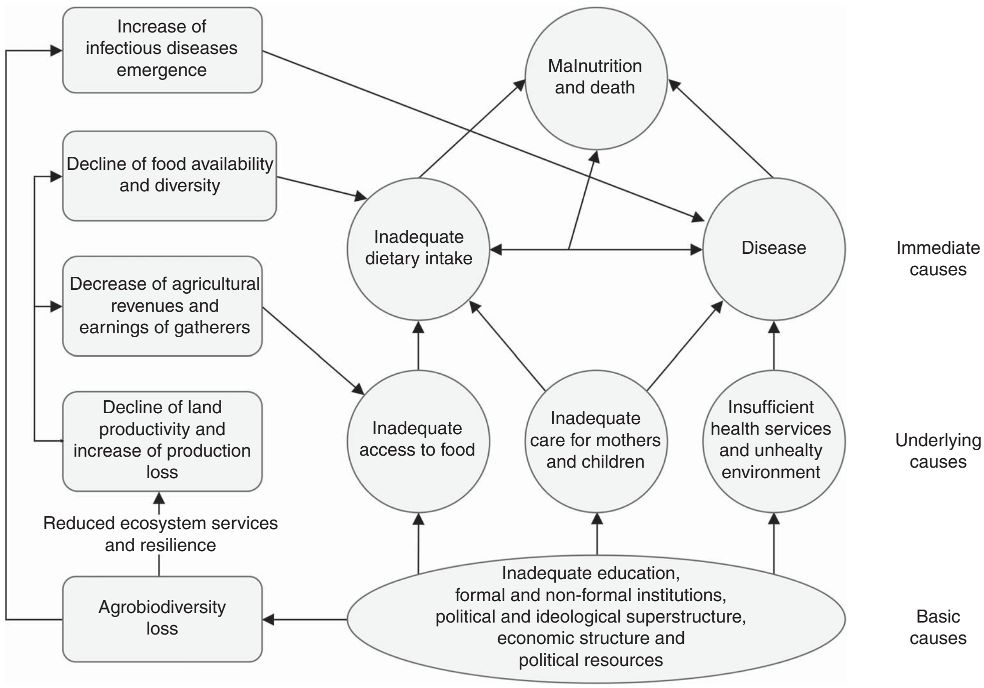

Fig. 1 Hypothetical relationship between agrobiodiversity degradation and causes of undernutrition (adapted from UNICEF[106])

alternatives to sustainably improve child nutrition[15–18]. These interventions account for diversified farming systems[19]; homestead food production, such as home gardens and small animal husbandry[20]; and conservation, utilization and marketing of neglected, underutilized species,* such as wild edible plants[21,22].† Nutrition is expected to be affected by these interventions through three main pathways (Fig. 1): (i) increasing availability of and accessibility to food types and dietary nutrients[23,24]; (ii) strengthening ecosystem functions and providing ecosystem services that could enhance the sustainability of farming systems[25,26]; and (iii) conserving genetic resources *in situ*/on-farm to enhance crops' nutritional content[27] or adaptability to climate change[28,29]. But, although the pathways are clear, the existing literature on these interventions is not conclusive about their effectiveness in combating child undernutrition[30–33].

Studies on the association among agrobiodiversity, diet and nutrition have delivered inconsistent results. Some scholars showed that cultivated agrobiodiversity can enhance food self-sufficiency[34–36] and food security[37–39], diversify diets and nutrient intakes[35,37,38,40–52] and increase agricultural revenues to purchase food[41,42,48,53,54]. However, other scholars found that it can negatively affect nutrition; cultivated agrobiodiversity can limit the available time for child care and feeding[55,56], offer lower yields and revenues than specialized agriculture[53] and increase child morbidity due to livestock ownership[57]. Moreover, evidence on wild agrobiodiversity showed that wild edible plants barely contributed to the daily nutrient requirements of farmers[58–60] (except for subsistence farmers[52]) despite wild edible plants' high micronutrient content[52,61,62]. In addition, the majority of the studies were carried out in Africa and Asia[30], neglecting America. Therefore, no conclusion could be drawn with respect to the effect of agrobiodiversity on nutrition from the existing studies. These inconsistencies expound the complexity of the association among agrobiodiversity, diet and nutrition[63] and call for a systematic, transdisciplinary approach[64].

We explored the relationship among agrobiodiversity, diet and nutrition using a food system framework and cross-disciplinary approach. We attempted to explore this relationship in Latin America, a neglected region in this subject of interest, combining methods from ethnobotany, ecology and nutritional science. Our framework correlates agrobiodiversity and child nutrition through dietary diversity, and explores the exogenous factors influencing the relationship, such as socio-economic status, ethnicity, agricultural extension services, maternal education and age, market distance, and land and livestock ownership (see Fig. 4). We hypothesized that higher agrobiodiversity is associated with a more diversified diet and better anthropometric status in rural Guatemala. This framework, although it does not attempt to be exclusive or complete, can be useful to systematically study this relationship in rural

* Species are denominated 'neglected and underutilized species' when the entire species or an edible part of it occupies low levels of utilization. For example, participants of the present study cultivated cassava, but they did not eat the leaves even though they are edible.

† 'Wild' does not mean the 'absence of human management as the plants can be cultivated, protected, tolerated or promoted without necessarily becoming a domesticated species'. Wild edible plants only means that plants are independent of human intervention for survival[111].

areas and evaluate nutrition-sensitive agricultural interventions.

Methods

Location and population

The study took place in a rural municipality in the department of Baja Verapaz in Guatemala. This municipality is characterized by a large Indigenous population of the Mayan Achí ethnic group, extensive traditional ecological knowledge[65], wide practice of subsistence agriculture and high rates of child undernutrition and poverty. The mean annual temperature is 22·39°C with a mean annual precipitation of 769 mm. Two seasons are reported by informants: a dry season, starting in November, when maize (*Zea mays* L.) is harvested; and a rainy season, beginning in May, when maize is planted.

Six villages in the highlands of the municipality were selected after considering ecological and geographical characteristics to ensure that the range of edible species produced in the villages does not vary. Altitude ranged between 1300 and 1800 m above sea level and supported subtropical wet and moist forest[66] on entisols and inceptisols according to US Department of Agriculture soil taxonomy[67]. In addition, the villages were located at increasing distance from the main market to test the association between remoteness to the market and dietary diversity[43].

The sample was composed of 154 randomly selected children aged 6–60 months and their 127 caregivers (e.g. mother, grandmother, aunt, sister), whom we refer to as 'mothers' in the present paper (Table 1). We used a sample size calculator[68] with a confidence level of 95 %, a total population size (n) of 260 children aged 6–60 months, a CI of 5 % and a population proportion of stunted children of 60 %[69]. Households were selected by convenience sampling due to the lack of demographic and cartographic data to randomize participants. Households with children were identified by a snowball sampling technique: asking people where children between 6 and 60 months of age lived.

Between March and July of 2016, face-to-face structured interviews were conducted to gather demographic and socio-economic information. The topics addressed were the following: demographic characteristics of the household (e.g. number of persons, level of education, age), agricultural practices (e.g. number of plots, edible species cultivated, agricultural inputs) and socio-economic information (e.g. housing conditions, assets ownership, sanitary conditions, income-generating activities). The last category helped to calculate the socio-economic status according to the method used by the Institute of Nutrition of Central America and Panama[70,71]. This method includes the following variables in the calculation: housing conditions, number of household members, economic activity of household head, assets ownership, and water, sanitation and hygiene (WASH).

We collaborated with a local non-governmental association* who approved our research and facilitated our access to the participants and local authorities. This association provides agricultural extension services and conducts nutrition-sensitive interventions based on the conservation of traditional ecological knowledge, utilization of native wild edible plants, and sustainable use of agrobiodiversity on home gardens and *Milpas*.† In addition, the study followed the International Society of Ethnobiology Code of Ethics to work with Indigenous people and biocultural diversity (traditional knowledge, biodiversity and cultural diversity)[72]. The objectives and procedures of the study were explained to all mothers and they provided verbal informed consent before the interview. We conducted the interviews in Spanish; no interpreter was needed.

Agrobiodiversity assessment

The crops cultivated by the participants were listed and identified to assess the agrobiodiversity status of the food systems.‡ During the interviews, the mothers recalled the crops cultivated for food, but edible plants used solely for medicinal purposes were omitted from the data organization. Then, during the visit to the participant's food systems (i.e. home gardens, *Milpas,* coffee plantations, tomato nurseries), we extended the list of cultivated crops, and we took plant pictures and specimens with the mothers' permission. Specimens were identified in collaboration with the herbarium staff at the University of San Carlos of Guatemala using dichotomous keys from the 'Flora of Guatemala'[73] and corroborating the latest accepted scientific names in *The Plant List*[74]. The correct taxonomic identification of species was essential to the present study because we calculated the nutritional functional diversity based on the features of each plant.

Three indicators of agrobiodiversity richness were calculated with the data gathered: (i) 'crop species richness' was determined by the number of edible crop species, both cultivated and wild, found in the participants' food systems; (ii) 'livestock ownership' was measured as the number of domestic animals bred for food by participants; and (iii) the 'nutritional functional diversity' (NFD) metric[75] was used to quantify the functions (i.e. dietary nutrients) provided to diet by the agrobiodiversity found in the participants' food systems[23,75,76]. The NFD metric was used as a proxy of nutritional diversity of the food systems. For instance,

* The names of the organization and villages have been deleted to preserve the anonymity of the participants.

† *Milpa* is a traditional system practised in Mesoamerica: intercropping of maize with beans, squash and other complementary crops, such as dark-green leafy vegetables (see Table 2).

‡ In the present paper, we use the term 'food system' to refer to any system where food can be produced, gathered or purchased, such as a farm, forest or market.

Table 1 Characteristics of the sample of Mayan Achí people (154 randomly selected children aged 6–60 months and their 127 caregivers) from six rural villages in Guatemala, March–July 2016

Characteristic	Village A		Village B		Village C		Village D		Village E		Village F		Total	
	Median or Mean	IQR or SD	Median or Mean	IQR or SD	Median or Mean	IQR or SD	Median or Mean	IQR or SD	Median or Mean	IQR or SD	Median or Mean	IQR or SD	Median or Mean	IQR or SD
Distance to market (km)*	6·8		8·2		9·5		10·2		13·4		15·2		–	
Altitude (masl)*	1345		1400		1610		1580		1750		1805		–	
Distance to nearest river (km)*	0·1		1·0		0·6		2·6		0·8		1·7		–	
Household characteristics														
No. of households	21		26		27		13		17		23		127	
No. of household members†	6·0	4·0	7·0	4·0	6·0	1·0	8·0	2·0	6·0	5·0	6·0	1·0	6·0	3·0
No. of children living in home†	1·0	1·0	2·0	1·0	2·0	1·0	2·0	1·0	1·0	1·0	2·0	1·0	2·0	1·0
SES‡	10·2	1·4	8·9	1·5	10·1	1·4	8·6	1·7	8·7	1·6	8·1	1·0	9·2	1·6
Safe sewage disposal (% yes)	4·3		0·0		7·4		9·1		11·8		4·3		6·0	
Access to water (% yes)	95·7		88·9		96·3		90·9		70·6		66·7		85·5	
Dirt floor (% yes)	56·5		83·3		63·0		45·5		58·8		81·0		65·8	
Access to electricity (% yes)	95·7		66·7		74·1		90·9		70·6		19·0		68·4	
Household head employment														
Farmer (%)	12·0		24·1		20·6		18·8		57·1		16·0		22·4	
Formal employment (%)	48·0		6·9		38·2		18·8		14·3		0·0		22·4	
Informal employment (%)	40·0		69·0		41·2		62·5		28·6		84·0		55·2	
Home garden ownership (% yes)	76·9		89·3		64·7		88·2		76·2		76·0		77·5	
Crop species richness in all systems (no. of edible crop species)†	15·0	8·0	17·0	7·0	13·5	9·0	16·0	13·0	17·0	10·0	13·0	8·0	15·0	8·0
Crop species richness in home gardens (no. of edible crop species)†	13·0	6·0	12·0	5·0	10·0	7·0	12·0	11·0	14·0	6·0	10·0	7·0	12·0	7·0
QA beneficiary (% yes)	7·7		96·2		11·8		68·4		85·7		20·7		50·4	
Child characteristics														
No. of children	26		29		34		19		21		25		154	
No. of children aged <24 months	14		11		13		9		7		4		58	
Age of child (months)†	23·0	15·0	33·0	32·0	28·0	30·0	30·0	31·0	28·0	27·0	35·0	18·0	29·0	26·0
Sex (% male)	50·0		27·6		55·9		36·8		52·4		48·0		45·5	
Mayan Achí (% yes)	100·0		96·6		82·4		100·0		90·5		32·0		83·12	
Morbidity in the last month (% yes)	63·6		100·0		84·6		100·0		38·9		50·0		67·1	
IYCDDS of children aged <24 months (no. of food groups/d)†	4·2	1·0	4·0	1·5	4·5	1·0	4·0	2·0	5·0	1·5	5·0	0·7	4·5	1·0
IDDS of children aged ≥24 months (no. of food groups/d)†	4·0	1·0	4·0	0·6	4·0	1·0	5·0	2·2	5·0	0·5	4·5	1·0	4·2	1·0
Stunting (%)														
Moderate	26·9		44·8		44·1		42·1		28·6		44·0		39·0	
Severe	19·2		27·6		8·8		31·6		14·3		32·0		21·4	
Underweight (%)														
Moderate	11·5		13·8		17·6		21·1		28·6		24·0		18·8	
Severe	0·0		3·4		0·0		0·0		0·0		0·0		0·6	
Maternal characteristics														
Primary caregiver education (years)†	7·0	4·0	6·0	3·0	4·0	3·0	1·0	3·0	3·0	4·0	3·0	4·0	4·0	4·0
Primary caregiver literacy (% no)	7·7		20·7		15·2		50·0		14·3		25·0		20·5	
Primary caregiver age (years)†	23·0	8·0	22·0	16·0	26·0	13·0	36·0	15·0	26·0	17·0	28·0	8·0	27·0	14·0

IQR, interquartile range; masl, metres above sea level; QA, agricultural extension services promoting home gardening and agroecology; SES, socio-economic status; IYCDDS, infant and young child dietary diversity score; IDDS, individual dietary diversity score.
*Characteristics measured at and from the village school (point of reference).
†Data presented as median and IQR.
‡Data presented as mean and SD.

systems comprising crops with similar nutritional values (e.g. maize, banana and potato) would have a lower NFD score than systems with the same number of crops but with different nutritional values (e.g. maize, beans and amaranth leaves).

The NFD scores were calculated using the nutritional values of the crops identified in the participants' food systems. The nutrient values were gathered from two food composition databases, those of the Institute of Nutrition of Central America and Panama[77] and the US Department of Agriculture[78], where data are presented per 100 g edible portion of food. Macronutrients (protein, fat, carbohydrate, fibre), minerals (Ca, P, Fe, Zn, Mg) and vitamins (thiamin, riboflavin, niacin, vitamin C, vitamin A, folate) content of the identified crops were gathered and used for the calculation of the NFD scores. These nutrient content values depended on the part of the crop utilized by the participants (e.g. both amaranth grain and leaves were included), the condition of the crop when consumed (e.g. mango was included twice because it is consumed in its green and ripe form), the preparation of the food (e.g. raw *v.* cooked) and the species variety cultivated (e.g. red, white and black beans). The data were entered as percentage of the RDA of a male adult[79]. The NFD scores reported are percentages of the potential NFD, when all the crops available in the municipality are included in one hypothetical parcel.

Child dietary assessment

The children diets were assessed using 24 h recalls and by estimating dietary diversity scores. The mothers were asked to recall their child's food intake during the previous two days; if the child's diet of one of those days was atypical (due to festivities or visits to town or friends), another day was recalled. The foods recalled were classified into the sixteen food groups[80] of the Food and Nutrition Technical Assistance Project (Table 2) and, then, the food groups were used to calculate the dietary diversity scores. The infant and young child dietary diversity score (IYCDDS)[81] was calculated for children aged 6–23 months using seven food categories, while the individual dietary diversity score (IDDS)[82] was calculated for children aged 24–60 months using nine food categories (Table 2). Moreover, the mothers were asked whether the foods consumed were self-produced, gathered in the forest or on the shore of the river, purchased, gifted, borrowed or provided as food aid.

Child anthropometric assessment

Anthropometric measures were conducted to determine the nutritional status of child participants. The weight of all children was measured using a digital scale (Tecnipesa, Guatemala); the length of the children aged 6–23 months and the height of the children aged 24–60 months were measured with a wooden stadiometer. Measurements were taken in collaboration with participating local nutritionists trained in anthropometric assessment. Height/length-for-age *Z*-score (HAZ), weight-for-age *Z*-score (WAZ) and weight-for-height/length *Z*-score (WHZ) were determined using the WHO Anthro macros[83] in R version 3.4.2. The children with HAZ $< -2{\cdot}0$ were categorized as stunted, children with WAZ $< -2{\cdot}0$ were categorized as underweight and children with WHZ $< -2{\cdot}0$ were categorized as wasted.

Statistical analysis

Correlations and comparison of groups were run on the collected data. The normality of the data was always checked using graphical and numerical methods. Spearman (r^{s}) and Pearson (r^{P}) correlations were used to quantify and determine the direction of the association between two variables, such as agrobiodiversity and dietary diversity scores. The *t* test and Mann–Whitney *U* test were used to compare two unpaired groups, such as Mayan Achí people and Ladino people (non-Indigenous). All data were analysed using R version 3.4.2 and the statistical software package IBM SPSS Statistics version 24.0.

Results

Agrobiodiversity

The participants' food systems were rich in agrobiodiversity. Five different systems supplied food to the participants; listed in decreasing order of crop species richness, they are: (i) the market, (ii) home gardens, (iii) *Milpas*, (iv) forest and river banks, and (v) coffee plantations and tomato nurseries (Fig. 2). These systems collectively contained ninety-two crop species; forty-two species were native to Mesoamerica and twenty-one were wild edible plants. The richest system in cultivated biodiversity, a home garden, contained twenty-eight edible species, the richest *Milpa* contained six species and the richest coffee plantation contained four species; all the tomato nurseries were monocultures. The ten most commonly cultivated crops were the following: (i) banana (*Musa × paradisiaca* L.); (ii) American black nightshade (*Solanum americanum* Mill.); (iii) peach (*Prunus persica* (L.) Batsch); (iv) maize (*Z. mays* L.); (v) coriander (*Coriandrum sativum* L.); (vi) amaranth (*Amaranthus* spp.); (vii) radish (*Raphanus raphanistrum* subsp. *sativus* (L.) Domin); (viii) coffee (*Coffea arabica* L.); (ix) orange (*Citrus sinensis* (L.) Osbeck); and (x) avocado (*Persea americana* Mill.).

The market was the richest food system in agrobiodiversity. The market was open all week long, but the main market days were Thursday and Sunday. On these days, farmers from different geographic regions took their produce to the market to sell it; thus, consumers could purchase a wide diversity of foods coming from the municipality villages (e.g. coffee from the highlands and tamarind from the lowlands), other regions of Guatemala (e.g. pineapple (*Ananas comosus* (L.) Merr.) and cantaloupe (*Cucumis melo* var. *cantalupo* Ser.)) or other

Table 2 Classification of crops cultivated in the municipality according to the IYCDDS and IDDS food groups

Food group (FANTA)	Food group (IYCCDDS[107])	Food group (IDDS[82])	Food and drink items
1. Cereals	Grains, roots and tubers	Starchy staples	**Amaranth** [grain] (*Amaranthus* spp.)*, **Maize** [dry; red, white, yellow] (*Zea mays* L.) {atol, pinol, tamal, tortilla}, **Oats** (*Avena sativa* L.) {horchata, mosh}†, **Rice** (*Oryza sativa* L.) {arroz con leche, horchata}†, **Wheat** (*Triticum aestivum* L.) {atol, bread, chomin, pasta}†
2. White roots and tubers	Grains, roots and tubers	Starchy staples	**Cassava** (*Manihot esculenta* Crantz), **Plantains** (*Musa × paradisiaca* L.), **Potatoes** (*Solanum tuberosum* L.)†, **Sweet potato** [red, purple, white] (*Ipomoea batatas* (L.) Lam.)†, **Taro** (*Colocasia esculenta* (L.) Schott)
3. Vitamin-A rich vegetables and tubers	Vitamin A-rich fruits and vegetables	Dark green leafy vegetables	**Carrot** (*Daucus carota* L.), **Pumpkin** [flower, orange and dark yellow flesh] (*Cucurbita pepo* L.), **Red pepper** [sweet] (*Capsicum annuum* L.)†, **Squash** [flower, orange and dark yellow flesh] (*Cucurbita* spp.), **Sweet potato** [orange or dark orange] (*Ipomoea batatas* (L.) Lam.)†
4. Dark-green leafy vegetables	Vitamin A-rich fruits and vegetables	Other vitamin A-rich fruits and vegetables	**Amaranth** [greens] (*Amaranthus* spp.)*, **American black nightshade** (*Solanum americanum* Mill.) {macuy, hierbamora}*, **Beet greens** (*Beta vulgaris* L.), **Broccoli** (*Brassica cretica* Lam.)†, **Chard** (*Beta vulgaris* L.), **Chipilín** (*Crotalaria longirostrata* Hook. & Arn.)*, **Coriander** (*Coriandrum sativum* L.), **Lettuce** [dark] (*Lactuca sativa* L.), **Mustard greens** (*Brassica rapa* L.), **Onion** [stalk] (*Allium cepa*), **Pumpkin** [leaves and vine shoot] (*Cucurbita pepo* L.)‡, **Purslane** (*Portulaca oleracea* L.)*, **Radish greens** (*Raphanus raphanistrum* subsp. *sativus* (L.) Domin)‡, **Squash** [leaves and vine shoot] (*Cucurbita* spp.)
5. Other vegetables	Other fruits and vegetables	Other fruits and vegetables	**Beans** [fresh pods] (*Phaseolus vulgaris* L.), **Beets** (*Beta vulgaris* L.), **Cabbage** (*Brassica oleracea* L.), **Cauliflower** (*Brassica cretica* Lam.)†, **Chayote** [fruit and vine shoot] (*Sechium edule* (Jacq.) Sw.)‡, **Chilacayote** (*Cucurbita ficifolia* Bouché), **Cucumber** (*Cucumis sativus* L.), **Flor de izote** (*Yucca gigantean* Lem.)*, **Flor de pito** (*Erythrina berteroana* Urb.)*, **Green pepper** [sweet] (*Capsicum annuum* L.)†, **Maize** [fresh] (*Zea mays* L.), **Onion** (*Allium cepa*), **Pacaya** (*Chamaedorea tepejilote* Liebm.)*, **Radish** (*Raphanus raphanistrum* subsp. *sativus* (L.) Domin), **Squash** [unriped] (*Cucurbita* spp.), **Tomato** (*Lycopersicon esculentum* Mill.), **Zucchini** [unriped] (*Cucurbita pepo* L.)
6. Vitamin-A rich fruits	Vitamin A-rich fruits and vegetables	Other vitamin A-rich fruits and vegetables	**Cantaloupe melon** (*Cucumis melo* L.)†, **Hog plum** (*Spondias purpurea* L.)*, **Loquat** (*Eriobotrya japonica* (Thunb.) Lindl.), **Mango** [ripe] (*Mangifera indica L.*), **Papaya** [ripe] (*Carica papaya* L.)
7. Other fruits	Other fruits and vegetables	Other fruits and vegetables	**Apple** (*Malus pumila* Mill.)†, **Avocado** (*Persea americana* Mill.), **Banana** (*Musa × paradisiaca* L.), **Berries** (*Morus alba* L. and *Rubus coriifolius* Liebm.)*, **Cashew nut fruit** (*Anacardium occidentale* L.), **Coconut** [flesh] (*Cocos nucifera* L.), **Custard-apple** (*Annona reticulata* L.)*, **Figs** (*Ficus carica* L.), **Guava** (*Psidium guajava*)*, **Lemon** (*Citrus limon* (L.) Osbeck), **Lime** (*Citrus medica* L.), **Machetón and Paterna** (*Inga edulis* Mart.)*, **Mamey sapote** (*Pouteria sapota* (Jacq.) H.E. Moore & Stearn)*, **Mango** [unripe] (*Mangifera indica L.*), **Matasano** (*Casimiroa edulis* La Llave), **Nance** (*Byrsonima crassifolia* (L.) Kunth), **Orange** (*Citrus sinensis* (L.) Osbeck), **Peach** (*Prunus persica* (L.) Batsch), **Pear** (*Pyrus communis* L.)†, **Pineapple** (*Ananas comosus* (L.) Merr.), **Pomegranate** (*Punica granatum* L.)†, **Sapodella** (*Manilkara zapota* (L.) P. Royen)*, **Soursop** (*Annona muricata* L.), **Strawberry** (*Fragaria sp.*)†, **Sunza** (*Licania platypus* (Hemsl.) Fritsch), **Sweet granadilla** (*Passiflora ligularis* Juss.)*, **Tamarind** (*Tamarindus indica* L.), **Tangerine** (*Citrus reticulata*), **Watermelon** (*Citrullus lanatus* (Thunb.) Matsum. & Nakai)
8. Organ meat	Flesh foods	Organ meat	Gizzard, Heart, Kidney, Liver, Stomach
9. Flesh meats	Flesh foods	Meat and fish	Beef, Chicken, Duck, Goat, Pork, Rabbit, Turkey
10. Eggs	Eggs	Eggs	Chicken eggs, Duck eggs
11. Fish and seafood	Flesh foods	Meat and fish	Canned fish {tuna, sardines}, Fresh or dried fish
12. Legumes, nuts and seeds	Legumes and nuts	Legumes, nuts and seeds	**Cashew nut** (*Anacardium occidentale* L.), **Common beans** [dry; black, red, white] (*Phaseolus vulgaris* L.), **Lentils** (*Lens culinaris*)†, **Peanut** (*Arachis hypogaea* L.)†, **Pigeon pea** (*Cajanus cajan* (L.) Millsp.), **Pumpkin seeds** (*Cucurbita* spp.), **Sesame seeds** (*Sesamum indicum* L.)†, **Soya bean** (*Glycine max*) {texturized soya protein}†
13. Milk and milk products	Dairy products	Milk and milk products	Cheese, Milk, Ricotta
14. Oils and fats	NA	NA	Butter, Cream, Lard, Margarine, Mayonnaise, Vegetable oils {canola, maize, African palm, other}
15. Sweets	NA	NA	Biscuits [sweet], Candies, Cookies, Honey, Jam, Juice drinks, **Sugarcane** (*Saccharum officinarum* L.) {panela, sugar}, Soda, Any other sweets
16. Spices, condiments and beverages	NA	NA	**Allspice** (*Pimienta dioica* (L.) Merr)†, **Annatto** (*Bixa orellana* L.), **Apazote** (*Dysphania ambrosioides* (L.) Mosyakin & Clemants)*, **Basil** (*Ocimum basilicum* L., *Ocimum campechianum* Mill.), Broth cubes {beef, chicken, vegetables}, **Celery** (*Apium graveolens* L.), **Chadon beni** (*Eryngium foetidum* L.)*, **Chilli** [dry and fresh] (*Capsicum annuum* L.), **Cinnamon** (*Cinnamomum verum* J. Presl)†, **Cocoa** (*Theobroma bicolor* Humb. & Bonpl.)†, **Coffee** (*Coffea arabica* L.), **Comino** (*Pectis uniaristata* DC. var. holostemma A. Gray)†, **Coriander** (*Coriandrum sativum* L.), **Garlic** (*Allium sativum* L.), **Hibiscus** (*Hibiscus sabdariffa* L.), **Miltomate** (*Physalis philadelphica* Lam.)*, **Mint** (*Mentha × piperita* L.), **Oregano** (*Origanum vulgare* L.), **Parsley** (*Petroselinum crispum* (Mill.) Fuss), **Rosemary** (*Rosmarinus officinalis* L.), Salt, Soya sauce, **Tea** (*Camellia sinensis* (L.) Kuntze)†

IYCDDS, infant and young child dietary diversity score; IDDS, individual dietary diversity score; FANTA, Food and Nutrition Technical Assistance Project; NA, not applicable.
The food group 'Spices, condiments and beverages' included foods used in very small quantities as seasoning; hence, some foods (e.g. carrots, red pepper and coriander) were categorized into this and another group because the quantity consumed depended on the preparation of the dish.
Crop name [part or condition of the crop consumed] (scientific name of crop, identified with plant specimens)[73,74] {local common names for crops}. Names are underlined when they are native to Mesoamerica[108,109].
*Wild edible plants.
†Crops that were not identified with plant specimens, but using pictures[73].
‡Neglected underutilized species.

countries (e.g. mangoes from Mexico). A substantial proportion of the sellers and consumers observed in the market were women who bought, sold and exchanged food.

Cultivated agrobiodiversity was not associated with the remoteness to the market. The price of public transportation to the market increased with the distance travelled. Consequently, a greater distance to the market was negatively correlated to the frequency of visits to it ($r^{s}_{(153)} = -0{\cdot}25$, $P < 0{\cdot}01$). Hence, it was expected that participants living far from the highly food-diverse market were more likely to cultivate higher agrobiodiversity in their own food system to increase food self-sufficiency and to compensate for the infrequent visits to the market. However, agrobiodiversity richness did not increase with the distance to the market. On the contrary, Village A, the closest village to the market, was more biodiverse than further villages, probably because the former was nearer to the river used for irrigation than the latter. Likewise, Village F, the remotest village to the market, showed the lowest cultivated agrobiodiversity, probably because the population of Village F was composed mainly of Ladino people; thus, their traditional ecological knowledge was smaller than other villages with more Mayan Achí people (e.g. Village A and Village E).

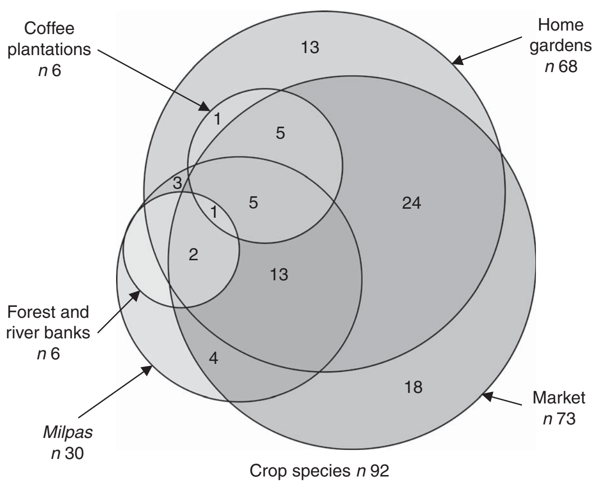

Fig. 2 Venn diagram of species found in the food systems of the sample of Mayan Achí people (154 randomly selected children aged 6–60 months and their 127 caregivers) from six rural villages in Guatemala, March–July 2016

Women heading households reported the importance of cultivating greater biodiversity for food consumption and commercialization. However, there was no statistical difference between women- and men-headed households for crop species richness and NFD scores, probably due to the disproportionate sample size. Many of these women were widows from the civil war in the municipality and described agriculture as their main or sole economic activity. Similarly, women in male-headed households reported that home gardens, small animal husbandry (e.g. chickens and turkeys) and gathering of wild edible plants provided them with an extra income to complement their spouse's earnings and to cover expenses related to health and education of their children.

The NFD scores showed that higher agrobiodiversity was associated with higher nutrient availability for participants, and that each food system was specialized in providing a specific set of nutrients, such as minerals, carbohydrates and proteins (Table 3). Home gardens were good suppliers of minerals (median $NFD_{minerals} = 33{\cdot}37$, interquartile range $= 11{\cdot}57$) because they contained a large number of species from the 'Dark-green leafy vegetables' food group. *Milpas* supplied considerable quantities of carbohydrates and proteins (median $NFD_{macronutrients} = 21{\cdot}58$, interquartile range $= 34{\cdot}84$) because they contained maize and beans. But coffee plantations and tomato nurseries were mediocre suppliers of nutrients due to their low agrobiodiversity rate and the inclusion of nutrient-poor species, such as coffee. Farmers who cultivated diverse food systems could cover the nutrient requirements of their household; one food system could complement the nutrients supplied by another food system. Moreover, an increment of one species within the food systems was associated with a higher NFD by 1·52 % ($r^2 = 0{\cdot}77$, $P < 0{\cdot}01$); thus, increasing cultivated agrobiodiversity could also increase the probability of covering the nutrient requirements of a farmer's household.

Participation in nutrition-sensitive programmes, ethnicity and home garden ownership were good predictors of

Table 3 Agrobiodiversity indicators of food production systems of the sample of Mayan Achí people (154 randomly selected children aged 6–60 months and their 127 caregivers) from six rural villages in Guatemala, March–July 2016

	Households cultivating (%)	Crop species richness (no. of edible crop species)			NFD (%)	
		Mean	SD	Maximum	Median	IQR
All	96·7	14·4	5·4	30·0	31·1	9·2
Home garden	77·5	12·1	4·6	28·0	24·9	7·5
Milpa	64·9	3·1	1·4	6·0	17·1	5·9
Other systems	16·2	1·9	1·2	5·0	0·3	0·1
Animals	77·3	2·0	1·0	5·0	–	–

NFD, nutritional functional diversity; IQR, interquartile range.

agrobiodiversity status. The participants who received local extension services, Extension Service$_{(+)}$, cultivated more crop species overall (median = 17·00 species) than people who did not receive assistance, Extension Service$_{(-)}$ (median = 14·00 species), $U_{(131)} = 2658{\cdot}00$, $P < 0{\cdot}05$. Similarly, Extension Service$_{(+)}$ cultivated more crop species in their home gardens (mean = 13·27, SD = 5·29 species) compared with Extension Service$_{(-)}$ (mean = 11·20, SD = 5·03 species in home gardens), $t_{(129)} = 2{\cdot}30$, $P < 0{\cdot}05$. In addition, results showed that crop species richness in the food systems belonging to Mayan Achí people (median = 16·00 species) was higher than that recorded in the Ladino people' systems (median = 13·00 species), $U_{(154)} = 2129{\cdot}50$, $P < 0{\cdot}05$. Also, Mayan Achí people cultivated more crop species in their home gardens (mean = 12·06, SD = 5·49 species) compared with Ladino people (mean = 9·23, SD = 4·37 species), $t_{(154)} = 2{\cdot}48$, $P < 0{\cdot}05$. Finally, participants who owned a home garden, HG$_{(+)}$, cultivated more crop species overall (median = 16·00 species) than participants without a home garden, HG$_{(-)}$ (median = 7·50 species), $U_{(151)} = 3368{\cdot}00$, $P < 0{\cdot}01$; meaning that home garden ownership encourages biodiversity conservation and use for food and nutrition.

Dietary diversity

The 'Cereals' food group was the most consumed group, while animal-source foods were the least consumed food type. Foods included in the 'Cereals' group represented 28·14 % of all the foods recalled by the participants. They recalled the consumption of 'Cereals' in every mealtime in the form of maize tortilla, the main food in Guatemala, or *atol*, a hot beverage made using nixtamalized* maize, oats, amaranth or wheat flour. In contrast, foods included in the food groups of 'Fish and seafood', 'Organ meats' and 'Flesh meats' were the least consumed by the participants: 0·05, 0·13 and 1·01 %, respectively. The high cost and low availability of animal-source foods caused their low consumption; participants recalled their consumption exclusively during festivities or market days. However, participants had access to other good sources of proteins, such as the food groups of 'Eggs' (3·85 % of the foods recalled), 'Milk and milk products' (2·37 % of foods recalled) and 'Legumes, nuts and seeds' (5·29 % of foods recalled). Yet, consumption of beans was lower and less frequent than expected; it is possible that participants underestimated their consumption as the frequent consumption of beans was locally seen as a 'poor people habit'.

Micronutrient-poor and energy-dense foods were frequently consumed in high quantities by participants. The 'Sweets' food group was the second most consumed food group: 19·28 % of the foods recalled were part of this group. Sugar was added to flavoured water, coffee and *atol*; often, participants mentioned that when sugar was lacking, they preferred not to drink any of those beverages. In addition, the food groups of 'Spices, condiments and beverages' and 'Oils and fats' respectively represented 13·22 and 2·22 % of all the foods recalled. High quantities of salt and oil were added to foods when cooking to enhance the taste of meals, and in the most limited situations, 'tortilla with salt' became a meal. Ultra-processed foods, such as pre-cooked noodles and potato chips, rich in salt and fats, represented 6·00 % of the foods consumed by the participants. The high consumption of sugar, salt and fats could explain the high prevalence of stunted child–overweight mother pairs observed in the region. In addition, the frequent consumption of coffee by children could also have contributed to the high prevalence of undernutrition because it prevents the correct utilization of nutrients, such as Fe absorption[84].

Nutrient-rich plants were neglected in the diet of the participants. Foods included in the food groups of 'Vitamin-A rich vegetables', 'Vitamin-A rich fruits' and 'Dark-green leafy vegetables' accounted for 0·67, 1·16 and 3·79 % of all the foods recalled by the participants, respectively. This demonstrates a disparity between production and consumption; although American black nightshade, coriander, amaranth, radish and chayote were the top foods cultivated by participants, they did not lead the list of consumed foods (Fig. 3). Probably, self-produced foods were not sufficient to cover the household requirements, so the participants relied on purchasing additional foods in the market, which seemed to be unhealthy foods rich in sugar, salt and fats.

Higher dietary diversity scores of the participants were positively associated with increased agrobiodiversity status. The IYCDDS was positively correlated to total crop species richness ($r^s_{(58)} = +0{\cdot}26$, $P < 0{\cdot}05$) and home garden crop species richness ($r^s_{(58)} = +0{\cdot}31$, $P < 0{\cdot}05$). The IDDS was also positively correlated to total crop species richness ($r^s_{(96)} = +0{\cdot}39$, $P < 0{\cdot}01$) and home garden crop species richness ($r^s_{(96)} = +0{\cdot}43$, $P < 0{\cdot}01$). Similarly, NFD scores were positively correlated with IDDS ($r^s_{(96)} = +0{\cdot}32$, $P < 0{\cdot}01$), but were not correlated with IYCDDS. Livestock ownership was positively correlated to IYCDDS ($r^s_{(58)} = +0{\cdot}29$, $P < 0{\cdot}05$) and IDDS ($r^s_{(96)} = +0{\cdot}33$, $P < 0{\cdot}01$). Ducks, chicken and turkeys were used for eggs and meat; pigs for meat; and cows for milk and rarely for meat production.

Food self-sufficiency of participants increased along with cultivated agrobiodiversity. Self-produced foods accounted for 13·23 % of participants' diets, and it was positively correlated to total crop species richness ($r^s_{(154)} = +0{\cdot}48$, $P < 0{\cdot}01$). Also, the percentage of food items included in the diet coming from home gardens (8·44 % on average) was positively correlated to crop species richness of home gardens ($r^s_{(154)} = +0{\cdot}50$, $P < 0{\cdot}01$). Similarly, results showed that the percentage of self-produced food items included in the diet was different between HG$_{(+)}$ (median$_{(117)}$ = 13·33 %) and HG$_{(-)}$ (median$_{(34)}$ = 0·00 %), $U_{(151)} = 3035{\cdot}50$, $P < 0{\cdot}01$.

* Process used to cook maize with lime.

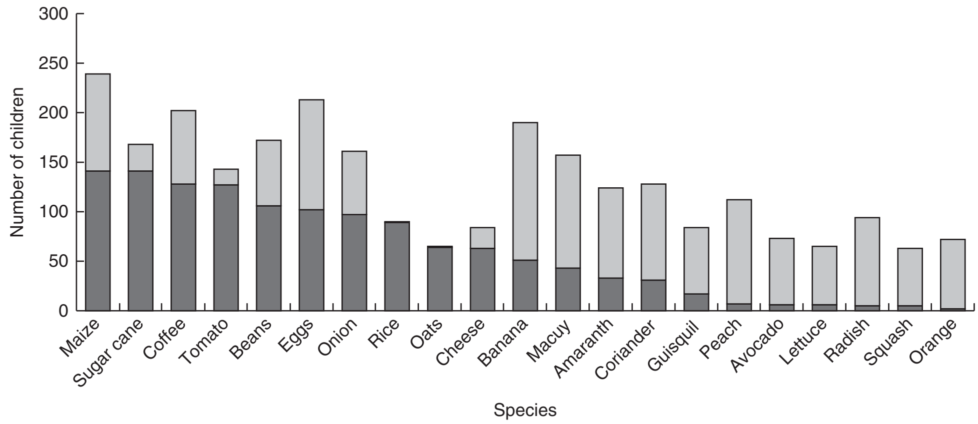

Fig. 3 Comparison of edible species consumed (■) and produced (□) by the sample of Mayan Achí people (154 randomly selected children aged 6–60 months and their 127 caregivers) from six rural villages in Guatemala, March–July 2016

Consumption of wild edible plants was not different between Mayan Achí and Ladino people. It was expected that Indigenous Mayan Achí people would consume wild edible plants more frequently than Ladino people because they possess more traditional ecological knowledge[65]; however, the difference between the groups was not statistically significant, $U = 870{\cdot}50$, $P = 0{\cdot}486$. The proportion of consumed food items gathered in the forest or on the shore of the riverbank (1·94 % on average) was very small in comparison to the proportion of self-produced (13·23 % on average) or purchased food items (~60 %). Many participants pointed out that wild edible plants are less frequently observed in the parcels and forest due to the increased use of 'poison', the term they used for chemical pesticides and herbicides, that 'have killed the soil'.

The correlations between maternal education and IYCDDS and IDDS were not significant. Yet, longer maternal schooling (years) was positively correlated with better socio-economic status ($r^{s}_{(150)} = +0{\cdot}40$, $P < 0{\cdot}01$), greater food items included in the child diet ($r^{s}_{(150)} = +0{\cdot}19$, $P < 0{\cdot}05$) and higher household dietary diversity scores ($r^{s}_{(150)} = +0{\cdot}21$, $P < 0{\cdot}05$), a proxy of food accessibility[85]. Probably, more educated women were more likely to get a better job and higher income than less-educated women, which improved their food access. However, socio-economic status was not directly correlated with IYCDDS nor IDDS; probably, the extra income was used to purchase foods other than nutrient-rich ones, such as sugar or ultra-processed foods. The frequency of visits to market was positively correlated to items included in the daily diet ($r^{s}_{(153)} = +0{\cdot}19$, $P < 0{\cdot}05$), household dietary diversity scores ($r^{s}_{(153)} = +0{\cdot}22$, $P < 0{\cdot}01$) and IDDS ($r^{s}_{(96)} = +0{\cdot}22$, $P < 0{\cdot}05$).

Child anthropometric status

Child undernutrition was extensive in the municipality. Stunting was the most prevalent malnutrition issue (60·40 % of participant children) followed by underweight (19·50 %) and wasting (1·30 %). No statistically significant correlation was found between child anthropometric status and dietary diversity scores, as expected, but there were other variables (i.e. child morbidity, socio-economic status, and maternal education and age) with a stronger association to child anthropometric status than diet.

Child morbidity was negatively associated with child anthropometric status. Children who had suffered from infections the month prior to the interview were more likely to have lower weight than healthy children. WAZ was statistically smaller in sick children (mean = −1·40, SD = 0·95) than in healthy children (mean = −0·86, SD = 0·96), $t_{(83)} = 2{\cdot}45$, $P < 0{\cdot}05$; and WHZ was statistically smaller in sick children (mean = −0·17, SD = 1·13) than in healthy children (mean = 0·33, SD = 0·86), $t_{(83)} = 2{\cdot}06$, $P < 0{\cdot}05$.

Socio-economic status might affect anthropometric status through WASH conditions. Agrobiodiversity status and dietary diversity scores were not correlated to anthropometric status nor socio-economic status. But, better socio-economic status was positively correlated to greater HAZ ($r^{p}_{(154)} = +0{\cdot}17$, $P < 0{\cdot}05$) and greater WAZ ($r^{p}_{(154)} = +0{\cdot}22$, $P < 0{\cdot}01$). Probably, socio-economic status was associated with nutrition through pathways other than diet. In fact, socio-economic status reflected the housing conditions that could impact child health status, such as regular and drinking-water availability, management of residues and sanitation condition. Therefore, we speculate that socio-economic status determines the risk of sickness and thereby the anthropometric status of children.

Maternal education, age and number of children were associated with the children's anthropometric status. Longer maternal schooling was positively correlated with greater HAZ ($r^{p}_{(150)} = +0{\cdot}20$, $P < 0{\cdot}05$) and greater maternal age was correlated with greater WAZ ($r^{p}_{(149)} = +0{\cdot}20$, $P < 0{\cdot}05$). Yet, age can be a confounding variable because mother's age was positively associated to the number of people living in the house ($r^{s}_{(146)} = +0{\cdot}44$, $P < 0{\cdot}01$), which in turn could reduce availability of and access to resources, such as food.

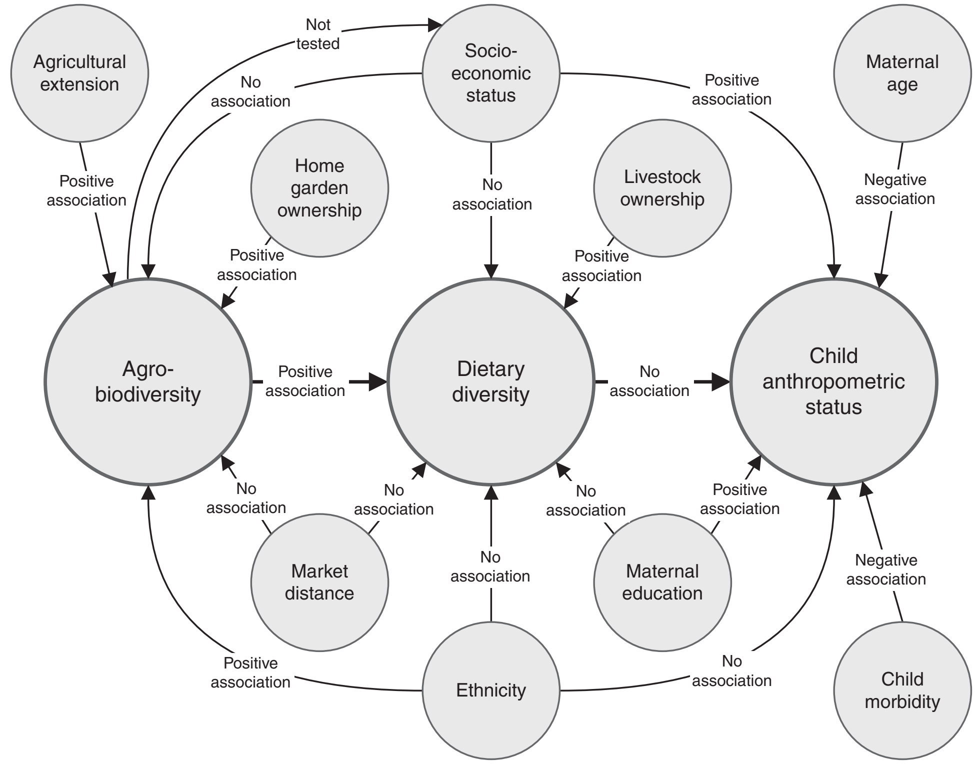

Fig. 4 Graphical summary of results: impact of agrobiodiversity on child nutrition through dietary diversification among the sample of Mayan Achí people (154 randomly selected children aged 6–60 months and their 127 caregivers) from six rural villages in Guatemala, March–July 2016

Figure 4 presents a graphic summarizing the present results on the impact of agrobiodiversity on child nutrition through dietary diversification.

Discussion

Interventions focused on conservation and sustainable use of agrobiodiversity have the potential to improve public health nutrition by increasing dietary diversity. In the present and other studies, cultivated agrobiodiversity (i.e. crop species richness and livestock ownership) was associated with higher dietary quality (i.e. dietary diversity scores)[35,40–44,48,86]. The farmers cultivating more agrobiodiversity consumed more micronutrient-rich food groups (i.e 'Dark-green leafy vegetables' and 'Vitamin A-rich vegetables and fruits')[40] and had better dietary diversity scores[35,46,87] than farmers cultivating less agrobiodiversity. Agrobiodiverse food systems can supply nutritious foods and diversify diets, and, in turn, improve nutrition.

In fact, higher cultivated agrobiodiversity can supply more variety and increased availability of nutrients (i.e. NFD scores). We found that the more species farmers cultivated, the more chances nutrient variety and availability would increase. This was especially true when local wild edible plants were cultivated by farmers because these species are good sources of Fe, Ca, vitamin C and vitamin A[77]. Our results are consistent with studies in Malawi[76], Kenya[23] and in the Millennium Villages Project in Africa[88] where higher crop species richness was correlated with higher NFD scores, and, thus, with more nutritional diverse food systems.

Likewise, food self-sufficiency can be improved by cultivated agrobiodiversity. The farmers producing more food types consumed a higher proportion of self-produced nutritious foods[35,36,46,89]. However, they consumed more micronutrient-poor, energy-dense food groups (i.e. 'Cereals' and 'Sweets' and 'Oils and fats') than micronutrient-rich food groups. The production of micronutrient-rich foods was probably not sufficient to cover the participants' nutritional requirements, and their price was higher than the price of unhealthy foods. Consequently, participants preferred to buy unhealthy foods to cover their requirements and, on some occasions, to sell their self-produced nutritious foods. Therefore, yields of nutritious foods should be increased and sustained over time to improve food self-sufficiency and dietary diversity.

For the reasons listed above, we support the idea that agrobiodiverse agriculture can provide higher nutritional benefits to farmers' households than specialized agriculture. The excessive consumption of ultra-processed foods makes us think that interventions based on specialization for improving agricultural revenues, supported by some scholars[42,43], would not increase consumption of healthy foods.

Our view is that specialization will accelerate the dietary transition towards processed foods that is already happening in the region[34] and thus worsen the incidence of diet-related diseases. Enhancing nutritional education[40,89–92], empowering women[46,55,56,87] and increasing yields of vegetables and fruits over time could motivate cultivation and consumption of nutritious foods.

However, agrobiodiversity cannot improve nutrition if food utilization is hampered by morbidity. Food utilization, the way the body makes the most of dietary nutrients, can be enhanced through improving health status, household characteristics and WASH conditions. In the present study and others, the association between dietary diversity scores and child anthropometric status was not significant[39,88,93,94] probably because children were frequently sick; we found a strong correlation between child morbidity and undernutrition[51,57,95]. Infections could compromise the integrity of the digestive and immunological system, affecting the absorption and proper use of consumed nutrients[96]. Poor WASH and housing conditions, reflected in the socio-economic status, could increase the risk of infections in children and thus child undernutrition.

Other underlying factors, such as poverty and low education, can also affect food utilization and prevent agrobiodiversity from improving nutrition. In the present study, poor family planning[97] and the number of household members[42] were negatively associated with child anthropometric status, probably because they compromised sanitation conditions and food availability. Other studies carried out in Guatemala have also shown that low maternal education and poor housing quality[98], frequent parasitic infections[97], Mayan ethnicity[99] and early age at first parturition[100] negatively affected child anthropometric status. In Guatemala, poverty and undernourishment are persistent problems within the ethnic Mayan people because they are severely discriminated against and have limited access to jobs and public services (e.g. roads, water, electricity, health care and education)[101,102].

Finally, agrobiodiverse agriculture can be translated into improved nutrition only if the nutritious foods produced are consumed by growing children and women of reproductive age. Especially children in their first 1000 d of life and pregnant or lactating women require more nutrients than people in another life stage. However, in some regions, such as Guatemala, food is preferably allocated to older boys, men and elders[33]. Nutritional education and empowerment of women can also help to overcome the poor understanding and awareness of undernutrition[103,104] and the unequal allocation of food within members of the household[33,104,105].

The present study used a cross-sectional design, so it could picture the status of agrobiodiversity and its impact on dietary diversity at a particular moment. Future studies would benefit from adopting a longitudinal design that would better describe the changes in food production systems due seasonal variations (e.g. rainfall and climate changes), fluctuations in food prices and availability at the market, and the changes in the height and weight of children.

Conclusion

Agricultural interventions that increase agrobiodiversity of both crops and livestock, for food production, are promising alternatives diversifying diets and increasing nutrient intakes. However, such interventions need to be accompanied with substantial improvements in WASH and housing conditions to reduce child morbidity and thus increase food utilization. In addition, these interventions need to include an important level of focus on family planning, nutritional education, and Indigenous and women's empowerment. We propose that agricultural interventions including all these elements could improve child nutrition through dietary diversification.

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