Dietary species richness as a measure of food biodiversity and nutritional quality of diets

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Edited by David Tilman, University of Minnesota, St. Paul, MN, and approved November 9, 2017 (received for review June 6, 2017)

Biodiversity is key for human and environmental health. Available dietary and ecological indicators are not designed to assess the intricate relationship between food biodiversity and diet quality. We applied biodiversity indicators to dietary intake data from and assessed associations with diet quality of women and young children. Data from 24-hour diet recalls (55% in the wet season) of $n = 6{,}226$ participants (34% women) in rural areas from seven low- and middle-income countries were analyzed. Mean adequacies of vitamin A, vitamin C, folate, calcium, iron, and zinc and diet diversity score (DDS) were used to assess diet quality. Associations of biodiversity indicators with nutrient adequacy were quantified using multilevel models, receiver operating characteristic curves, and test sensitivity and specificity. A total of 234 different species were consumed, of which <30% were consumed in more than one country. Nine species were consumed in all countries and provided, on average, 61% of total energy intake and a significant contribution of micronutrients in the wet season. Compared with Simpson's index of diversity and functional diversity, species richness (SR) showed stronger associations and better diagnostic properties with micronutrient adequacy. For every additional species consumed, dietary nutrient adequacy increased by 0.03 ($P < 0.001$). Diets with higher nutrient adequacy were mostly obtained when both SR and DDS were maximal. Adding SR to the minimum cutoff for minimum diet diversity improved the ability to detect diets with higher micronutrient adequacy in women but not in children. Dietary SR is recommended as the most appropriate measure of food biodiversity in diets.

sustainable diets | diet quality | malnutrition | biodiversity | food biodiversity

Food systems are a key driver of biodiversity loss worldwide (1). Globally, key drivers of food system transformations include climate change, population growth, economic development, urbanization, globalization, and production system intensification and homogenization (2–4). As a result, human diets that used to be composed of a wide variety of plants and animals have gradually shifted to a diet composed of mostly processed foods and comprising a limited number of species (5). While an estimated 300,000 edible plant species are available to humans, more than half of the global energy need is currently met by only four crops: rice, potatoes, wheat, and maize (6).

Low-quality diets are the leading risk factor for ill health worldwide (7) and are determined by socioeconomic and political factors including income, education, social cohesion, gender empowerment, and inequality (8). The diversity of species used in agricultural and livelihood systems is essential for human nutrition and sustainable food systems (9). Agricultural biodiversity contributes to farm resilience, particularly in the face of shocks such as climate change, disease outbreaks, and market price fluctuations (10). Wild food diversity, obtained in or around agricultural fields or extracted from forests and other natural landscapes, is an additional source of resilience in the food system, in particular during the lean season (9). Adequate management and use of biodiversity can help to restore ecosystems and address micronutrient deficiencies in vulnerable populations (11).

Surprisingly, the world's wild and agricultural biodiversity hot spots often coincide with low-income areas with high poverty levels, ecosystem degradation, and malnutrition (12, 13). Reduced biodiversity of both wild and agricultural species can have detrimental effects for diet quality and environmental sustainability by reducing availability and access to nutritious, seasonal foods and loss of ecosystem functions (14). Sustainable management of food biodiversity—the diversity of plants, animals,

Significance

Current research linking biodiversity and human diets has used metrics without justification from a nutritional point of view. Diet species richness, or a count of the number of different species consumed per day, assesses both nutritional adequacy and food biodiversity of diets for women and children in rural areas. The positive association of food species richness with dietary quality was observed in both the wet and the dry season. Food biodiversity contributes to diet quality in vulnerable populations in areas with high biodiversity. Reporting the number of species consumed during dietary assessment provides a unique opportunity to cut across two critical dimensions of sustainable development—human and environmental health—and complements existing indicators for healthy and sustainable diets.

Author contributions: C.L., J.E.R., R.R., and C.T. designed research; C.L. and J.E.R. performed research; J.E.R., G.K., and H.T.K. contributed data from Vietnam; D.P. contributed data from Ecuador; K.V., D.H., and D.R. contributed data from Sri Lanka; G.N.-B. contributed data from Benin; P.V.D. contributed data from Democratic Republic of Congo, Ecuador, and Cameroon; W.V. contributed data from Cameroon; F.O.O. contributed data from Kenya; C.T. contributed data from Democratic Republic of Congo, Benin, Kenya, and Cameroon; J.E.R., P.K., P.V.D., and R.R. contributed new reagents/analytic tools; C.L., K.W.S., P.K., B.D.B., and R.R. analyzed data; and C.L., J.E.R., K.W.S., P.K., P.V.D., K.V., D.P., W.V., G.K., D.H., F.O.O., G.N.-B., B.D.B., D.R., H.T.K., R.R., and C.T. wrote the paper.

The authors declare no conflict of interest.

This article is a PNAS Direct Submission.

Data deposition: Anonymized individual-level data and protocols for each country are publicly available (https://dataverse.harvard.edu/dataverse/DietarySpeciesRichness).

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This article contains supporting information online at www.pnas.org/lookup/suppl/doi:10.1073/pnas.1709194115/-/DCSupplemental.

and other organisms used for food, both cultivated and from the wild—is essential for sustainable food systems (15).

While hunger, food security, and sustainability are addressed in the Sustainable Development Goals (SDGs), the current indicators used for SDGs 2 and 15 capture nutritional status, sustainable management of terrestrial ecosystems, and agricultural sustainability dimensions separately and do not consider diet quality or food biodiversity loss (16). Evidence within the context of sustainable diets is particularly limited when it comes to human diet and biodiversity (17). Research linking biodiversity, agricultural production diversity, and human diets has used multiple metrics without validation from a dietary point of view (18). Existing diet diversity indicators such as the diet diversity score (DDS) or food variety score are used as proxies for dietary quality and measure the diversity of unique food groups and food items consumed, respectively (19). Neither of these indicators specifically captures the biological contribution of diverse plant and animal species to human diets. Luckett et al. (20) applied the nutritional functional diversity score to diets, but within the context of measuring the contribution of different food source outlets to diet diversity and without validating the nutritional adequacy of the measure. We argue that indicators to monitor progress in achieving healthy and environmentally sustainable diets must integrate diet quality and biodiversity (21).

The present study aimed to recommend a cross-cutting indicator that measures food biodiversity in human diets and helps guide interventions toward human and environmental health simultaneously. We applied three ecological biodiversity indicators to dietary intake data of women and children in seven low- and middle-income countries and evaluated how these indicators were associated with nutrient adequacy. Associations between food biodiversity, diet diversity, and nutrient adequacy as three complementary dimensions of diet quality were examined. Finally, we assessed the use of a cutoff for minimal food biodiversity to identify diets with higher nutrient adequacy and compared it with the existing cutoff for minimum diet diversity.

Methods

Data Sources. Existing data were first mapped using a systematic literature review (22). The search syntax was applied to 10 databases: (*i*) Agricola, (*ii*) Agris, (*iii*) Bioline International, (*iv*) EMBASE, (*v*) IngentaConnect, (*vi*) Web of Knowledge, (*vii*) Medline (through PubMed), (*viii*) Science Direct, (*ix*) Cochrane Library of Systematic Reviews, and (*x*) Worldcat. A combination of "(food OR diet OR nutrition) AND biodiversity," was used as syntax and tailored to the database. A detailed syntax was reported elsewhere (22). The database of papers was further searched for studies on dietary quality using "energy," "energy intake," "micronutrient," "dietary diversity," and "food diversity" as keywords. Only studies on food biodiversity and human nutrition were considered, while those on animal nutrition, biofuels, simulations, microbiology, and genetically modified organisms were excluded. Researchers who reported species consumed in diets were contacted to identify relevant data (23). We selected datasets that (*i*) used a quantitative and comparable data collection method, (*ii*) were concerned with identifying foods and drinks to at least the species level, and (*iii*) assessed dietary intake of either women or children or both. Researchers that supervised these studies collaborated for the present analysis. All studies used an interviewer-administered quantitative 24-h recall and considered wild and agricultural sources of food. Because not all studies had a repeated recall, only the first day was included. Study characteristics and data collection methods are summarized in *SI Appendix*, Table S1. The Food and Agricultural Organization of the Food and Agriculture Organization (FAO) and the International Institute for Applied Systems Analysis (IIASA) global agro-ecological zone and FAO–World Bank farming systems classification were used to describe the sample area (24).

Food intake data during the wet season were obtained from rural areas in Benin, Cameroon, the Democratic Republic of Congo, Ecuador, Kenya, Sri Lanka, and Vietnam. Data from the dry season were also available in Vietnam, Kenya, and Benin (*SI Appendix*, Table S1). All data were collected between July 2009 and April 2015, and samples were representative of the village population. Anonymized individual-level data and protocols are available (https://dataverse.harvard.edu/dataverse/DietarySpeciesRichness).

Food Biodiversity Indicators. We calculated three types of diversity metrics based on all species (plant, livestock, and fish) consumed over the 24-h recall period: species richness (SR), a count of the number of species consumed by each individual; Simpson's index of diversity (D), which represents the number of different species consumed and how evenly the amounts consumed of these different species are distributed based on quantity consumed; and the functional diversity (FD), as the total branch length of a functional dendrogram. FD reflects the diversity in nutrient composition of species consumed by each individual (25). The three metrics represent different aspects of diversity [i.e., SR, evenness and richness combined (D), FD]. Here, these are regarded as food biodiversity indicators.

SR was calculated as a count of the number of different species (plants or animals) consumed by an individual. D was calculated using the ineq package in Stata, taking into account the weight of species consumed (grams) in relation to the total weight of all species consumed per individual per day. Similar to previous studies (26), FD was calculated with the nutritional composition of the species consumed [i.e., content of the vitamin A (retinol activity equivalent μg/100 g), vitamin C (mg/100 g), folate (μg/100 g), calcium (mg/100), iron (mg/100 g), and zinc (mg/100 g) regarded as traits using the picante and ade4 library in R].

Foods and drinks were identified at the species level following best-practice guidelines (27) using local taxonomical references and technical expertise. Some studies, especially those with an ethnobotanical focus, had thorough documentation of species verified through a local herbarium, botanical museum, or botanist or biologist. Only data from Vietnam and Sri Lanka identified variety or breed level where possible. Species-level data were utilized to calculate the biodiversity indicators. When it was not possible to identify the specific species, the identified genus was followed by "sp." Given specific disambiguation challenges (28), all bananas were recorded as *Musa* sp. Disambiguation of scientific names was performed using published databases (The Plant List, www.theplantlist.org/; Species 2000 & ITIS Catalogue of Life, www.catalogueoflife.org/col). Taxonomical information was not available if the food consumed was a mixed preparation where the ingredients and quantities of ingredients were unknown (five recipes accounting for <0.04% of the total energy consumed in the sample). When the only food consumed in a food group was not identifiable at species level, at least one species was counted for that specific food group to calculate the SR. Because the study assessed the level of food biodiversity in the diet, intake of breast milk was not considered in the calculation of biodiversity indicators. The consumption of different parts of particular plant or animal species was counted once, with no minimum quantity. No minimum quantity consumed was applied to include a species in the biodiversity indicators.

Nutritional Indicators. Food-composition data for vitamin A, vitamin C, calcium, folate, iron, and zinc were mostly sourced from national food-composition tables (*SI Appendix*, Table S1). In the case that variety-level information was available, this was used to calculate nutrient intake. When food-composition data were missing, best-matching values were obtained from similar settings, countries, or foods. Adjustments for bioavailability were considered as per previous protocols for calcium (29), iron (30), and zinc (31).

As a measure of nutritional quality, the mean adequacy ratio (MAR) was calculated as the arithmetic mean of the quantity of a nutrient consumed per its requirement for each individual on a daily basis. Individual nutrient adequacy ratios (NAR) were capped at 1, so nutrients with high levels of consumption could not compensate for those with lower levels when calculating MAR. Higher values of MAR correspond to a higher adherence of the diet to nutritional requirements for the micronutrients included in the MAR. Estimated Average Requirements were used from FAO (30), the Institute of Medicine (32), and the European Food Safety Authority (33).

The DDS for women was a count of the total number of food groups consumed from a list of 10: (*i*) grains, white roots and tubers, and plantains; (*ii*) pulses; (*iii*) nuts and seeds; (*iv*) dairy; (*v*) meat, poultry, and fish; (*vi*) eggs; (*vii*) dark-green leafy vegetables; (*viii*) other vitamin A-rich vegetables and fruits; (*ix*) other vegetables; and (*x*) other fruits (34). For children, a seven-food-group classification was used, including the following: (*i*) grains, white roots and tubers, and plantains; (*ii*) legumes, nuts, and seeds; (*iii*) dairy; (*iv*) meat, poultry, and fish; (*v*) eggs; (*vi*) vitamin A-rich fruits and vegetables; and (*vii*) other fruits and vegetables (35). As recommended (34, 35), a 15-g minimum quantity consumed was considered as a cutoff for species inclusion in the DDS for women but not for children. The Minimum Dietary Diversity (MDD) was used as a cutoff for higher nutrient adequacy and refers to a minimum of five and four food groups for women and children, respectively.

Except in Sri Lanka where the protocol was exempted from clearance, all studies were approved by an ethics committee. The present analysis was approved by the Ethics Committee of Ghent University (NR B670201422403).

Data Analysis. Because every sample was considered equally representative, the overall summary statistics were calculated averages for women and children separately, per country and across countries. We compared mean MAR, DDS, and food biodiversity indicators between women and children or

Table 1. MAR, DDS, and food biodiversity indicators in women and children by country and season

Indicators	Benin (n = 2,439 children)		Cameroon (n = 125 children)	Congo (n = 462 women)	Ecuador (n = 258 women)	Kenya (n = 790 women, 790 children)		Sri Lanka (n = 36 women, 20 children)	Vietnam (n = 642 women, 664 children)		All (n = 2,188 women, 4,038 children)	
	Wet	Dry	Wet	Wet	Wet	Wet	Dry	Wet	Wet	Dry	Wet	Dry
MAR												
Women	—	—	—	0.64 ± 0.15	0.65 ± 0.12	0.62 ± 0.16	0.71 ± 0.15	0.53 ± 0.16	0.69 ± 0.13	0.67 ± 0.14	0.63 ± 0.06	0.69 ± 0.03
Children	0.44 ± 0.24	0.46 ± 0.24	0.61 ± 0.16	—	—	0.57 ± 0.20	0.64 ± 0.19	0.68 ± 0.18	0.70 ± 0.22	0.69 ± 0.16	0.60 ± 0.10	0.60 ± 0.12
DDS												
Women	—	—	—	2.89 ± 1.27	5.28 ± 1.21	3.93 ± 1.13	4.13 ± 1.11	4.00 ± 1.07	4.67 ± 1.24	4.07 ± 1.20	4.16 ± 0.90	4.11 ± 0.05
Children	4.05 ± 0.97	4.08 ± 1.01	3.62 ± 0.97	—	—	3.85 ± 0.95	3.95 ± 0.99	4.45 ± 1.36	4.14 ± 1.14	4.12 ± 1.12	4.00 ± 0.33	4.06 ± 0.08
SR												
Women	—	—	—	9.64 ± 3.57	16.39 ± 3.09	8.20 ± 2.02	8.51 ± 1.84	8.08 ± 2.95	9.04 ± 3.33	8.16 ± 2.88	10.27 ± 3.48	8.34 ± 0.25
Children	9.00 ± 3.20	9.21 ± 3.33	7.90 ± 2.45	—	—	8.88 ± 2.43	9.42 ± 2.51	8.80 ± 4.09	6.40 ± 2.74	6.29 ± 2.57	8.22 ± 1.11	8.31 ± 1.75
D												
Women	—	—	—	0.84 ± 0.11	0.94 ± 0.02	0.81 ± 0.12	0.84 ± 0.10	0.87 ± 0.05	0.87 ± 0.06	0.83 ± 0.05	0.87 ± 0.05	0.84 ± 0.01
Children	0.79 ± 0.13	0.80 ± 0.13	0.85 ± 0.07	—	—	0.87 ± 0.46	0.88 ± 0.08	0.90 ± 0.33	0.88 ± 0.08	0.86 ± 0.06	0.86 ± 0.04	0.85 ± 0.04
FD												
Women	—	—	—	0.74 ± 0.2	0.95 ± 0.26	0.45 ± 0.11	0.52 ± 0.10	0.53 ± 0.21	0.43 ± 0.12	0.42 ± 0.11	0.62 ± 0.22	0.48 ± 0.07
Children	0.57 ± 0.15	0.50 ± 0.12	0.56 ± 0.16	—	—	0.45 ± 0.13	0.53 ± 0.11	0.57 ± 0.27	0.30 ± 0.11	0.31 ± 0.10	0.50 ± 0.12	0.45 ± 0.12
Unique species*	11	17	8	17	36	9	13	14	51	65	143	98

Congo, Democratic Republic of Congo.

*No. of different species that were only consumed in one country. Means and SDs are tabulated.

seasons using t test with averages per country. Means ± SDs are reported. To quantify the association between the measures of food biodiversity consumed and the micronutrient adequacy of diets, a random-effects model was used accounting for different associations per country. The model included season as a fixed-effects variable and used an unstructured covariance matrix. To ensure comparable estimates, food biodiversity indicators were expressed as z scores in these models and standardized coefficients were used.

Because intake of species is potentially associated with total dietary energy intake, we also performed the analysis after adjusting the food biodiversity indicators for energy intake using the residual method (36). Associations between variables were visualized using locally weighted regression curves. We used heat maps with the mean MAR per DDS for the different food biodiversity indicators to assess the associations of food biodiversity across food group diversity and micronutrient adequacy. We compared test characteristics of the food biodiversity indicators and DDS to identify diets with higher nutrient adequacy using receiver operating characteristic (ROC) curves.

Finally, we assessed if adding a component of food biodiversity to the MDD cutoff would increase the ability to define higher nutrient adequacy compared with MDD. To account for nutritional differences and the contribution of species between food groups, the product of DDS × SR was used for this purpose. An MAR >50% was considered a threshold for minimal nutrient adequacy. Similar to the validation of MDD (37), a minimal sensitivity (Se) and specificity (Sp) of 60% was used to determine a DDS × SR cutoff. Test diagnostics properties were compared using ROC curves and test Se and Sp. Stata 14 (StataCorp) was used for data analysis.

Results

Dietary intake data were obtained for n = 3,449 (55%) and n = 2,777 participants during the wet and dry season, respectively. Women (n = 2,188; 34%) were mainly of childbearing age (mean age: 31.0 ± 11.7 y). Apart from n = 32 Kenyan children, all children (n = 4,038) were between 6 and 24 months old. On average, 94% of the energy intake was identified at the species level. Items that were not identified at the species level were sweets, water, salt, and bicarbonate and food items with missing species information at data collection. For processed food specifically, only five foods accounting for 0.04% of total energy from food were not identified. Of foods included in the DDS, >93% were identified at the species level. Those foods that were not assigned to a food group of the DDS were consumed in small quantities (~5 g/d) (*SI Appendix*, Table S2).

MAR was comparable for children and women (0.61 ± 0.09 vs. 0.63 ± 0.06; P = 0.85; Table 1). Diets were particularly inadequate with regard to iron (*SI Appendix*, Table S3). MAR, DDS, and food biodiversity indicators were comparable across seasons when only the countries with data on the two seasons were used (P = 0.90, P = 0.93, and P = 0.51, respectively; Table 1). NAR were also comparable, except for vitamin A, which was particularly higher in the wet season (*SI Appendix*, Table S3). The quantity of staple food consumption was only marginally higher in the dry season. The average quantity of pulses, dark-green leafy vegetables, and vitamin A-rich vegetables consumed was notably higher (>15 g) in the dry season than in the wet season (*SI Appendix*, Table S2). The average number of species consumed per food group was comparable in the dry and wet season (*SI Appendix*, Table S4).

A total of 234 different species were consumed by participants and mean SR was lower in children than in women (8.24 ± 1.17 vs. 10.19 ± 3.52; P < 0.001). The species consumed per country are included as *SI Appendix*, Tables S5 and S6. An average of 1.73 ± 0.94 species were consumed per food group. Less than one-third of

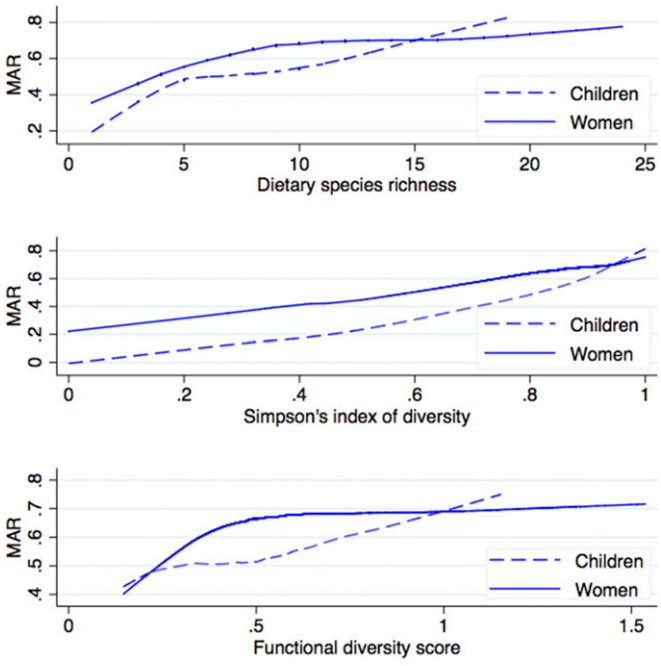

Fig. 1. Association of biodiversity indicators with MAR for 6,226 women and children in seven countries (wet and dry season combined).

Table 2. Association between biodiversity measures and MAR

Biodiversity measures	Unstandardized β	Unstandardized SE	Standardized β	Standardized SE
SR	0.03	0.001	0.10	0.003
D	0.70	0.02	0.08	0.08
FD	0.52	0.02	0.06	0.002

Mixed-effects linear regression model with season (fixed effects) and country as random effects. All β coefficients are $P < 0.001$.

species were consumed in more than one country. Overall, 58% ($n = 143$) and 40% ($n = 98$) of species were consumed only in a single country in the wet and dry season, respectively. Of all species, 53% ($n = 125$) were consumed during both seasons and 40% ($n = 93$) and 7% ($n = 16$) of the species were unique to the wet or dry season, respectively.

In the wet season, nine species [*Arachis hypogaea* L., *Bos taurus* Linnaeus, 1758, *Glycine max* (L.) Merr, *Manihot esculenta* Crantz, Oryza *sativa* L., *Solanum lycopersicum* L., *Solanum tuberosum* L., *Sus scrofa* Linnaeus, 1758, and *Zea mays* L.] were consumed in all countries and provided, on average, 61%, 10%, 24%, 42%, 51%, 65%, and 35% of the total energy, vitamin A, vitamin C, folic acid, iron, zinc, and calcium intakes, respectively. In the dry season, 19 species (including all species that were common to all countries in the wet season except for *S. tuberosum* L.) were common to all three countries with dry season data and provided 87%, 35%, 31%, 51%, 74%, 85%, and 45% of the energy, vitamin A, vitamin C, folic acid, iron, zinc, and calcium intakes on a daily basis, respectively.

All three food biodiversity indicators were positively associated with MAR (Fig. 1). Per increase in SR, D, or FD *z* score, MAR increased, on average, by 0.03, 0.7, and 0.52, respectively (Table 2). The standardized coefficients indicate that SR has a slightly stronger association with MAR than D and FD. Compared with the other food biodiversity indicators, ROC analysis also indicated a slightly higher ability for SR to define higher nutrient-adequate diets (Fig. 2). The positive association with nutrient adequacy was consistent between the countries for SR (Fig. 3) and FD (*SI Appendix*, Fig. S1) but less apparent for Simpson's index (*SI Appendix*, Fig. S2). MAR increased with both the SR and DDS (Fig. 4). The associations of MAR and DDS with Simpson's index and FD, however, were less consistent (*SI Appendix*, Figs. S3 and S4).

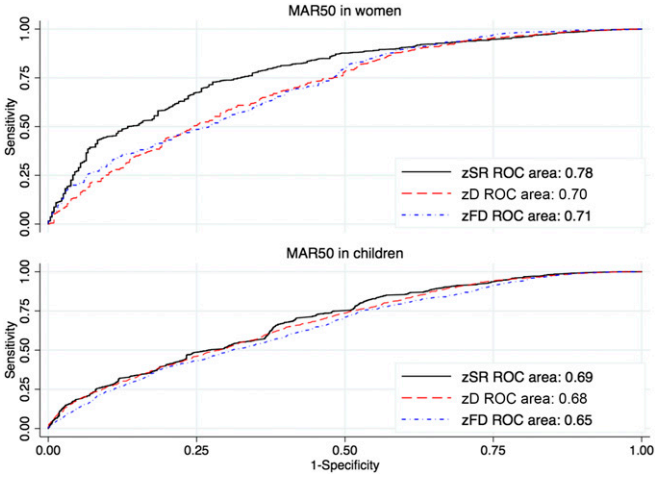

Fig. 2. ROC curves of standardized biodiversity indicators with micronutrient adequacy in women and children. MAR50, diet with 50% mean adequacy of vitamin A, vitamin C, folate, calcium, iron, and zinc; zFD, standardized FD; zD, standardized D; zSR, standardized SR.

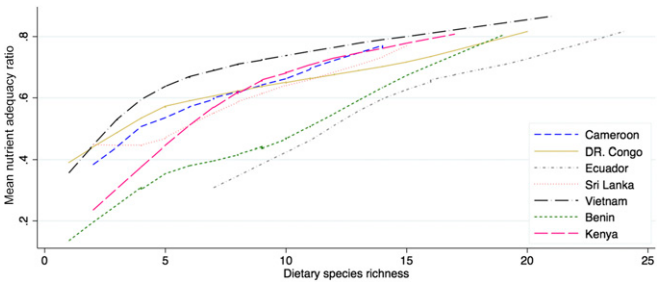

Fig. 3. Association of MAR with SR for 6,226 women and children in seven countries (wet and dry season combined). DR, Democratic Republic.

Because of its stronger and consistent associations, and simplicity in application, we used SR for further evaluation as a food biodiversity indicator. The dry season and being a woman were associated with an average increase of 0.03 and 0.01 (both $P < 0.001$) in MAR per additional species consumed, respectively. For vitamin A, vitamin C, folate, and calcium, nutrient adequacy increased by 0.07 and for iron and zinc by 0.02 and 0.05, respectively (all $P < 0.001$) per additional species consumed. Adjusting the models for total energy intake did not modify the findings.

The best cutoff to define a diet with higher nutrient adequacy was an MAR of 50% (*SI Appendix*, Table S7). The area under the curve for DDS, SR, and DDS × SR to define MAR ≥50% was comparable for both women and children (Fig. 4). In brief, adding SR to DDS considerably increased the ability to identify higher-quality diets in women. Compared with the MDD, a cutoff of 24 DDS × SR increased Se by 39% in women, with an acceptable Sp (*SI Appendix*, Tables S8 and S9). Although test Se of a DDS × SR cutoff was lower compared with MDD, overall acceptable Se and Sp estimates were obtained in children (Table 3).

Discussion

To our knowledge, no previous studies have applied common measures of biodiversity to measure levels of food biodiversity in the diet. All three biodiversity indicators assessed food biodiversity in the diet and were positively associated with micronutrient adequacy. SR showed stronger and more consistent associations with diet quality indicators (MAR and DDS) than Simpson's index of D index and FD. Given that SR can more easily be calculated in comparison with D and FD, we recommend Dietary Species Richness (DSR) as the most appropriate measure of food biodiversity in diets.

Decision makers often struggle to reconcile environmental and food policies. DSR is a valuable tool in this regard, because it integrates biodiversity, nutrition, and health aspects of food systems. The use of an indicator such as DSR offers an opportunity to capture both biodiversity and dietary quality with a single metric.

The positive association found between DSR and MAR was consistent across countries, populations, and both seasons. The present findings demonstrate a wide species diversity consumed by rural populations in low- and middle-income countries. The majority of species consumed were unique to each study site, highlighting the importance of local food biodiversity to diets.

Micronutrient adequacy and DSR were similar in both seasons despite seasonal changes in the local production system and increased food availability associated with the dry season. This was unexpected, because an earlier systematic literature review (38) reported considerable intra-annual variations in diet quality. However, none of these reviewed studies considered the consumption of underutilized, wild, or semiwild foods. Communities are not entirely composed of subsistence farmers. It is possible that households have supplemented their diets with foods sourced from the market and the wild to compensate for changes or decreases in local food production availability. Unfortunately, information on food sources (own production, market, wild) was not included in the analysis.

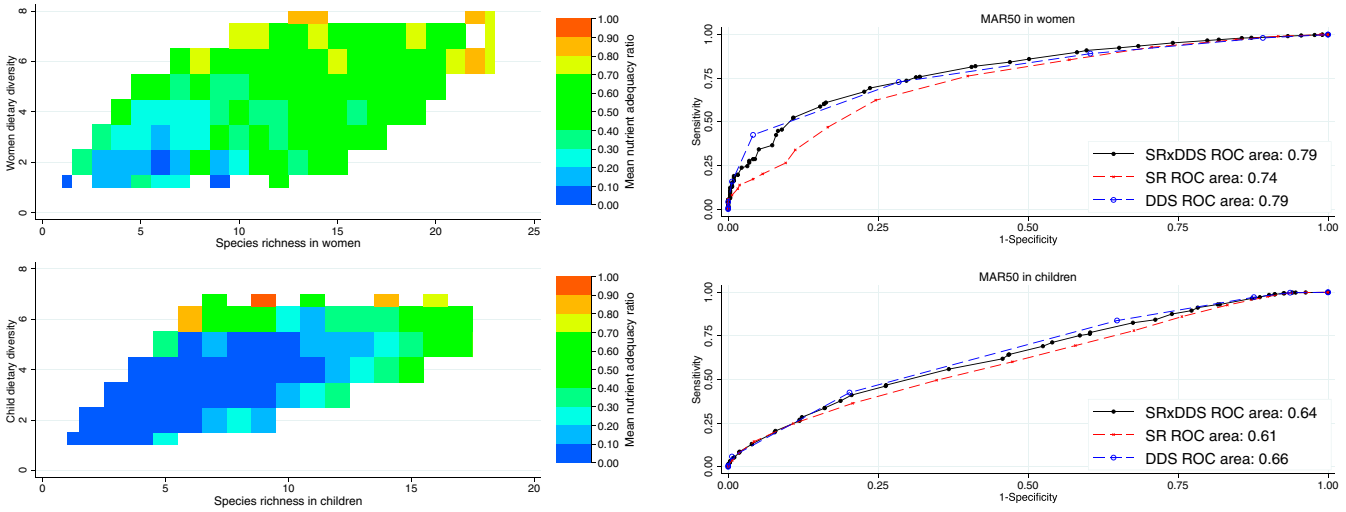

Fig. 4. MAR against SR and DDS (*Left*) and ROC curves for SR × DDS, SR, and DDS (*Right*) for 6,226 women and children in seven countries. MAR50, diet with 50% mean adequacy of vitamin A, vitamin C, folate, calcium, iron, and zinc.

As a result, it is not possible to perform a more in-depth analysis of the exact role markets or wild foods played in the diet. Lack of seasonal variation in the diet may also be explained by differences in the local production systems in terms of primary crops, harvest periods, time to receive income after harvesting, and lean seasons. It is recommended that studies further examine how DSR correlates with diet quality in the lean and abundant seasons, rather than in different climatic seasons, and further also consider the sources of foods consumed to better understand how diet quality is maintained across different climatic seasons.

DSR was more strongly associated with MAR in the dry season, suggesting that it may be easier to increase nutrient adequacy in the dry season. This may be attributed to the observed higher quantities consumed of legumes, vitamin A-rich fruits and vegetables, and dark-green leafy vegetables in the dry season. The availability of these foods is highly seasonal. Innovative processing and storage methods and the introduction of species and varieties that are productive "out of season" may extend their availability in the wet season when smaller quantities were consumed.

We used DSR, which captures both agricultural and wild food biodiversity. Our study therefore does not reveal the contribution of agricultural vs. wild biodiversity in the diet. Earlier research showed that DDS is positively associated with farm production diversity as well as with market access (18). The contribution of wild biodiversity to the dietary quality is less clear (9). Future intake assessments should record the source of each food item to shed more light on the relative contribution of locally available agricultural and wild biodiversity to dietary quality. This is important because it has implications for biodiversity conservation management in which focus on agricultural diversity might be at the expense of wild biodiversity conservation and vice versa.

Scholars have called for dietary indicators that consider multiple dimensions to provide more comprehensive assessments of diet quality (18). DDS is a common measure to assess diversity and diet quality and is widely applied in population surveys. The joint use of DSR and DDS ensures that complementary dimensions of diet quality and diversity are included during dietary assessments. We report a positive association between DSR and DDS. Diets with higher nutrient adequacy were observed when both DSR and diet diversity were maximal. The DSR thus captures both the dimension of biodiversity as well as diet diversity. The combined application of both DDS and DSR as a minimum cutoff combining food biodiversity and food group diversity concepts improved the ability to detect diets with higher nutrient adequacy in women. The improvement in test diagnostic properties, however, was small and not observed in children.

On the other hand, assessing DSR can be challenging, because it was estimated that previous studies misidentified between 6% and 10% of species (39). Guidelines were recently prepared to adequately record species during food-intake studies (15). Using an open recall or species-level food list during MDD data collection would also enable DSR calculation. Cost-effective technologies and approaches, such a mobile apps, that enable MDD enumerators to identify and record species-level details of foods consumed can be helpful in population diet-quality surveillance surveys.

Foods not classified in a DDS food group for women essentially contained species consumed as condiments or spices, or that were consumed in small quantities. These foods were included in the food biodiversity indicators (when the species could be identified) and in MAR calculations. The large number of foods consumed, but not captured by the DDS, highlights the contribution of these biodiverse foods that are consumed in small serving sizes, but with likely nutritional benefits.

Identifying food species diversity in diets is a useful first step toward sustainability assessment of diets. Adding additional estimates on the environmental impact or ecosystem services (40) of the species consumed (e.g., chicken vs. beef vs. pork) would allow for better assessment and modeling of the sustainability of the diet. Such assessment will improve assessment of the environmental and natural resource impacts from agricultural production or from extraction from natural ecosystems (41).

As is the case with other studies (42), a limitation of the present work is a lack of nutrient-composition data of some foods, species, and varieties consumed. The composition of various indigenous,

Table 3. Test classification properties of SR and DDS cutoffs for higher dietary quality (MAR >50%)

SR and DDS cutoffs	Sensitivity, %	Specificity, %
Women		
DDS ≥5*	42	96
DDS × SR ≥24	81	60
Children		
DDS ≥4†	84	35
DDS × SR ≥36	62	54

*Minimum DDS for women.
†Minimum DDS for children.

wild, neglected, or underutilized species was often not available and was substituted with values from similar foods. It is expected that wider identification of species and varieties consumed will guide food-composition assessment toward nutritionally relevant and currently undocumented species. We used a single 24-h recall per subject. Although this method is appropriate to estimate population average intakes, it does not allow accounting for within-person variability and estimation of usual dietary intake.

Finally, we used dietary intake data from rural areas of middle-income countries where locally produced food is the major contributor to diets. Food systems in (peri)urban areas and high-income countries have a higher degree of complexity than in rural areas and middle-income countries. This complexity is mainly caused by the consumption of processed foods that have often not been locally produced but have been obtained from retail outlets or urban markets. Nevertheless, in diets with higher contributions of processed foods, we expect all three biodiversity indicators to remain a valid measure of food biodiversity. Depending on processing and fortification practices, however, the strength of the association between the food biodiversity indicators and diet quality may differ from the present findings. Further assessment of the validity and applicability of DSR in diets with a higher contribution of foods obtained from urban markets or of processed foods is warranted.

Nutrition-sensitive agricultural and ecosystem conservation interventions, specifically those related to diversification, clearly have an untapped potential to address global hunger and micronutrient deficiencies (11). Monitoring the contribution of species in the diet enables identifying species with the greatest potential to improve diets in different local contexts and provides additional granularity to assess the importance of food diversity in ensuring diet quality. Global datasets such as FAOSTAT identify general food items or food groups and do not facilitate valorization of the full range of food biodiversity. In addition, international food security efforts have hence focused on the production of a handful of staple foods (mostly cereals) to meet human energy needs (6). The present study provides evidence on the role of nonstaple foods to both energy and micronutrient intakes in rural areas. Identifying foods consumed at the species level adds information that supports both conservation and sustainable food system initiatives.

ACKNOWLEDGMENTS. The research was funded by the Agriculture for Nutrition and Health (A4NH) CGIAR Research Programme (CRP). The following sources funded studies from which the data was used: Benin: Ministry of Foreign Affairs Finland (FoodAfrica project); Cameroon and Ecuador: Flemish Interuniversity Council; Congo: Flemish Interuniversity Council, Leopold III fund for Nature Exploration and Conservation, and Stichting Roeping; Sri Lanka: Global Environment facility, United Nations Environmental Programme, Food and Agriculture Organization, and Bioversity International; and Kenya and Vietnam: Humidtropics and A4NH CRPs. R.R. received a grant from Daniel and Nina Carasso Foundation for research on nutrition-sensitive landscapes. The funders of the study had no role in study design, data collection, analysis or interpretation, or writing of the manuscript. The corresponding author had full access to all of the data in the study and had final responsibility for deciding to submit for publication.

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