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Measuring nutritional diversity of national food supplies

Roseline Remans[a,b,*,1], Stephen A. Wood[c,d,1], Nilanjana Saha[d], Tal Lee Anderman[e], Ruth S. DeFries[d]

[a] Agriculture and Food Security Center, The Earth Institute, Columbia University, Addis Ababa, Ethiopia
[b] Bioversity International, Addis Ababa, Ethiopia
[c] Agriculture and Food Security Center, The Earth Institute, Columbia University, New York, USA
[d] Department of Ecology, Evolution, and Environmental Biology, Columbia University, New York, USA
[e] Environmental Defense Fund, 301 Congress Avenue, Austin, USA

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ABSTRACT

Improvements in agricultural production have drastically increased grain yields in the past half-century. Despite this growth in productivity and calories available per capita, malnutrition – both undernutrition and, increasingly, overweight – remains pervasive. Though nutrition is critical to human health, it has yet to be systematically integrated into assessments of agricultural and food systems. Using three complementary diversity metrics, we find strong associations between nutritional diversity of national food supplies and key human health outcomes, while controlling for socio-economic factors. For low-income countries the diversity of agricultural goods produced by a country is a strong predictor for food supply diversity; for middle- and high-income countries national income and trade are better predictors. Our results highlight the importance of diversity in national food systems for human health. We provide metrics for agricultural and food security policies to consider nutritional diversity.

1. Introduction

In addition to producing sufficient calories, a major often overlooked challenge in agricultural and food systems is to provide an adequate diversity of nutrients, necessary for a healthy life. A human diet requires at least 51 nutrients in consistently adequate amounts continuously (Graham et al., 2007). Diet diversity has long been recognized as important for adequate nutrient intake (Shimbo et al. 1994; Hatloy et al., 1998; Foote et al., 2004; Steyn et al., 2006; Moursi et al., 2008) and human health (Arimond and Ruel, 2004; Kant et al., 1993; Slattery et al., 1997; Levi et al., 1998), but the concept of nutritional diversity has yet to be integrated into planning and assessments of agricultural and food systems and policies. Success of agricultural systems is evaluated primarily by metrics of crop yields, economic output and cost-benefit ratios (IAASTD, 2009). Yet these metrics do not reflect the diversity of nutrients provided by the system and required for a healthy diet. While grain yields have increased drastically in the past half century (Evenson and Gollin, 2003), it has been argued that changes in agricultural production systems from diversified cropping systems towards ecologically simpler, cereal-based systems have contributed to poor diet diversity, micronutrient deficiencies and resulting malnutrition (Welch and Graham, 1999; Frison et al., 2006; Negin et al., 2009; DeClerck et al. 2011).

In this paper we apply ecological diversity metrics at global level to explore the relationships between nutritional diversity of national food supplies, food production and nutrition-related health outcomes among countries. We address three central questions: (1) What is the distribution of nutritional diversity – both produced and supplied – across nations? (2) What is the contribution of nutritional diversity of national food supplies to nutrition-related health outcomes at the national scale? (3) Do countries with more diverse food production systems have greater diversity in their food supply and how does this relationship vary across an economic gradient?

2. Methodology

2.1. Data

To address these three questions we integrated agricultural, economic, and health data for low to high income countries from the Food and Agriculture Organization (FAOSTAT) and the World Bank database (Worldbank database) for two time periods: 2000–2009

* Corresponding author at: Agriculture and Food Security Center, The Earth Institute, Columbia University, ILRI campus, P.O. Box 5689, Addis Ababa, Ethiopia.
E-mail address: rremans@ei.columbia.edu (R. Remans).
[1] R.R and S.A.W contributed equally to this work

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(results in main paper) and 1990–1999 (Supplementary Information). We compiled information on crop and livestock production and supply at the national level from FAOSTAT (FAOSTAT, 2013). Production data included the quantity of each crop and livestock/animal-based product produced in a country. Supply data covered the per capita supply of each food item available for human consumption in grams per capita per day. Supply per capita data take into account production, import, export, feed and waste to calculate the food available for human consumption. We paired this dataset with food composition data (FAO International Network of Food Data Systems INFOODS, 2013) for seven key nutrients for which dietary intake is often inadequate and food composition data are available: carbohydrates, protein, vitamin A, vitamin C, iron, zinc, and folate. From the nutrition database, we calculated the percent of dietary reference intake for each nutrient in each food item. We then multiplied this value by the amount of the crop/animal-based product produced or supplied in each country and for which data is available at FAOSTAT.

We further compiled data on nutrition-related health outcomes and socio-economic variables at the national level from the World Bank database (World Bank database). For nutrition-related health indicators, we included percent stunting (height-for-age z-score < -2), percent underweight (weight-for-age z-score < -2), percent wasting (weight-for-height z-score < -2), and percent overweight (body mass index > 25) among children less than five years of age.

Guided by the UNICEF framework that outlines the determinants of child and maternal nutrition (UNICEF, 1990), and based on data availability, we included the following variables as major confounding factors: log gross national income (GNI) per capita, calories available per capita per day, Gini index, percent of the population with access to an improved water source, percent of the population living in urban areas, literacy rate, number of physicians per 1000 people, export of goods and services as percent of gross domestic product (GDP), import of goods and services as percent of GDP, agricultural import/export, and food import/export as percent of GDP. Data for all confounding factors were obtained from the World Bank database (World Bank Database, 2013).

To integrate the datasets and take into account yearly fluctuations, we used averages from ten-year time periods for the available data: the average from 2000–2009, results of which are reported in the main paper, and the average from 1990–1999, results of which are reported in Supplementary Information. Data for several of the key variables, including the nutrition-related health indicators, were too scarce for earlier or later 10-year time periods.

2.2. Calculating diversity metrics

To assess nutritional diversity of food production and supply, we used two ecological diversity metrics – Shannon Entropy and Modified Functional Attribute Diversity (MFAD) – and the percent of energy coming from non-staples (Text box 1).

Text box 1–Three complementary diversity metrics

Shannon Entropy diversity metric (Shannon), or species diversity: reflects how many different types of food items there are in a certain country, and how evenly these different types are distributed

Modified Functional Attribute Diversity (MFAD), or functional diversity: reflects the diversity in nutrients provided by the different food items based on the nutritional composition and amount of each food item present

Percent of energy coming from non-staples (% energy non staples): indicates the proportion of energy derived from food items that are not grains or tubers.

Shannon Entropy (Shannon, 1948) is a commonly used diversity metric that weights the richness of species – food items in this case – by the evenness of their distribution. As such, it is a measure of the relative abundance of each food item within a country. The metric identifies the diversity of crops in each country without explicit consideration of their nutrients.

The use of functional diversity metrics has grown in ecology to measure the diversity of functional traits in a given area (Petchey et al., 2009; Schleuter et al., 2010; Weiher, 2012). We use a measure of functional attribute diversity (FAD), which is defined as the sum of the pairwise functional dissimilarities of a collection of species (Walker et al., 1999; Petchey and Gaston, 2006) measuring the dispersion of species within a functional trait space (Ricotta, 2005). The functional attribute approach has the advantage of not needing to know the entire species pool in order to calculate the metric. This is preferable in this study because not all of the food items produced by or available in a country are represented in the FAOSTAT database. We use a modified version of the original functional attribute approach (Walker et al., 1999) that meets two essential criteria that functional diversity should not increase with functionally identical species, but should increase with functionally dissimilar species (Schmera et al., 2009). Modified Functional Attribute Diversity accomplishes this by weighting FAD by the number of functional types. It is given as (Schmera et al., 2009):

$$MFAD = \frac{\sum_{i=1}^{n} \sum_{j=1}^{n} d_{ij}}{N}$$

where n is the number of species – or food items, in this case – and d is the dissimilarity between species i and j as defined by multiple traits – or nutritional components – measured using some distance algorithm, such as Euclidean distance. N is the number of functional units (Ricotta, 2005), such that different species that are identical in their trait composition are considered the same functional unit. For example, if there are two food items with the same nutritional composition, then they are not counted twice.

To facilitate interpretation and comparison between countries, regions and metrics, the Shannon and MFAD metric were scaled to a 0–1 scale, with 0 representing no diversity (only one food item or food items of the same composition) and 1 representing the highest value among the countries.

The percent of energy coming from non-staples represents the percent of the total energy of food items supplied and available in a country coming from non-staple crops, this is food items different from grains and staple tubers.

These three metrics provide distinct but related pictures of global food diversity. For example, countries in West Africa show high Shannon Entropy diversity of food items produced, yet these items, most of which are staples (e.g. rice, maize, sorghum, plantain), tend to be similar in nutrient composition, resulting in a low functional diversity (MFAD) and a high percent of energy coming from staples. Taken together, these three metrics provide a more comprehensive view of nutritional diversity than any single metric.

2.3. Models and statistical analysis

To test for differences in means between regions, we apply one-way Analysis of Variances (ANOVA).

To assess relationships between variables, we fit the variables into linear regression models assuming a Gaussian distribution. All independent variable coefficients were standardized to compare the magnitude of their effects on the response variable. Collinearity was systematically checked using variance inflation factors. Variables with a variance inflation factor of less than five were retained in the model.

The models or regression functions analyzed include:

(1) Child nutrition indicator=f (supply diversity metric, calories available per capita, log GNI per capita, GINI index, % urban population, literacy rate, % pop access to improved water, number of physicians per 1000, exports of goods and services as % of GDP). This is the full model for assessing the nutrition health—food supply relationship.
(2) Child nutrition indicator=f (supply diversity metric, calories available per capita, log GNI per capita). This is the reduced model for assessing the nutrition health—food supply relationship..
(3) Supply diversity=f (production diversity, log GNI per capita, cereal yield, fertilizer per land unit, tractors per land unit, % ag land, Ag GDP, Ag R&D, exports as % of GDP).

For models relating the diversity of food supply to food production, we binned countries into four income categories commonly used by the World Bank: low-income (GNI per capita $\leq$ 1025 USD yr^{-1}), low middle-income (GNI per capita $>$ 1025 & $\leq$ 4035 USD yr^{-1}), high middle-income (GNI per capita $>$ 4035 and $\leq$ 12,475 USD yr^{-1}) and high-income (GNI per capita $>$ 12,475 USD yr^{-1}).

Country case studies were included to illustrate patterns of change over time from 1960 to 2012 (based on available data). The case studies were chosen as examples and not to be representative of the income group to which they belong.

3. Results

3.1. Global distribution of nutritional diversity

Considering diversity of national food systems at a global scale (Fig. 1 and Table 1) provides several insights.

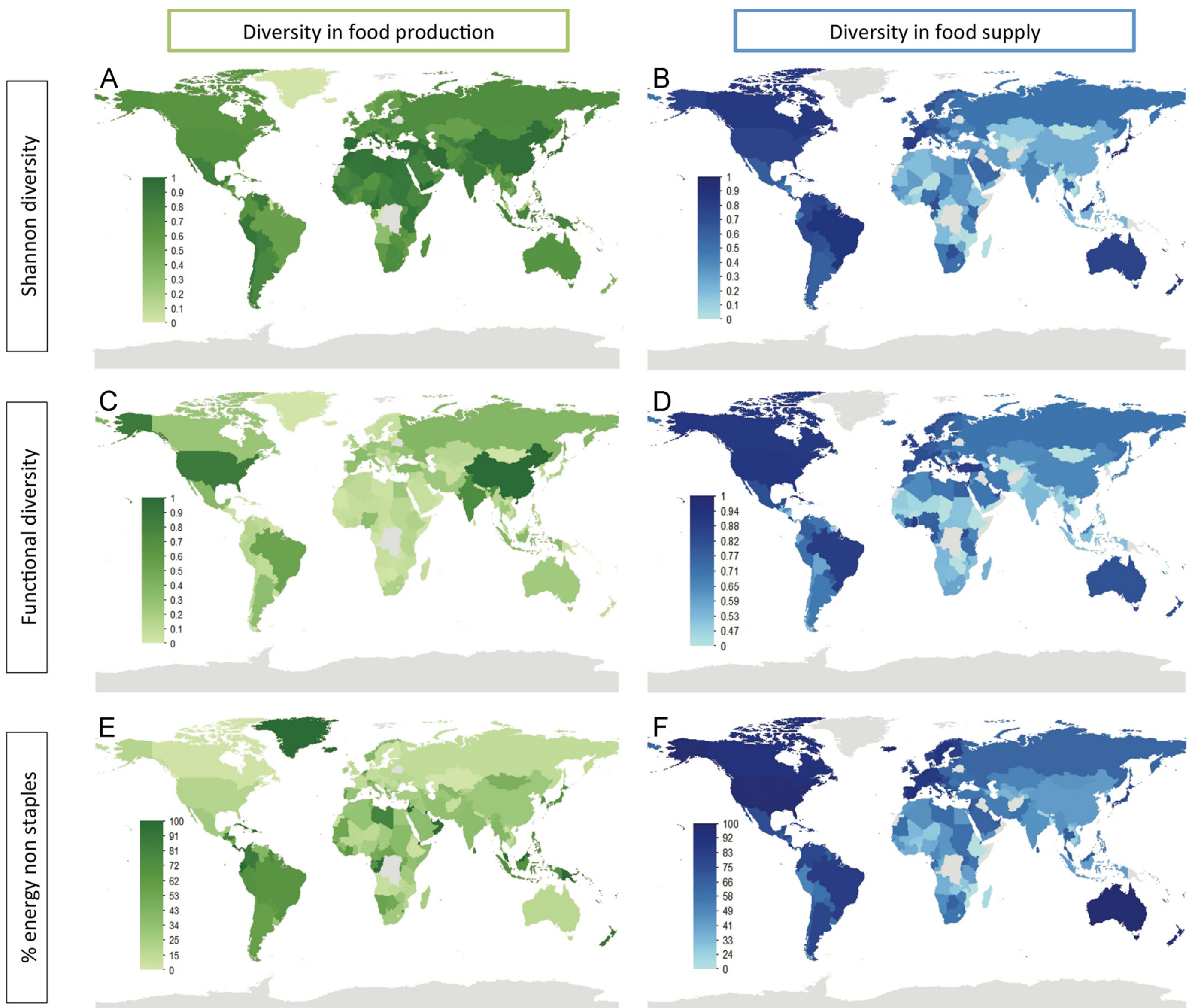

Fig. 1. Global map of nutritional diversity. Column one presents the level of diversity in food production for each country using three complementary diversity metrics. Column two shows the level of diversity in the national food supply using the same metrics. We present: Shannon Entropy diversity, describing the diversity of food items produced (A) and supplied (B); Modified Functional Attribute Diversity (MFAD) describing the diversity in nutritional composition of food items produced (C) and supplied (D); and percent of energy coming from non-staples in food production (E) and supply (F). To facilitate interpretation and comparison between countries, regions and metrics, the Shannon and MFAD metric were scaled to a 0–1 scale, with 0 representing no diversity (only one food item or food items of the same composition) and 1 representing the highest value among the countries.

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Table 1
Food production and supply diversity per geographic region using three diversity metrics. Values represent means of countries ± standard deviations and ANOVA *p*-values testing for differences between regions are indicated. Shannon: Shannon Entropy diversity or species diversity; MFAD: Modified Functional Attribute Diversity or functional diversity; energy non staples%: percentage of total energy in food supply that is coming from non staple crops (grains and tubers); GNI: Gross National Income.

	Shannon diversity		MFAD		energy from non staples (%)		GNI per capita (USD)
	Production	Supply	Production	Supply	Production	Supply	
South Asia	0.71 ± 0.16	0.85 ± 0.10	0.13 ± 0.17	0.71 ± 0.11	40 ± 35	43 ± 19	6372 ± 10394
East Asia and the Pacific	0.76 ± 0.18	0.87 ± 0.08	0.12 ± 0.23	0.71 ± 0.10	47 ± 30	44 ± 16	7714 ± 10755
Sub-Saharan Africa	0.80 ± 0.17	0.83 ± 0.06	0.05 ± 0.05	0.71 ± 0.11	32 ± 23	34 ± 10	1565 ± 2629
Middle East and Northern Africa	0.92 ± 0.08	0.86 ± 0.03	0.08 ± 0.08	0.82 ± 0.09	47 ± 27	46 ± 8.0	9403 ± 12390
Europe and Central Asia	0.82 ± 0.12	0.88 ± 0.06	0.08 ± 0.23	0.80 ± 0.09	21 ± 16	52 ± 12	17,290 ± 17455
North America	0.80 ± 0.01	0.95 ± 0.01	0.44 ± 0.33	0.94 ± 0.00	11 ± 5.0	66 ± 2.6	36,741 ± 7234
Latin America and the Caribbean	0.78 ± 0.13	0.92 ± 0.03	0.08 ± 0.09	0.80 ± 0.09	57 ± 23	55 ± 12	4307 ± 2649
p-value	0.0125	0	0.0002	0	0	0	0

Regions differ significantly in food production and supply diversity (Table 1). For production, it is noticeable that some regions e.g. Sub-Saharan Africa, show relatively high Shannon diversity but low functional diversity (MFAD) and low percentage of energy coming from non staples. This can be explained by the large number of staple crops produced, which are relatively similar in their nutritional composition and thereby add species diversity but no functional diversity. The US and China show average Shannon diversity but exceed in functional diversity, indicating that the food items produced provide a diversity of nutrients. The relatively large amounts of different vegetables and livestock produced in the US and China can partly explain this pattern.

For supply, patterns between the three metrics differ less than for production. Independent of the diversity metric used, North America, Europe and Central Asia, Australia and Latin America show the greatest diversity in food supply. This is partly related to the higher income level of these regions (the average GNI per capita for these regions is USD 13,403 ± 1,780 as compared to USD 8330 ± 1,511 for the other regions (p-value = 0.017)), which allows more importation of nutritious foods. Supply diversity (Shannon, MFAD and % energy from non staples) is strongly correlated to the log GNI per capita of a country (Bonferroni adjusted significance level $p < 0.0001$, Spearman correlation coefficient = 0.73 for Shannon, 0.69 for functional diversity and 0.80 for % energy from non staples). Production diversity, on the other hand, is not significantly correlated with a country's income level (p-value > 0.05, Spearman correlation coefficient = −0.07 for Shannon, −0.14 for functional diversity and 0.19 for % energy from non staples).

Within regions, variability between countries is larger for production than for supply diversity as indicated by the standard deviations per region (Table 1).

Taken together, considering the three diversity metrics provide a more comprehensive view of nutritional diversity at a global scale than any single metric, this is particularly true for production diversity.

3.2. What is the contribution of nutritional diversity of national food supplies to nutrition-related health outcomes at the national scale?

Controlling for per capita availability of calories and national income, we find a significant negative relationship between diversity of national food supplies and the national prevalence of child stunting (low height-for-age, reflecting chronic undernutrition), wasting (low weight-for-height, reflecting acute undernutrition), and being underweight (low weight-for-age, reflecting a combination of acute and chronic undernutrition) (Table 2). Overweight prevalence increases with calories available per capita, but is independent of food supply diversity. All three diversity metrics show the same directional relationship between food supply diversity and health outcomes. The significance level is highest for the percent of energy from non-staples. The relationships are consistent in direction and magnitude under both the reduced-form model (Table 2) and the fully specified model (Table S1), which has a larger set of socio-economic controls selected based on known determinants of child nutrition (UNICEF, 1990). We report a reduced-form model because of the greater number of degrees of freedom and larger sample size. Similar results were found for the time period 1990–1999 (Tables S2, S3). These findings highlight a significant relationship between food supply diversity and key health outcomes at the national level, independent of national income, calories available per capita, and other socio-economic variables. Results suggest that ensuring food supply diversity, in terms of species diversity (Shannon) and nutritional diversity (MFAD, % energy from non staples), at the national level is important for achieving healthy food systems.

3.3. Do countries with more diverse food production systems have greater diversity in their food supply and how does this relationship vary across an economic gradient?

The relationship between production and supply diversity depends on the income level of the country (Fig. 2 shows the relationship between production and supply diversity for the Shannon diversity metric, Supplementary Fig. S1 shows this relationship for MFAD and % energy from non staples). For low-income countries (GNI per capita ≤ 1025 USD yr^{-1}), the diversity of foods produced is a strong predictor for the food supply diversity available for human consumption. This relationship is further illustrated in a case study of Nepal (Fig. 3A, B). Nepal is a low-income country in which food supply and production diversity have increased together over time (Fig. 3A), suggesting that the country is achieving food supply diversity through a system of diverse food production.

For low-middle-income (1025 USD < GNI ≤ 4035 USD), high-middle-income (4035 USD < GNI ≤ 12,475 USD), and high-income (GNI > 12,475 USD) countries, food supply diversity is independent of production diversity (Fig. 2); and GNI and factors such as international trade are better predictors for a country's supply diversity (Table S4).

Many low- and middle-income countries have undergone economic transitions to higher-income wealth brackets (Hilson and Garforth, 2013). We examine time-series data of two country case studies (Ghana and Malaysia), as examples of different trajectories for acquiring nutritional diversity of national food supplies during economic transitions.

In the case of Malaysia, we observe a decoupling between production and supply diversity over time, as the country transitioned from low-income to high middle-income wealth status (Fig. 3C, D). During this period, Malaysia shifted to large oil palm

Table 2
Relationship between food supply diversity and nutrition-related health outcomes. Regression coefficients and standard errors (in parentheses) are shown for prevalence of stunting (low height for age), wasting (low weight for height), underweight (low weight for age) and overweight (high BMI) among children under five years of age, as a function of food supply diversity metrics, log GNI (gross national income), and calories available per capita. For each nutrition outcome, results are shown for regressions functions including Shannon diversity (1st row and 1st column), Functional diversity (2nd row and 2nd column), or energy from non-staples % (3rd row and 3rd column). All regression coefficients are standardized. All countries for which data are available, were included in the analysis. Data sources include FAOSTAT and Worldbank. A full model, including a larger set of socio-economic variables, is shown in Table S1.Significance level: $^{***}p<0.001$; $^{**}p<0.01$; $^{*}p<0.05$.

	Stunting (%)			Wasting (%)			Underweight (%)			Overweight (%)		
Shannon diversity	−3.10*** (1.05)			−1.15** (0.51)			−2.39*** (1.01)			−0.30 (0.67)		
Functional diversity MFAD		−0.50 (1.13)			−1.90*** (0.51)			−3.10*** (1.02)			0.19 (0.70)	
% Energy non staples			−5.10*** (1.20)			−1.63*** (0.60)			−4.35*** (1.15)			0.45 (0.77)
log GNI per capita	−8.19*** (1.95)	−11.3*** (1.69)	−6.33*** (1.96)	−2.03** (0.94)	−2.81*** (0.76)	−1.59 (0.98)	−5.83*** (1.86)	−7.67*** (1.53)	−3.97** (1.87)	0.33 (1.21)	−0.01 (1.02)	−0.41 (1.27)
Calories available per capita	−6.07*** (1.36)	−5.05*** (1.53)	−6.07*** (1.30)	−0.73 (0.66)	−0.64 (0.69)	−0.70 (0.65)	−3.83*** (1.30)	−1.47 (1.39)	−3.89*** (1.24)	2.28*** (0.86)	2.24** (0.93)	2.41*** (0.85)
Constant	20.0*** (0.98)	19.6*** (1.01)	20.0*** (0.94)	5.29*** (0.48)	5.30*** 0.46	5.28*** (0.47)	8.95*** (0.94)	8.86*** (0.92)	8.97*** (0.90)	9.28*** (0.62)	9.23*** (0.62)	9.21*** (0.62)
Number of countries	113	113	113	113	113	113	113	113	113	108	108	108
R-squared	0.71	0.68	0.73	0.34	0.39	0.35	0.56	0.57	0.59	0.16	0.15	0.16

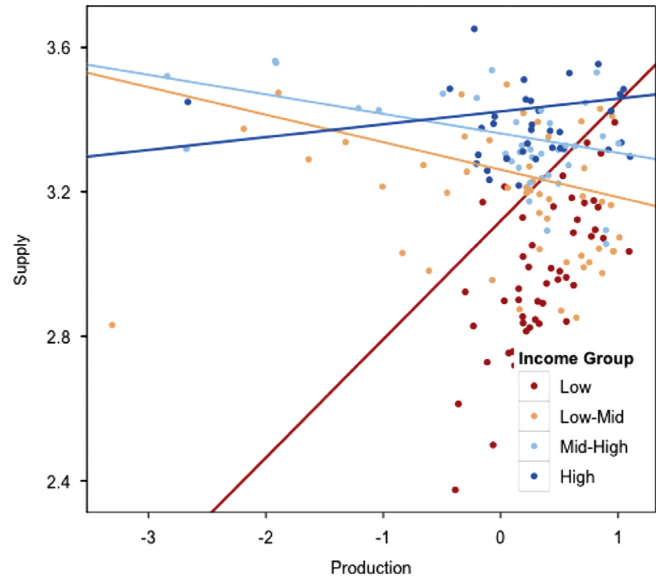

Fig. 2. Supply diversity as a function of production diversity per income category. Diversity results are given using the Shannon Entropy index. Low-income: GNI per capita ≤ 1025 USD yr^{-1}; low middle-income: GNI per capita > 1025 USD yr^{-1} & ≤ 4035 USD yr^{-1}; high middle-income: GNI per capita > 4035 USD yr^{-1} & ≤ 12,475 USD yr^{-1}; high-income: GNI per capita ≥ 12,475 USD yr^{-1}. Production diversity is standardized to reflect the data included in the regression model. Regression lines are the slopes of production diversity run for each income bracket, controlling for a series of potential confounding factors (see methods). Fig. S1 shows this relationship for MFAD and percent energy from non-staples.

plantations, resulting in lower production diversity (Fitzherbert et al., 2008). This transition coincided with a period of sudden rise in export and import values as a percent of GDP (Fig. 3D), suggesting that changes in macroeconomic policies drove the divergence between supply and production diversity. Malaysia's ability to maintain supply diversity suggests that it compensated for low production diversity by purchasing its nutritional diversity through trade. Therefore, as low-income countries transition to specialized production of fewer crops, trade through the international market can ensure diversity of the national food supply.

The case of Ghana shows a slight decrease in supply diversity between about 1970 and 1997, paired with a decrease in production diversity during a period of limited international trade (Fig. 3E, F). Food and cacao production declined in Ghana during the 1970s, along with total area under cultivation and per capita income and trade (Tabatabai, 1988). This may be attributable to a migration of the labor force to Nigeria and Cote d'Ivoire during the 1970s oil boom (Tabatabai, 1988; Dormon et al., 2004). International trade began increasing around 1997, followed by an increase in supply diversity and an uncoupling from production diversity. The Ghana case study illustrates the potential for declines in nutritional diversity of national food supplies under cash-crop (cacao) oriented agricultural production when national income was low; the decline was halted when Ghana's GNI increased and Ghana's food supply became more diverse through trade.

Taken together, these case studies illustrate multiple trajectories for nutritional diversity of national food supplies as countries move through economic transitions, change agricultural production, and respond to shifting global food prices (Brinkman et al., 2010; Webb, 2010; Webb and Block, 2012). We chose these examples to illustrate varying trajectories. Other countries follow these trajectories to varying degrees.

Analyzing trends over time at a global level by aggregating the values of all countries at the global level, it can be observed that while yields and calories available per capita have increased worldwide, the nutritional diversity of the global food system has remained largely stagnant (Fig. 4 and Fig. S2).

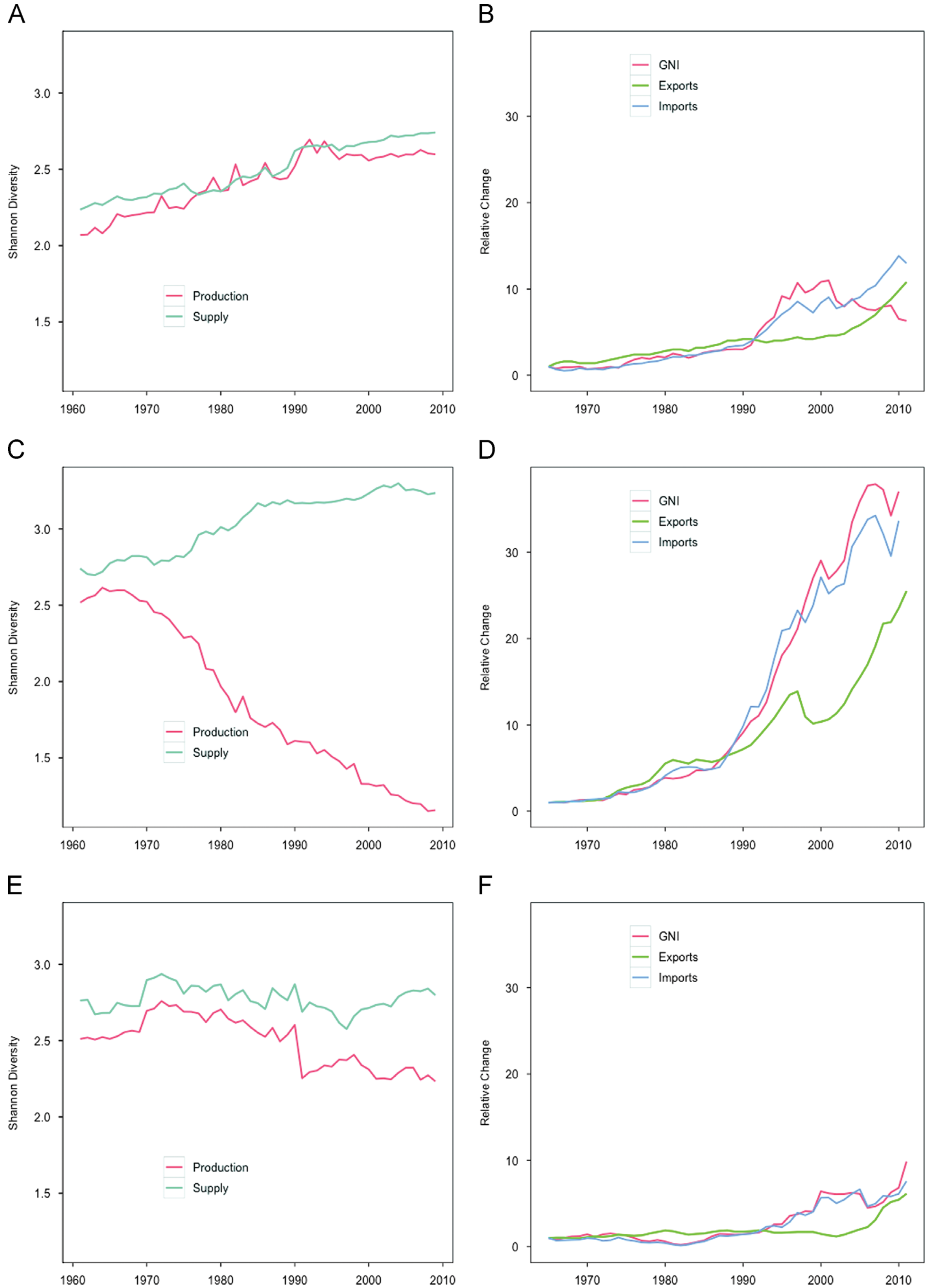

Fig. 3. Patterns of change over time for individual country case studies including Nepal (A, B), Malaysia (C, D) and Ghana (E, F) showing Shannon Entropy diversity (A, C, E) of food production and supply and relative changes in economic indicators compared to 1965 (B, D, F). Fig. S2 shows temporal changes for all diversity metrics.

4. Discussion and policy recommendations

Investment in agriculture is now widely recognized as a critically important opportunity for reducing malnutrition (Herforth et al., 2012; Ruel and Alderman, 2013). But there is limited evidence on how agriculture can improve nutrition outcomes. The pathway between agriculture and nutrition-related health outcomes, including anthropometric measures, is long and complex. The agriculture-nutrition community struggles to build an evidence base on how agriculture is related to these nutrition

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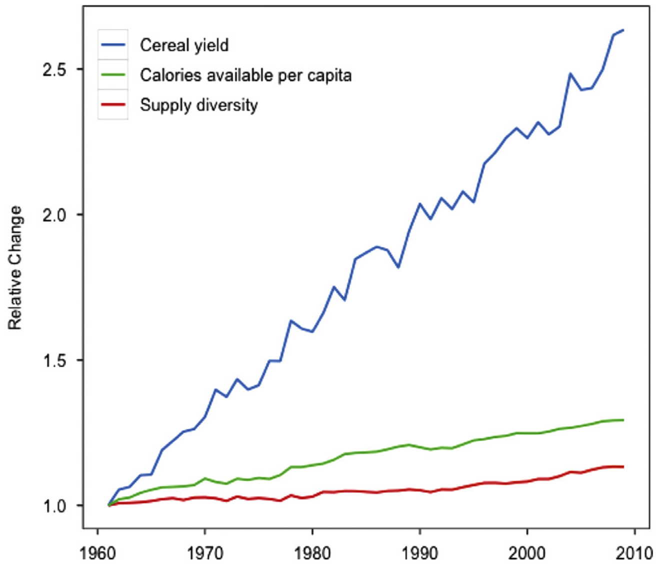

Fig. 4. Changes in food production and supply from 1960 to 2010 at the global scale. Included are data for cereal yield, calories available per capita, and Modified Functional Attribute Diversity (MFAD) of nutritional crop traits for food production and supply. Shannon entropy and percent of energy from non-staples is presented in Fig. S2. The *y*-axis represents the relative change of each variable compared to its baseline in 1960.

health outcomes, which are impacted by a multitude of different factors. In addition, the programs considered in combined agriculture and nutrition reviews are mostly all community-based approaches focused on home production and consumption. The impact of larger agricultural programs (e.g., national subsidy programs, agricultural extension programs, irrigation investments, agricultural trade policies, etc.) on nutrition-related outcomes is still largely unknown (Domenech and Ringler, 2013; Webb, 2013).

Our national-level assessment illustrates that metrics are available for national agricultural and food security strategies to consider nutritional diversity. Our results demonstrate the importance of diversity in national food systems for key nutrition health outcomes and thereby offer a potential intermediate indicator in the agriculture–nutrition pathway to which agricultural and food strategies can work towards in order to contribute to improve nutrition. As new investments and attention galvanize action on the potential role of agriculture for nutrition, a vigorous debate is required to ensure that agricultural progress is evaluated based on metrics that go beyond economic cost/benefit ratios and calories per person, but that also consider the limitations of agriculture to impact nutrition health outcomes. The identification of intermediate indicators, such as diversity of production and supply systems that address the complexity of nutritional diversity required for human health, is therefore important. Here we contribute to this process by providing practical candidate metrics and also hopes to stimulate research to identify other important pathway indicators or alternative metrics.

Calculation of the diversity metrics used in this study is straightforward and can be applied to different systems and scales, which makes comparison feasible between settings and studies. A recent study in Malawi demonstrates a positive association between farm production diversity and dietary diversity at the household level (Jones et al., 2014), similar to the relationship we identified between production and supply diversity at the national level across low-income countries. This illustrates the usefulness of diversity metrics at different scales of the food system.

Diversity in food systems is not only important for nutrition outcomes, but can benefit multiple aspects of the food system. Species diversity has been shown to stimulate productivity, stability, ecosystem services, and resilience in natural and in agricultural ecosystems (Cadotte et al., 2012; Gamfeldt et al., 2013; Zhang et al., 2012; Kremen and Miles, 2012; Khoury et al., 2014). In general, increasing the number of species in a community or system will enhance the number of functions provided by that community, and will reinforce the stability of provision of those functions (DeClerck et al., 2011). By using diversity metrics in agriculture–nutrition strategies, synergies with other outcomes, e.g. environmental benefits, can be evaluated and become more likely. In view of global national food supplies that have become more homogeneous in composition (Khoury et al., 2014), monitoring and ensuring diversity for nutrition and other outcomes seems increasingly important.

Our results also suggest that strategies for addressing nutritional gaps should be tailored to the economic and agricultural conditions in particular countries. For example, low-income countries might target diversification of production, while middle- and high-income countries could focus on using economic capital to purchase nutritional diversity on international markets.

Current differences between regions in food supply diversity as observed in this study correspond to patterns in human trophic level (Bonhommeau et al., 2013). For example, human trophic levels and food supply diversity are highest in North America, Europe, Australia and parts of Latin America. Most countries in Sub-Saharan Africa and South Asia present low food supply diversity and a relatively low human trophic level (Bonhommeau et al., 2013).

The larger variability within regions for production than for supply diversity suggests an important role for regional markets in food trade. Existing regional market systems (e.g. the European Union (EU), the Common Market for Eastern and Southern Africa (COMESA), the Economic Community Of West African States (ECOWAS), Association of Southeast Asian Nations (ASEAN)) have indeed a strong agriculture and food trade dimension and are expected to play an important buffering role for food security, particularly in times of crises and price volatility (Hebebrand and Wedding, 2010; Chandra and Lontoh, 2010).

Regional and global markets also contribute to the increasing homogeneity of global food supplies (Khoury et al., 2014). Globally national food supplies have become more and more similar in composition, based upon a suite of truly global crop plants (Khoury et al., 2014). The growth in reliance on these crops heightens interdependence among countries in their food supplies, plant genetic resources and nutritional priorities and proposes a threat for future options for food security (Khoury et al., 2014).

Some major limitations of our analyses need to be emphasized in order to correctly interpret these results. First, by limiting our analysis to the national level we do not address important household-level barriers to food production, access and utilization or differences in distribution of income, agro-ecological settings and food security within countries. Food and nutritional security is ultimately a household-level property affected by numerous social, political, and economic factors at multiple scales, ranging from household-level decisions to national policies and international markets (UNICEF, 1990). It is however interesting to note that some of the patterns we identify at national scale are also observed at household scale (Jones et al., 2014).

Second, given the nature of the model, we cannot claim causality for any of these production- supply- health relationships. We report on associations, not on causal relationships. Third, we use secondary national level data and the insights of our analysis are dependent on the quality of these data. Not all food items produced in a country are reported by FAOSTAT, particularly less utilized indigenous crops are missing in the global database and thus are not considered in our calculations. Field studies would enrich our diversity calculations, and local market studies could add a dimension of price and access to our assessments.

Despite these limitations, our study allows to formulate two key policy recommendations for healthy food systems:

1. To include measures of food production and supply diversity into national monitoring and decision-making,
2. To aim for national food supply diversity through production and trade, for which the balance needs to be considered based on the local and global context, in particular the country's national income and access to regional and global markets, and the role of agricultural biodiversity for other aspects of environmental and human health.

Examples of agricultural interventions that contribute to diversity in food availability and diets can be found in studies performed at household and community level. Investments in home-gardens, the production and promotion of animal-based products, legume intercropping/rotational cropping and agroforestry, have shown potential to enhance diversity of the food basket at community and household level (Ruel, 2001; Masset et al., 2011, Leroy and Frongillo, 2007; Kawarazuka, 2010; Fanzo et al., 2013; Dawson et al., 2013). Questions as to which agricultural, market or institutional interventions can be employed to enhance diversity at a national scale, remain however largely unanswered and trigger new interesting domains for operational nutrition-sensitive research.

Diversity metrics, such as those used in our study, offer a way to monitor nutritional diversity in the design and evaluation of agricultural and food system policies that better meet the nutritional needs of a healthy population (Story et al., 2008; Hawkes, 2012). Our national-level assessment demonstrates the importance of diversity in national food systems for key human-health outcomes and suggests that national agricultural strategies for addressing nutritional gaps should be tailored to the economic and agricultural conditions in particular countries. Doing so may alleviate some of the barriers to meeting nutritional needs by eliminating policies bolstering production strategies that impinge on nutrition security and/or introducing policies to promote diversification towards the production of more nutritious foods.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.gfs.2014.07.001.

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