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Measuring nutritional quality of agricultural production systems: Application to fish production

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ABSTRACT

Reorienting food systems towards improving nutrition outcomes is vital if the global goal of ending all forms of malnutrition is to be achieved. Crucial to transitioning to nutrition-sensitive agriculture is valuing and measuring nutritional quality of the outputs of agricultural production. We review existing indicators which capture an element of nutritional quality applicable to different stages of the food and nutrition system. Applying relevant indicators from the agricultural production stage to selected aquaculture systems, we compare and contrast their strengths and limitations. 'Nutritional yields', 'potential nutrient adequacy' and 'Rao's quadratic entropy' show particular promise in capturing the ability of a production system to nourish the most people and could be useful tools for prioritising investments and decision-making in the public, non-government and private sectors driving agriculture.

1. Introduction

Malnutrition in its various forms directly affects one third of the global population and combined with poor diets, is the leading driver of the global burden of disease (IFPRI, 2016). At the heart of this problem are food systems which are narrowly focused on maximising yields and economic value, without due consideration of the impacts on human health. Through the Sustainable Development Goals (SDGs), the world has committed to ending all forms of malnutrition (United Nations, 2015). Reorienting food systems across all actors and levels, towards improving nutrition outcomes (nutrition-sensitive food systems) is central to achieving this goal, as was recognised in the second International Conference on Nutrition (ICN2) Framework for Action (FAO and WHO, 2014). In line with this, The Global Panel on Agriculture and Food Systems for Nutrition has recently called for a paradigm shift in food systems thinking away from 'feeding people' to 'nourishing people', emphasising the importance of nutrition as an outcome of food systems (Global Panel on Agriculture and Food Systems for Nutrition, 2016). This is further strengthened in the recently declared United Nations (UN) Decade of Action on Nutrition 2016–2025 which aims to increase visibility of nutrition at the highest levels and ensure measurement of progress towards sustainable food systems (FAO and WHO, 2016). It is suggested here that a vital advancement in this pursuit lies in valuing and prioritising nutritional quality of agricultural production rather than yields alone. Decision-making at the farm level depends on a complex interplay of on-farm factors including socioeconomic and biophysical conditions; and off-farm factors including access to markets, support services (e.g. agricultural extension), scientific and indigenous knowledge, and policies, rules and regulations (French, 1995). The public sector, non-government organisations, and the private sector all play important roles in influencing such factors and therefore the production systems which farmers choose to adopt. It is envisioned that a clear and simple indicator of nutritional quality could assist decision-makers, through their traditional levers of influence (such as input subsidies, agricultural extension support, and market incentives), to encourage farmers to improve nutritional quality of production, and therefore progress this paradigm shift. The objective of this analysis is to examine indicators which capture the ability of a production system to nourish the most people which could be useful for decision-making in agricultural production systems.

Food systems can be conceptualised as consisting of all of the inputs and activities required to produce and distribute food for human consumption. Various conceptual models of food systems include several stages such as agricultural production (consisting of a number of subsystems), distribution, and consumption; each of which involves inputs, which undergo transformation and result in various outputs which

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continue their flow throughout the system (Global Panel on Agriculture and Food Systems for Nutrition, 2016; Ingram, 2011; National Health and Medical Research Council, 2013). Several authors propose a broader concept of food systems which incorporates nutrition and health outcomes, emphasising the interdependence of agricultural production, food consumption and nutritional status (Burchi et al., 2011; Nugent, 2011; Sobal et al., 1998). An advantage of this conceptual approach is that an understanding of the drivers of, inputs to, transformations within, interactions between, and outputs at each stage of the system allows more effective guidance of interventions at various stages in the system to achieve desired nutrition and health outcomes.

Within the food and nutrition systems framework (see Fig. 1), it is clear that nutritional quality of foods as consumed (the inputs of the consumption stage), in turn (albeit with varying and often considerable processing and transformation) rely on the nutritional quality of outputs from the agricultural production stage (whether at a local or global scale). It is recognised that processed foods play an increasingly larger role in dietary patterns across the world (Baker, 2016). However this should not detract from the fact that many whole foods, such as fruit, vegetables and animal- source foods, particularly in rural food systems still pass from production to consumption relatively unchanged in terms of nutritional value. The premise here is that whilst food processing and markets have a key role to play in improving food safety, reducing loss and waste, improving shelf life and providing convenient and nutritious foods; the basis of all foods (processed or not) must be *production* of high quality food. There is a large body of literature on methods and indicators for measuring nutritional quality of diets as consumed (see indicators related to the consumption stage in Fig. 1), however, significantly less work has been done on measuring nutritional quality of the outputs of the agricultural production stage. This is because agricultural production systems are not designed explicitly to meet the health and nutrition needs of populations; but rather, to maximise yield and economic gains for producers (Bouis and Welch, 2010). It is anticipated that calls to action for agriculture to become more nutrition-sensitive, will not be realised unless a nutritional quality dimension is incorporated into measurement of outputs.

There is on-going tension between the benefits of diverse agricultural production systems and the economies of scale feasible with less diverse systems, for achieving high quality diets (Fanzo, 2017). Greater on-farm production diversity can improve dietary quality of household members (Jones, 2014, 2017; Jones et al., 2014; Koppmair et al., 2017). On the other hand, a more market-oriented approach to production (assuming adequate access to markets) can increase income, allowing the household to purchase nutrient-rich foods (Koppmair et al., 2017; Sibhatu et al., 2015). However, as others have noted, this debate fails to capture the relationship between production and consumption across scales (Fanzo, 2017; Remans et al., 2015). Global food production has become increasingly homogenous (Khoury et al., 2014). In Bangladesh, increased supply of fish through rapid expansion of aquaculture has failed to improve nutritional quality of diets (Bogard et al., 2017). People are eating more fish, but intakes of vital micronutrients from fish have actually decreased, related to the generally lower nutritional quality of farmed species compared to the nutrient-rich small indigenous species from capture fisheries. This demonstrates that individual production sub-systems must have an impetus to maximise nutritional quality, irrespective of market orientation.

This study presents a comparative analysis of the merits and limitations of existing indicators that capture some elements of nutritional quality of the outputs of agricultural production sub-systems (individual systems within the production stage of the broader food and nutrition system, Fig. 1). First, a brief summary of available indicators, how they are calculated and a discussion of some of the contexts in which they have been previously applied, is provided. Next, a case study of aquaculture production systems in Bangladesh (as an example of an agricultural production sub-system) is presented as the context for application and comparison of selected indicators. The conclusions drawn from this analysis are used to inform recommendations for inclusion of appropriate indicators in the evaluation of agricultural production sub-systems to maximise their potential to not only feed people, but to nourish them.

2. Methods

Two comprehensive collections of indicators have been published recently which are highly relevant for this analysis. The first is a user's guide for 33 types of existing indicators that measure the various dimensions of food and nutrition security published by the Food Security Information Network global initiative and essentially provides a benchmark for the adequacy of the food and nutrition system (Lele et al., 2016). The second is a compendium of 58 indicators for nutrition-sensitive agriculture published by the Food and Agriculture Organization, which presents a best-practice guide for measuring the impact of agricultural interventions on nutrition (Herforth et al., 2016). An additional indicator (nutritional yield) not captured in the above reviews, but highly relevant to this analysis, was identified in the recent literature and so is included here (DeFries et al., 2015). Indicators from these sources were examined for their relevance in capturing some aspects of food/nutrient availability, access, consumption or utilisation (n = 43). Indicators which capture important determinants of nutrition and health outcomes, but are not explicitly relevant to food or nutrients were excluded from this analysis (e.g. indicators of sanitation, income, women's empowerment). Applicable indictors were then categorised according to the relevant food and nutrition system stage (see Fig. 1), based on the scale at which data is collected in order to calculate the indicator (e.g. the indicator ‘availability of specific foods in markets’ is based on data collected at the market level, and so grouped in the distribution stage). Indicators relevant to the agricultural production stage were then further examined; indicators (n = 4) which are only relevant in the context of total food supply and therefore are not useful for decision-making around individual production sub-systems (e.g. sub-systems 1.1–1.5, in Fig. 1), are listed in Fig. 1 for completeness, but are excluded from further analysis. For example, a common indicator used by the Food and Agriculture Organization (FAO) as a reflection of nutritional quality of the food supply, is the percentage of dietary energy from non-staple foods, with a high proportion of energy from non-staple foods reflecting a more diverse food supply. However, this indicator does not offer any interpretation of the nutritional quality of outputs from an individual production sub-system, such as a rice production system.

Based on this process, two groups of indicators were identified that are relevant for further discussion as measures of nutritional quality of the outputs of agricultural production sub-systems; nutritional yield, and measures of functional diversity (including production diversity). It is noted that the various indicators discussed here are only relevant to agricultural production that is destined for human consumption and therefore excludes crops such as tobacco, cotton and jute. A summary of each relevant indicator, including a description, method of calculation, strengths and limitations is included in Table 1.

3. Indicators of nutritional quality of agricultural production

3.1. Nutritional yield

Nutritional yield is defined as the “number of adults who would be able to obtain 100% of the dietary reference intakes (DRI) of different nutrients for one year from a food item produced annually on one hectare” (DeFries et al., 2015). It is calculated separately for individual nutrients, which could be combined into an index score of selected nutrients of interest in a given context. So far, this indicator has been applied to cereal crop production in two studies, one in India (Defries et al., 2016), and one on the global scale (DeFries et al., 2015). A modified version of this indicator was also included in recent analyses

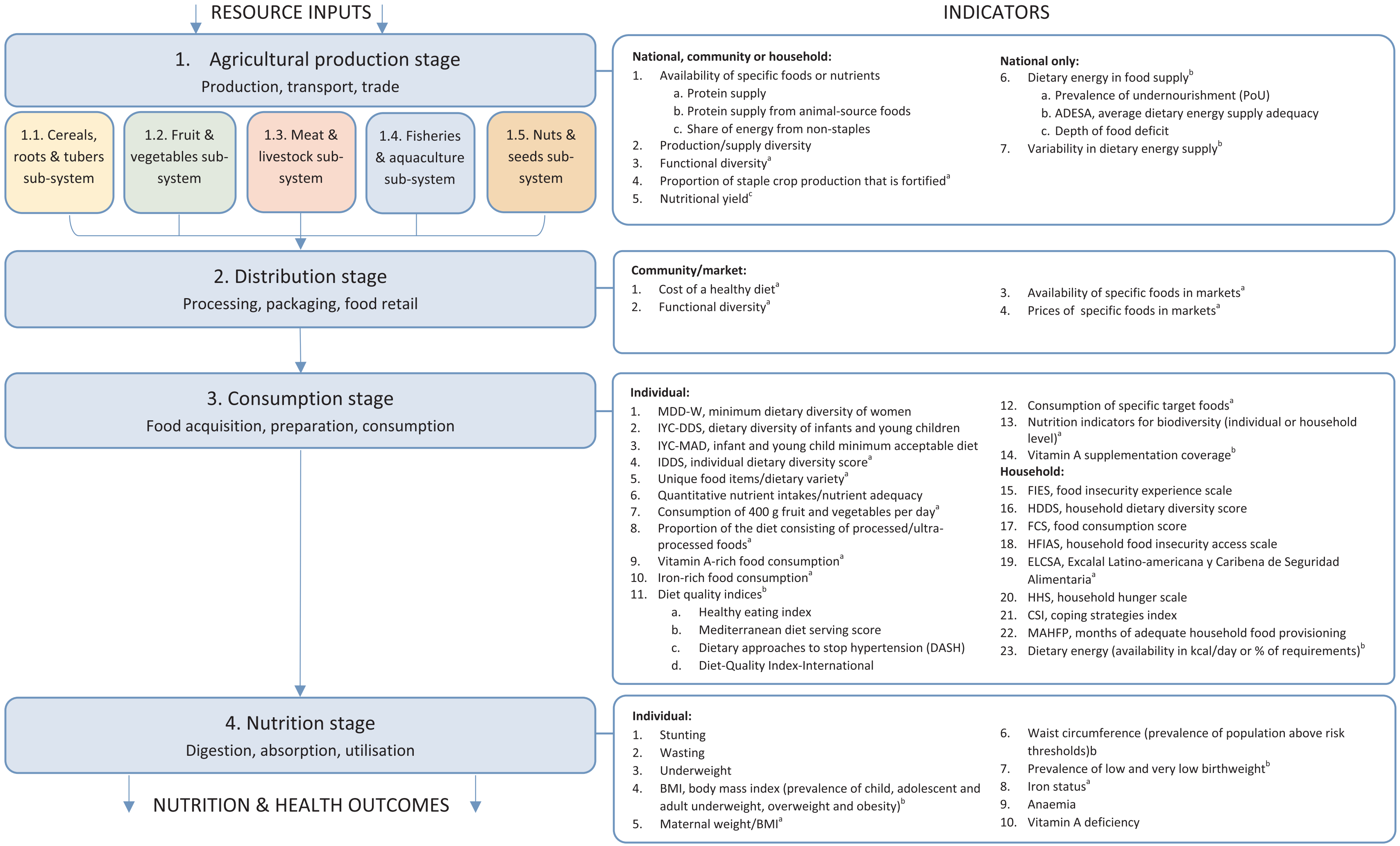

Fig. 1. Schematic diagram of the food and nutrition system, including four main stages and indicators relevant to nutritional quality. Source: Authors, schematic adapted from Heywood and Lund-Adams (1991) and Sobal et al. (1998). Indicators from Herforth et al. (2016) and Lele et al. (2016). Note that the schematic is presented linearly, though in reality there are likely to be multiple feedback mechanisms at play throughout the system. [a] Indicator mentioned only in FAO compendium. [b] Indicator mentioned only in FSIN technical guide. Indicators with no superscript were included in both sources. [c] Indicator identified in published literature elsewhere, but included here as highly relevant for this analysis.

Table 1
Summary of indicators that capture an element of nutritional quality of food production sub-systems.

Indicator	Description	Method of calculation	Strengths	Limitations
Nutritional yield (NY)	Number of adults who would be able to obtain 100% of the dietary reference intakes (DRI) of selected nutrients for one year from a food produced annually on one hectare	$NY_{ij} = \frac{fraction\ of\ DRI_i}{100_{gi}} \times \frac{tonnes_i}{ha\ /\ yr} \times \frac{10^4}{365}$ i = the selected nutrient of interest j is the selected food item DRI for nutrient i = average recommended daily allowance (RDA) of a female (not pregnant or lactating) and male adult, aged 19–50 years Fraction of DRI for nutrient i = contribution to DRI from 100 g of the food item of interest	Relatively simple to calculate and interpret; accounts for differences in quantities of foods/species produced	Needs to be calculated for each individual nutrient of interest so does not reflect overall nutritional quality (across several nutrients in a single score)
Potential nutrient adequacy (PNA)	Magnitude of the fraction of people potentially nourished, weighted by the evenness of potential nutrient adequacy across all of the nutrients of interest	$PNA = \frac{\sum_{i=1}^{N}[s_i > 1]}{N} * \overline{S}$ N = population S = nutritional yield for selected nutrients i	Captures difference in nutrient composition of foods produced and their relative quantity, across multiple nutrients in a single score	Relatively more complex to calculate. Requires data on population which may be a limitation in some contexts.
Production diversity (PD)	Number of foods produced by a given entity such as a farm or household	Simple count of foods, species or food groups in a defined production system	Relatively simple to calculate and interpret	Does not reflect differences in quantities or nutrient composition of different foods produced
Shannon diversity (H)	Number of foods produced by a given entity such as a farm or household, weighted by the relative abundance of each food. It quantifies the uncertainty in predicting the type of food randomly selected from a defined population.	$H = \sum_{i=1}^{S} -(P_i \times \ln P_i)$ P_i = fraction of the entire population made up of species i S = numbers of foods encountered ln = natural logarithm	Captures differences in quantities[a] of foods produced (the evenness in production)	Does not reflect differences in nutrient composition of foods produced
Simpsons index (SI)	Number of foods produced by a given entity such as a farm or household, weighted by the relative abundance of each food. It quantifies the probability that two foods randomly selected from a defined population will be the same type.	$SI_i = 1 - \sum s_j^2$ S_j = fraction of the entire population i made up of food j	Captures differences in quantities[a] of foods produced (the evenness in production)	Does not reflect differences in nutrient composition of foods produced
Nutritional functional diversity (NFD)	Diversity of nutrients and complementarity in nutrients among foods produced on a farm relative to nutrient needs for optimal human health	$NFD = \frac{\Delta d + \overline{dG}}{\Delta \lvert d \rvert + dG}$ Δd = sum of abundance weighted deviances Δ|d| = absolute abundance weighted deviances from the centre of gravity dG = mean distance to centre of gravity	Captures difference in nutrient composition of foods produced across multiple nutrients in a single score	Does not account for differences in quantity of foods produced
Modified functional attribute diversity (MFAD)	Diversity of nutrients and complementarity in nutrients among foods produced on a farm relative to nutrient needs for optimal human health	$MFAD = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n} d_{ij}}{N}$ n = number of foods d = dissimilarity between each food i and j (as measured by nutrient composition of selected nutrients using a distance algorithm). N = number of functional units, where a functional unit represents the number of food which are nutritionally distinct (i.e. two foods with the same nutrient composition would be considered one functional unit).	Captures difference in nutrient composition of foods produced across multiple nutrients in a single score	Does not account for differences in quantity of foods produced
Rao's quadratic entropy (Q)	Diversity of nutrients provided by the system, weighted by the relative abundance of each food	$Q = \sum_{i-1}^{S-1}\sum_{j=i+1}^{S-1} d_{ij} p_i p_j$ S = total food richness d = dissimilarity between each food i and j (as measured by nutrient composition of selected nutrients using a distance algorithm). p_i = relative abundance of food i	Captures difference in nutrient composition of foods produced and their relative quantity[a], across multiple nutrients in a single score	Relatively more complex to calculate

[a] Note that this is dependent on how quantity or abundance is measured for calculation. In some cases, this may be actual yields from the system over a defined period such as a season or year. It may also be measured as the area of cultivation, as was done, for example, in calculation of the Simpson index by Jones et al. (2014).

of the contribution of different farm sizes to global food and nutrient production (Herrero et al., 2017).

3.1.1. Potential nutrient adequacy

Potential nutrient adequacy (PNA) is an indicator which builds on nutritional yield by calculating the proportion of people in a population potentially nourished, weighted by the evenness of potential nutritional adequacy across all of the nutrients of interest. For example, a production system which meets the nutritional needs of a relatively constant proportion of people across several nutrients of interest would have a higher PNA score compared to one which meets the nutritional needs of a large proportion for some nutrients, and a small proportion for other nutrients. This new indicator is introduced in a recent analysis of household production systems in Senegal (Wood, 2017, forthcoming).

3.2. Functional diversity

Functional diversity indicators stem from ecological sciences in which they are used extensively to assess the degree to which species or varieties in a defined system vary according to specific traits which influence the functioning of the system. Recently, functional diversity indicators have been applied to the field of nutrition in a handful of studies (summarised below), in which the traits of different species or varieties (referred to as foods from now on in this paper), depending on the indicator, are defined by their nutrient composition.

3.2.1. Production diversity

Production diversity reflects the number of different foods produced in a defined system (e.g. a plot of land, farm or household). It does not consider specific nutritional traits of the individual foods, though greater diversity in nutritional quality is implied with higher production diversity. A positive relationship between production diversity in a farming system and various nutrition related outcomes including; household dietary diversity (Dillon et al., 2015; Jones, 2017; Jones et al., 2014; Koppmair et al., 2017; Sibhatu et al., 2015); household food security (M'Kaibi et al., 2015); dietary diversity of women (Keding et al., 2012; Koppmair et al., 2017; Malapit et al., 2015; Torheim et al., 2004) and various measures of child diet quality, feeding practices or anthropometric indicators (Jones, 2014; Koppmair et al., 2017; M'Kaibi et al., 2015; Malapit et al., 2015) has been identified in several studies though not in all circumstances (Keding et al., 2012; Remans et al., 2011). However, production diversity indicators do not account for variability or similarity in the nutrient profiles of distinct foods. For example, a production system with only a few different foods but with very different nutritional qualities (e.g. a farm producing poultry, maize and spinach) may contribute more to a nutritionally complete diet than a system that includes several foods, all of which are nutritionally similar (e.g. three varieties of maize). Conversely, a farm producing only a single crop e.g. orange sweet potato, may be producing multiple nutritionally distinct food items (e.g. green leafy vegetables and starchy roots), but the production diversity (if counting varieties) would only be considered as one. The counting unit used to reflect production diversity, whether it be species, variety, food, or food group, is therefore critical to appropriate interpretation (Berti, 2015).

3.2.2. Shannon diversity and Simpsons index

Shannon diversity (also known as Shannon entropy or the Shannon index) and the Simpson index, are conceptually very similar in that they both build on production diversity by incorporating a measure of the relative abundance of foods produced (though they differ mathematically, see Table 1). For example, they offer a distinction between two farms which both produce three different foods (production diversity of 3); with farm 1) producing equal amounts of foods *a, b* and *c*, in contrast to farm 2) having 80% of production from food *a*, 15% of production from food *b* and 5% from food *c*. The calculation is based on a simple count of the foods produced in addition to a measure of relative abundance, which may be yields in a defined period such as a season or year, or some other measure of abundance such as the unit area of cultivation. Note that how ‘abundance’ is measured is extremely important for how results are interpreted. Shannon diversity and the Simpson index are therefore an improvement on production diversity as they allow for differentiation between farms of the same production diversity with a different distribution of individual foods. Similar to production diversity, Shannon diversity and the Simpsons index do not consider differences in nutrient composition of individual foods. Related to nutrition, Shannon diversity has been used in two recent studies; one presents a regional analysis of global food production and supply diversity (Remans et al., 2014); and the other, in relation to global and regional farm size distributions (Herrero et al., 2017). Related to nutrition, the Simpsons index has been used in a study linking farm level production diversity to household dietary diversity in Malawi (Jones et al., 2014). In this study, the abundance was measured as the area of cultivation of each crop, rather than yields from each crop. It is noted that several other indicators such as the Margalef index and Pielou's evenness index are used in ecology which differ mathematically from Shannon diversity and the Simpson index, but similarly capture elements of diversity and evenness; these are not discussed here to avoid repetition (Khoury et al., 2014; Sibhatu et al., 2015).

3.2.3. Nutritional functional diversity

Nutritional functional diversity (NFD) is defined as ‘the diversity of nutrients provided by a farm and the complementarity in nutrients among species [foods] on a farm’ in relation to the variety of nutrients needed for human health’ (Remans et al., 2011). A system with several foods which are nutritionally similar will have a lower NFD than a system with the same number of foods which are more nutritionally distinct. Calculation of this indicator requires determination of all of the foods within a production system, quantification of the nutrient composition of foods, and a series of cross tabulations of the nutrients provided by those foods. These tabulations can then be used to generate a score which reflects the sum of the distances between foods, determined by distinctness in nutrient composition; a higher score reflects great nutritional diversity. It does not however, reflect differences in abundance or quantity of each food. This indicator has been applied in three studies; one at the farm level in selected villages in Kenya, Malawi and Uganda (Remans et al., 2011); at the household level in Senegal (Wood, 2017, forthcoming); and at the household level in Malawi, applied to home production, market purchases and overall consumption (Luckett et al., 2015).

3.2.4. Modified functional attribute diversity

Modified functional attribute diversity (MFAD) is a measure similar to NFD, which also incorporates a weighting for the number of distinct functional types of foods produced (two foods with the same nutritional value would be considered one functional type) (Remans et al., 2014). Note that MFAD does not consider relative abundance of different foods produced in a system, rather only the *number* of nutritionally distinct foods. This indicator has been used in two global studies; a country and regional analysis of global food production and supply (Remans et al., 2014); and a regional analysis of food production relative to farm sizes (Herrero et al., 2017).

3.2.5. Rao's quadratic entropy

Rao's quadratic entropy (Q) provides a measure of the diversity in nutrient composition of foods in a system, weighted by their relative abundance or yields. So far, Q has not been included in published analyses relevant to human nutrition, though, it is included here in response to limitations recognised in a previous study presenting NFD and the need for indicators that incorporate relative abundance (Remans et al., 2011).

Table 2
Matrix of fish species included in homestead pond polyculture systems explored in this study.

Production sub-system		Rui (*Labeo rohita*)	Catla (*Catla catla*)	Mrigal (*Cirrhinus mrigala*)	Mirror carp (*Cyprinus carpio*)	Silver carp (*Hypophthalmichthys molitrix*)	Tilapia (*Oreochromis niloticus*)	Mola (*Amblypharyngodon mola*)	Darkina (*Esomus danricus*)	Dhela (*Osteobrama cotio cotio*)	Chapila (*Gudusia chapra*)
1	Indigenous carp polyculture	X	X	X							
2	Mixed carp polyculture 1	X	X	X	X						
3	Mixed carp polyculture 2	X	X	X		X					
4	Indigenous carp polyculture + Tilapia	X	X	X			X				
5	Mixed carp polyculture 1 + Tilapia	X	X	X	X		X				
6	Mixed carp polyculture 2 + Tilapia	X	X	X		X	X				
7	Indigenous carp polyculture + Mola	X	X	X				X			
8	Mixed carp polyculture 1 + Mola	X	X	X	X			X			
9	Mixed carp polyculture 2 + Mola	X	X	X		X					
10	Indigenous carp polyculture + Tilapia + Mola	X	X	X			X	X			
11	Mixed carp polyculture 1 + Tilapia + Mola	X	X	X	X		X	X			
12	Mixed carp polyculture 2 + Tilapia + Mola	X	X	X		X	X	X			
13	Indigenous carp polyculture + Mixed SIS	X	X	X				X	X	X	X
14	Mixed carp polyculture 1 + Mixed SIS	X	X	X	X			X	X	X	X
15	Mixed carp polyculture 2 + Mixed SIS	X	X	X		X		X	X	X	X
16	Indigenous carp polyculture + Tilapia + Mixed SIS	X	X	X			X	X	X	X	X
17	Mixed carp polyculture 1 + Tilapia + Mixed SIS	X	X	X	X		X	X	X	X	X
18	Mixed carp polyculture 2 + Tilapia + Mixed SIS	X	X	X		X	X	X	X	X	X

SIS, small indigenous fish species.

Table 3
Nutritional yields and functional diversity of selected pond aquaculture production sub-systems in Bangladesh.

	Production system	**Nutritional Yield**									**Functional Diversity**				
		Energy	**Protein**	**Fat**	**Iron**	**Zinc**	**Calcium**	**Vitamin A**	**Vitamin B12**	**PNA**	**PD**	**H**	**NFD**	**MFAD**	**Q**
1	Indigenous carp polyculture	*1.36	16.33	*0.84	2.79	*3.59	17.04	1.27	69.31	1.17	*3	*1.1	0.86	*0.52	*5432
2	Mixed carp polyculture 1	1.39	*16.11	1.01	2.63	4.34	13.17	0.99	54.38	0.98	4	1.39	1.02	0.76	6888
3	Mixed carp polyculture 2	1.44	16.30	1.16	4.23	3.74	22.23	0.95	54.38	1.09	4	1.39	1.45	0.79	7047
4	Indigenous carp polyculture + Tilapia	1.40	16.84	0.89	2.63	3.59	13.77	1.14	55.03	0.99	4	1.39	1.00	0.72	6606
5	Mixed carp polyculture 1 + Tilapia	1.42	16.56	1.02	*2.53	4.19	*11.33	0.94	*45.95	*0.87	5	1.61	1.17	0.96	6685
6	Mixed carp polyculture 2 + Tilapia	1.46	16.71	1.14	3.81	3.71	18.58	*0.91	*45.95	0.96	5	1.61	1.60	1.01	6971
7	Indigenous carp polyculture + Mola	1.56	18.21	1.11	4.07	4.70	21.17	ˆ23.32	85.42	2.77	4	1.31	1.45	0.95	20,925
8	Mixed carp polyculture 1 + Mola	1.59	17.99	1.28	3.91	5.44	17.30	23.04	70.49	2.45	5	1.57	1.62	1.2	23,214
9	Mixed carp polyculture 2 + Mola	1.64	18.18	ˆ1.44	5.51	4.85	26.36	23.00	70.49	ˆ3.16	5	1.57	1.81	1.21	23,230
10	Indigenous carp polyculture + Tilapia + Mola	1.60	ˆ18.72	1.16	3.91	4.70	17.91	23.19	71.15	2.47	5	1.57	1.60	1.18	22,890
11	Mixed carp polyculture 1 + Tilapia + Mola	1.62	18.45	1.29	3.81	5.29	15.46	23.00	62.06	2.27	6	1.77	1.77	1.42	23,638
12	Mixed carp polyculture 2 + Tilapia + Mola	ˆ1.66	18.60	1.41	5.09	4.82	22.71	22.97	62.06	2.90	6	1.77	1.95	1.45	ˆ23,780
13	Indigenous carp polyculture + Mixed SIS	1.54	18.04	1.07	4.31	4.71	21.89	10.42	ˆ85.55	2.56	7	1.45	2.42	1.92	12,730
14	Mixed carp polyculture 1 + Mixed SIS	1.57	17.82	1.24	4.15	ˆ5.46	18.02	10.14	70.62	2.24	8	1.71	2.58	2.2	15,026
15	Mixed carp polyculture 2 + Mixed SIS	1.62	18.01	1.40	ˆ5.75	4.86	ˆ27.08	10.10	70.62	2.91	8	1.71	2.63	2.18	14,995
16	Indigenous carp polyculture + Tilapia + Mixed SIS	1.58	18.55	1.12	4.15	4.71	18.63	10.29	71.27	2.26	8	1.71	2.56	2.23	14,712
17	Mixed carp polyculture 1 + Tilapia + Mixed SIS	1.60	18.28	1.25	4.05	5.31	16.18	10.09	62.18	2.06	ˆ9	ˆ1.91	2.73	ˆ2.49	15,463
18	Mixed carp polyculture 2 + Tilapia + Mixed SIS	1.64	18.43	1.37	5.33	4.83	23.43	10.06	62.18	2.65	ˆ9	ˆ1.91	2.77	ˆ2.49	15,566

PNA, potential nutrient adequacy; PD, production diversity; H; Shannon diversity; NFD, nutritional functional diversity; MFAD, modified functional attribute diversity; Q, Rao's quadratic entropy. Note that functional diversity indicators were calculated based on 7 'traits' which are the nutrient composition of species relative to average daily recommended intakes for adults for seven macro- and micronutrients: protein, fat, iron, zinc, calcium, vitamin A and vitamin B12.

ˆ Highest value within a column.

* Lowest value within a column.

4. Case study: fisheries in Bangladesh

Fish is the most important animal-source food in the Bangladeshi diet, both in terms of quantity and frequency of consumption across all population groups (Belton et al., 2014; Bogard et al., 2016). Fish production systems are in transition in Bangladesh, as they are also globally. Capture fisheries production is stagnant, and demand for fish is increasingly being met by growth in aquaculture (fish farming). Aquaculture production in Bangladesh is dominated by pond polyculture systems (usually a selection of 3–5 carp species) which are mostly for domestic consumption; and shrimp and prawn systems which are largely export-oriented (Hernandez et al., 2017). These pond polyculture sub-systems might be considered 'diverse' because they produce a number of different fish species, but often these species are nutritionally similar and are generally of lower nutritional quality compared to indigenous species from capture fisheries (Bogard et al., 2015). The result of this transition has been that national fish consumption per person per day increased by 30% (from 1991 to 2010, with the largest proportional increase among the extreme poor), but intake of micronutrients from fish did not keep pace, and even declined for some essential micronutrients (Bogard et al., 2017). It is worth considering whether inclusion of a measure of nutritional quality in the research and development phases of aquaculture systems would have influenced the combination of species selected for production. Measurement of nutritional quality (using the indicators described in the previous section) of the outputs of different production sub-systems commonly in use, may provide useful insights into how those sub-systems that offer the greatest potential to nourish the most people could be prioritised in policy and decision-making.

4.1. Methods

The nutritional quality of outputs of 18 distinct pond polyculture production sub-systems (see Table 2) was analysed, using selected indicators; nutritional yield, PNA, production diversity, Shannon diversity, NFD, MFAD and Q. Nutrient composition of fish species used in calculations was sourced from published literature (Bogard et al., 2015). Nutrients examined here; iron, zinc, calcium, vitamin A and vitamin B12 are of public health concern in the context of Bangladesh, based on documented deficiency or inadequate dietary intakes among vulnerable groups (Arsenault et al., 2013; icddrb et al., 2013). Protein, fat and dietary energy are also examined as fish is an important source of these macronutrients. In calculating nutritional yields, instead of using recommended dietary allowances from the USA Institute of Medicine as per original methodology (DeFries et al., 2015), recommended nutrient intakes (RNI) were used, as they were considered more applicable to the Bangladeshi population (FAO and WHO, 2004). Iron requirements were based on 10% bioavailability. RNIs for zinc were taken from the International Zinc Nutrition Consultative Group, assuming an unrefined cereal-based diet, consistent with the typical Bangladeshi diet (Hotz et al., 2004). The following average daily RNIs for women and men, aged 19–50 years are used in the calculations: energy, 10,700 kJ; protein, 44 g; fat, 80 g; iron, 21.6 mg; zinc, 14 mg; calcium, 1000 mg; vitamin A, 550 µg RAE; vitamin B12, 2.4 µg. Functional diversity indicators were calculated using the software FDiversity (version 2008) (Di Rienzo et al., 2008), with guidance from the user manual (Casanoves et al., 2008). Nutritional traits for each production sub-system are defined as the nutrient composition of each species per 100 g raw, edible parts as a proportion of the average adult RNI. The average household size in Bangladesh (4.5 persons per household) was used as the population in calculation of PNA (NIPORT et al., 2015).

Management of pond polyculture systems in Bangladesh vary widely in terms of stocking densities of different species, inputs, harvesting and several other factors, all of which influence yields. Therefore, for the purpose of examining indicators, the total yields of small and large fish from pond polyculture systems used are 204 and 1841 kg/ha/year, respectively, the average yields reported in the literature (Karim et al., 2017). Species included in 'small' and 'large' fish categories for the various systems are based on production systems described in the literature from Bangladesh (Ali et al., 2016; Alim et al.,

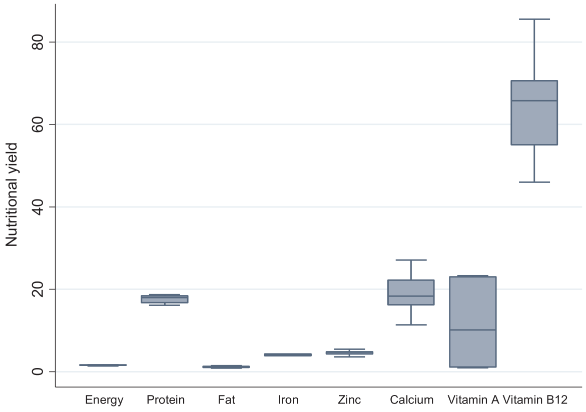

Fig. 2. Nutritional yields of selected pond aquaculture production sub-systems.

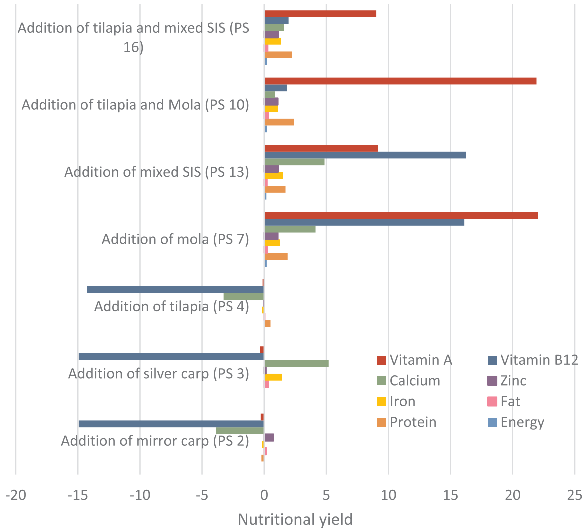

Fig. 3. Change in nutritional yield through addition of different species to the indigenous carp polyculture production system (production sub-system 1).

2005; Murshed-e-Jahan et al., 2015; Roos, 2001). The average yields are distributed evenly across species within a category included in the system. For example, a polyculture system with one small fish species has the same total yield from small fish (204 kg/ha/year) as the system with four species of small fish (51 kg/ha/year per species, a total of 204 kg/ha/year of small fish). This assumption is made due to lack of more detailed data in the literature on species-specific yields of pond polyculture production systems.

4.2. Indicators of nutritional quality of aquaculture production systems

4.2.1. Nutritional yield

The nutritional yield of various nutrients for selected pond aquaculture systems are shown in Table 3. The highest nutritional yield for each nutrient are all from systems which include SIS (sub-systems 7–18); whereas, the lowest nutritional yield for each nutrient are all from large fish systems (sub-systems 1–6). This is driven both by higher overall average yields from systems with SIS, and the higher nutritional value of SIS compared to carp. However not *all* systems with SIS (either mola, (*Amblypharyngodon mola*); or mixed SIS) have higher nutritional yields for fat, iron, calcium and vitamin B12 compared to carp polyculture systems without SIS. Fig. 2 clearly shows that there is very little variation in nutritional yields for energy or fat, some variability in the nutritional yields for protein, iron and zinc, and much larger variability in nutritional yields for calcium, vitamin A and vitamin B12. From a decision-making perspective, it is likely mainly of interest to focus on nutrients which exhibit greater variability across different systems.

Comparisons between nutritional yields of different systems also elucidate how the inclusion or exclusion of particular species influence nutritional yields of the overall system (Fig. 3). For example, compared to the indigenous carp polyculture system (production sub-system 1), inclusion of mirror carp (*Cyprinus carpio)*, silver carp (*Hypophthalmichthys molitrix*) and tilapia (*Oreochromis niloticus*, sub-systems 2, 3 and 4, respectively) – all large fish species, notably reduces nutritional yield for vitamin B12; and inclusion of mirror carp and tilapia (sub-systems 2 and 4 respectively) notably reduces nutritional yield for calcium. This is driven by a smaller proportional contribution to total yield from mrigal (*Cirrhinus mrigala*) which has a relatively high vitamin B12 and calcium content. This highlights that increased diversity in the system may not always increase nutritional quality of the system. Addition of mola or mixed SIS (sub-systems 7 and 13, respectively) to the indigenous carp polyculture system (production sub-system 1) results in the largest increase in nutritional yields, particularly of vitamin A, vitamin B12 and calcium.

Prioritising or selecting one sub-system over another for production based on nutritional yields is not straightforward because there is no single system with higher nutritional yields across all nutrients. This limitation is addressed, however, in calculation of PNA. The lowest PNA score was for production sub-system 5 - mixed carp polyculture with tilapia, whilst the highest PNA score is for production sub-system 9 - mixed carp polyculture with mola.

4.2.2. Functional diversity

Functional diversity of selected pond aquaculture systems is shown in Table 3 and Fig. 4. Production diversity ranges from 3 to 9 species, with the most diverse systems being production sub-systems 17 and 18. The Shannon index reflects a combined measure of diversity and evenness in abundance of the different species. For example, sub-systems 2, 3, 4 and 7 all produce four different fish species, but the higher Shannon Index for sub-systems 2, 3 and 4 compared to sub-system 7 indicates that the abundance of the four species in those systems is more evenly distributed.

NFD and MFAD both reflect a similar pattern to production diversity and Shannon diversity. NFD and MFAD are both lowest for the indigenous carp polyculture system (sub-system 1), and highest for the carp polyculture with tilapia and mixed SIS (sub-system 17 and 18). Adding mixed SIS to the carp polyculture system increases MFAD substantially (sub-system 13, 14 and 15 around three-fold higher than sub-systems 1, 2 and 3 respectively), whilst adding Tilapia to the carp polyculture system only increases MFAD slightly (sub-systems 4, 5 and 6 compared to sub-systems 1, 2 and 3 respectively). This reflects the large diversity in micronutrient content that is added to the production system with mixed SIS. Q exhibits a different trend (see Fig. 4e), whereby the carp polyculture systems with mola (systems 7–12) have much higher values of Q than carp polyculture systems with mixed SIS (systems 13–18) and carp polyculture systems with large fish only (sub-systems 1–6). This indicates that when abundance (or quantity of individual species) is taken into account, those systems which include mola as the predominant SIS (systems 7–12) are of higher nutritional quality. From a decision-making perspective, in this case, the use of production diversity, Shannon index, NFD and MFAD, would each lead to the same conclusion: production sub-system 18 to be prioritised. However, if Q were the indicator of choice, the sub-system for prioritisation would be sub-system 12.

5. Discussion and conclusion

Examination of existing indicators which capture some element of nutritional quality, in reference to the different stages of the food and nutrition system highlights that there are a large number of indicators relevant to the latter stages of the system (particularly the consumption stage), and much fewer indicators relevant at the agricultural

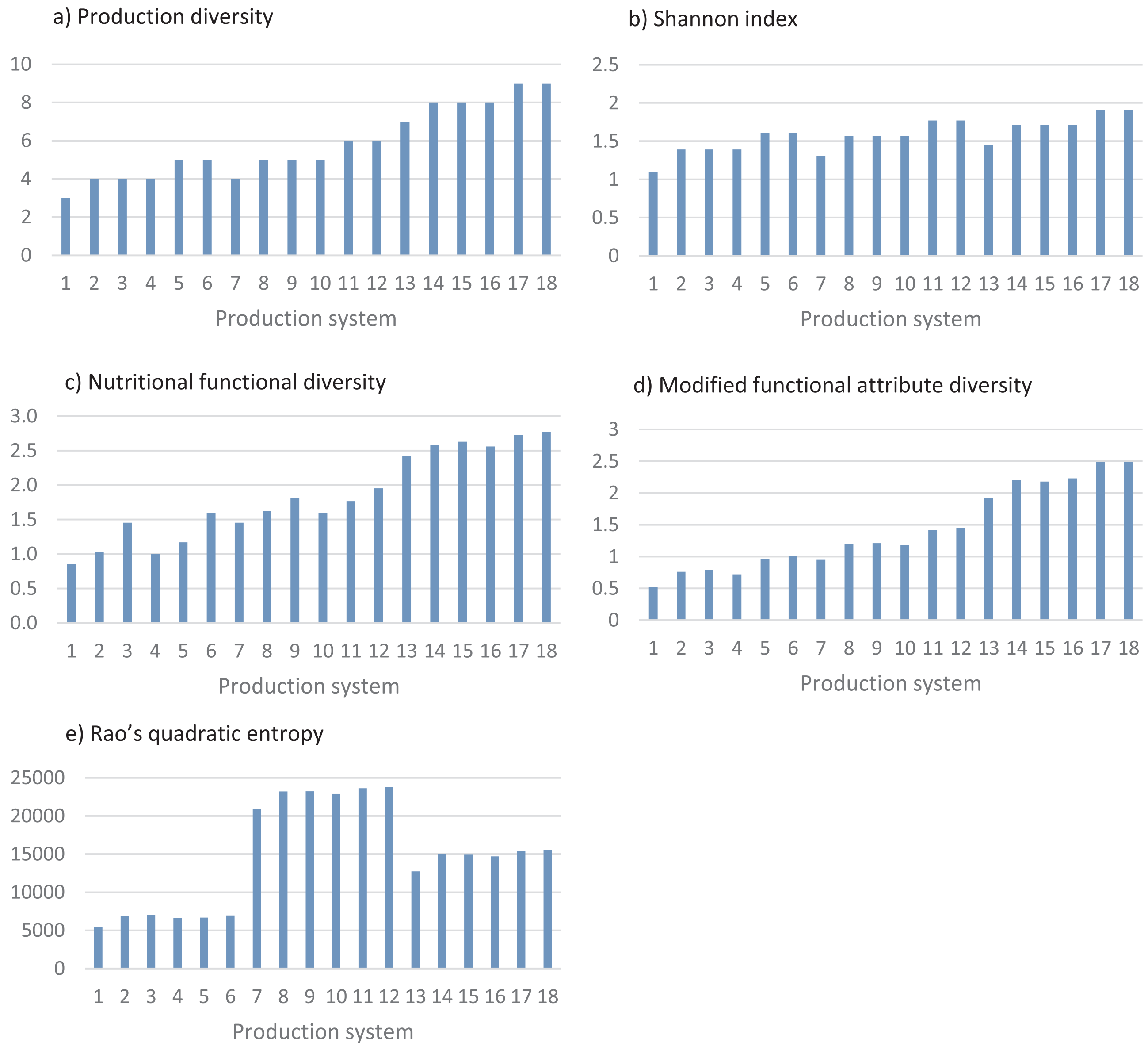

Fig. 4. Nutritional diversity indicators of common fish production sub-systems (based on seven nutrients; protein, fat, iron, zinc, calcium, vitamin A and vitamin B12).

production stage. By applying different indicators to selected aquaculture production sub-systems, it is clear that they capture quite different aspects of nutritional quality, so use of a combination of different indicators is needed for comprehensive evaluation. The purpose here was to identify indicators which capture the ability of a production sub-system to nourish the most people, and which could potentially be useful for decision-making and prioritising of agricultural production sub-systems. Indicators, therefore, which reflect nutrient composition of species produced, diversity in nutrients produced, and the abundance or quantity of those nutrients, and at the same time are simple to calculate and interpret by decision-makers are desirable. Such indicators are of significant value in many countries where agricultural policy is linked to nutrition outcomes, as they offer an objective method by which such policies can be mobilised and evaluated. This is also likely to be of increasing relevance as national level policies are developed in response to the SDGs and the UN Decade of Action on Nutrition described in the introduction of this paper.

Nutritional yields are relatively simple to calculate, and reflect both the nutrient composition of foods and the quantities in which those foods are produced by different sub-systems. One potential disadvantage, depending on the policy context, is that the indicator is calculated for individual nutrients which does not allow for comparison of the nutritional quality of the production sub-system overall. From a policy and decision-making perspective, if production of a single nutrient is to be prioritised, then interpretation is simple; however, given that micronutrient deficiencies rarely occur in isolation, this is unlikely to be of practical use. If the policy priority is to maximise production of several nutrients simultaneously, interpretation of nutritional yields is more challenging. This limitation is addressed in the recently proposed PNA, which reflects the proportion of people in a population potentially nourished, weighted by the evenness of potential nutritional adequacy across several nutrients of interest in a single score (Wood, 2017, forthcoming). The case study presented in this paper demonstrates that an important consideration is the degree of variability in nutritional yields for different nutrients, particularly those which are of priority or concern in a given context (e.g. existing micronutrient deficiencies). Rather than attempting to optimise nutritional yields across all nutrients, it is likely mainly of interest to focus decision-making on nutrients which exhibit large variability in nutritional yields across different sub-systems and, therefore, selection of one sub-system over another is likely to have the greatest impact on the potential of the system to nourish people.

An advantage of the various functional diversity indicators is that comparison across different sub-systems is simplified to a single value. The more important question though, is which measure of functional diversity best captures the ability of a system to nourish the most people. The case study presented in this paper shows that sub-systems with the same production diversity can exhibit large variability in other measures of nutritional quality. Therefore, whilst production diversity may provide an indication of nutritional diversity (and the simplest to calculate of all indicators examined here), it fails to capture some important elements. Building on production diversity, Shannon diversity and Simpsons index both incorporate a measure of evenness in abundance of different foods, but neither indicator reflects differences in the macro- or micronutrient content of foods produced in different sub-systems. NFD, MFAD and Q do, though, in different ways and with different meanings. NFD reflects the distinctness in nutrient composition of species within a system; and MFAD is weighted by the number of nutritionally distinct foods within the sub-system. Therefore, maximising NFD or MFAD may be an appropriate goal for production sub-systems which are the primary source of foods and nutrients for a particular population group (for example, in settings with limited market access where household members rely on own production for consumption). In contrast, Q is weighted by the abundance or quantity of different foods from the production sub-system. In this sense, maximising Q is likely an appropriate goal, if seeking to maximise the potential of the sub-system to nourish the most people, with nutrients of interest. Returning to the case study presented in this paper; had nutritional quality (as measured by PNA or Q) been one of the deciding factors for the kinds of aquaculture systems promoted by the extension services and supported through other policy levers, production systems in Bangladesh would undoubtedly differ from what exist currently. Specifically, polyculture systems incorporating mola (particularly production sub-systems 9 and 12, see Table 2) may have been more actively promoted.

There are several limitations to this analysis. In keeping the focus on the agricultural production stage of food systems, the review of indicators focused on key sources in the food and nutrition security literature, thereby, potentially excluding indicators of nutritional quality from other sources. In the presentation of the case study, due to the paucity of species-specific yield data in the literature for common aquaculture systems in Bangladesh (yields are commonly reported in broader categories such as 'indigenous carp species' or 'small fish'), the sensitivity of the results is limited. Related to this, the production sub-systems presented in the case study are realistic of the kinds of systems commonly found in Bangladesh. However, the sub-systems which include mola and other small fish do not reflect 'optimised systems' for which optimal management practices have been developed, under experimental conditions. From a decision-making perspective, this limits the utility of comparing results across these sub-systems.

In reality, there are multiple factors that must be considered when prioritising among alternative production sub-systems. These include the cost of inputs, labour requirements, environmental impacts, yield and market value of the foods produced. Furthermore, decisions about which foods to produce are ultimately made by farmers, based on their own priorities, knowledge, skills and resources. It is impractical to assume that farmers can or will simply shift to production systems of higher nutritional quality, without economic or other benefits. However, there are a number of levers which can be put to use at policy and programme level to influence and encourage certain practices for improving the nutritional quality of the outputs of production sub-systems. For example, with appropriate high-level support and capacity development, agricultural extension services, through provision of improved information, training, skills and services can promote production systems of higher nutritional quality (Fanzo et al., 2015). From a policy perspective, the public sector can play a role through the provision of financial incentives, for example, subsidised costs of agricultural inputs needed for production sub-systems which maximise nutritional quality of outputs. Shifting thinking away from 'feeding people' to 'nourishing people' requires a simple measure of nutritional quality relevant at the production sub-system level which can be drawn on to shape policy and decision-making. The indicators presented in this analysis, particularly nutritional yields, PNA and Q are likely to be of significant value as a means to achieving this goal.

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References

Ali, H., et al., 2016. Factors determining the productivity of mola carplet (Amblypharyngodon mola, Hamilton, 1822) in carp polyculture systems in Barisal district of Bangladesh. Aquaculture 465, 198–208. http://dx.doi.org/10.1016/j.aquaculture.2016.09.017.

Alim, M.A., et al., 2005. Effects of increasing the stocking density of large carps by 20% on 'cash' carp–small fish polyculture of Bangladesh. Aquac. Res. 36 (4), 317–325. http://dx.doi.org/10.1111/j.1365-2109.2004.01199.x.

Arsenault, J.E., et al., 2013. Very low adequacy of micronutrient intakes by young children and women in rural Bangladesh is primarily explained by low food intake and limited diversity. J. Nutr. 143 (2), 197–203. http://dx.doi.org/10.3945/jn.112.169524.

Baker, P., 2016. Project Future Trends of Processed Food Consumption. School of Regulation and Global Governance. Australian National University.

Belton, B., et al., 2014. Faltering fisheries and ascendant aquaculture: implications for food and nutrition security in Bangladesh. Food Policy 44, 77–87. http://dx.doi.org/10.1016/j.foodpol.2013.11.003.

Berti, P.R., 2015. Relationship between production diversity and dietary diversity depends on how number of foods is counted. Proc. Natl. Acad. Sci. USA 112 (42), E5656. http://dx.doi.org/10.1073/pnas.1517006112.

Bogard, J.R., et al., 2017. Higher fish but lower micronutrient intakes: temporal changes in fish consumption from capture fisheries and aquaculture in Bangladesh. PLoS One 12 (4). http://dx.doi.org/10.1371/journal.pone.0175098.

Bogard, J.R., et al., 2016. Non-farmed fish contribute to greater micronutrient intakes than farmed fish: results from an intra-household survey in rural Bangladesh. Public Health Nutr. 20 (4), 702–711. http://dx.doi.org/10.1017/S1368980016002615.

Bogard, J.R., et al., 2015. Nutrient composition of important fish species in Bangladesh and potential contribution to recommended nutrient intakes. J. Food Compos. Anal. 42, 120–133. http://dx.doi.org/10.1016/j.jfca.2015.03.002.

Bouis, H.E., Welch, R.M., 2010. Biofortification: a sustainable agricultural strategy for reducing micronutrient malnutrition in the global south. Crop Sci. 50 (2), S20–S32. http://dx.doi.org/10.2135/cropsci2009.09.0531.

Burchi, F., et al., 2011. The role of food and nutrition system approaches in tackling hidden hunger. Int. J. Environ. Res. Public Health 8 (2), 358–373. http://dx.doi.org/10.3390/ijerph8020358.

Casanoves, F., et al., 2008. User Manual FDiversity: Statistical Software for the Analysis of Functional Diversity, First edition. Cordoba, Argentina.

DeFries, R., et al., 2015. Metrics for land-scarce agriculture. Science 349 (6245), 238–240. http://dx.doi.org/10.1126/science.aaa5766.

Defries, R., et al., 2016. Synergies and trade-offs for sustainable agriculture: nutritional yields and climate-resilience for cereal crops in Central India. Glob. Food Secur. 11, 44–53. http://dx.doi.org/10.1016/j.gfs.2016.07.001.

Di Rienzo, J.A., et al. 2008. FDiversity, version 2008. Cordoba, Argentina. Retrieved from 〈www.fdiversity.nucleodiversus.org〉.

Dillon, A., et al., 2015. Agricultural production, dietary diversity and climate variability. J. Dev. Stud. 51 (8), 976–995. http://dx.doi.org/10.1080/00220388.2015.1018902.

Fanzo, J.C., 2017. Decisive decisions on production compared with market strategies to improve diets in rural Africa. The Journal of Nutrition 147 (1), 1–2. http://dx.doi.org/10.3945/jn.116.241703.

Fanzo, J., et al., 2015. Integration of nutrition into extension and advisory services: a synthesis of experiences, lessons, and recommendations. Food Nutr. Bull. 36 (2), 120–137. http://dx.doi.org/10.1177/0379572115586783.

FAO, WHO, 2004. Vitamin and mineral requirements in human nutrition: report of a joint FAO/WHO expert consultation. Geneva: Food and Agriculture Organization, World Health Organization.

FAO, WHO, 2014. Framework for Action: outcome document. Second International Conference on Nutrition. Rome, Italy: Food and Agriculture Organization.

FAO, WHO, 2016. United Nations Decade of Action on Nutrition 2016–2025. Food and

Agriculture Organization of the United Nations.

French, J.H., 1995. Farm Household Decision Making and Extension Framework for Understanding Farm Household-level Decision Making and Design of Agroforestry Extension Strategies. Food and Agriculture Organization, Asia-Pacific Agroforestry Network, Bogor.

Global Panel on Agriculture and Food Systems for Nutrition, 2016. Food systems and diets: Facing the challenges of the 21st century. London, UK.

Herforth, A., et al., 2016. Compendium of Indicators for Nutrition-sensitive Agriculture. Food and Agriculture Organization, Rome.

Hernandez, R., et al., 2017. The quiet revolution in the aquaculture value chain in Bangladesh. Aquaculture. http://dx.doi.org/10.1016/j.aquaculture.2017.06.006.

Herrero, M., et al., 2017. Farming and the geography of nutrient production for human use: a transdisciplinary analysis. Lancet Planet. Health 1 (1), 33–42. http://dx.doi.org/10.1016/S2542-5196(17)30007-4.

Heywood, P., Lund-Adams, M., 1991. The Australian food and nutrition system: a basis for policy formulation and analysis. Aust. J. Public Health 15 (4), 258–270.

Hotz, C., et al., 2004. International Zinc Nutrition Consultative Group (IZiNCG) technical document #1. Assessment of the risk of zinc deficiency in populations and options for its control. Food Nutr. Bull. 25 (1 suppl 2), S99–S203.

icddrb, 2013. National Micronutrients Status Survey 2011–2012. icddrb, Dhaka.

IFPRI, 2016. Global Nutrition Report: From Promise to Impact - Ending Malnutriton by 2030. International Food Policy Research Institute, Washington DC.

Ingram, J., 2011. A food systems approach to researching food security and its interactions with global environmental change. Sci. Sociol. Econ. Food Prod. Access Food 3 (4), 417–431. http://dx.doi.org/10.1007/s12571-011-0149-9.

Jones, A.D., 2014a. The production diversity of subsistence farms in the Bolivian Andes is associated with the quality of child feeding practices as measured by a validated summary feeding index. Public Health Nutr. 18 (2), 329–342. http://dx.doi.org/10.1017/s1368980014000123.

Jones, A.D., 2017. On-farm crop species richness is associated with household diet diversity and quality in subsistence- and market-oriented farming households in Malawi. J. Nutr. 147 (1), 86–96. http://dx.doi.org/10.3945/jn.116.235879.

Jones, A.D., et al., 2014b. Farm production diversity is associated with greater household dietary diversity in Malawi: findings from nationally representative data. Food Policy 46 (0), 1–12. http://dx.doi.org/10.1016/j.foodpol.2014.02.001.

Karim, M., et al., 2017. Carp–mola productivity and fish consumption in small-scale homestead aquaculture in Bangladesh. J. Eur. Aquac. Soc. 25 (2), 867–879. http://dx.doi.org/10.1007/s10499-016-0078-x.

Keding, G.B., et al., 2012. Relating dietary diversity and food variety scores to vegetable production and socio-economic status of women in rural Tanzania. Food Secur. 4 (1), 129–140. http://dx.doi.org/10.1007/s12571-011-0163-y.

Khoury, C.K., et al., 2014. Increasing homogeneity in global food supplies and the implications for food security. Proc. Natl. Acad. Sci. USA 111 (11), 4001–4006. http://dx.doi.org/10.1073/pnas.1313490111.

Koppmair, S., et al., 2017. Farm production, market access and dietary diversity in Malawi. Public Health Nutr. 20 (2), 325–335. http://dx.doi.org/10.1017/S1368980016002135.

Lele, U., et al., 2016. Measuring Food and Nutrition Security: An Independent Technical Assessment and User's Guide for Existing Indicators. Food Security Information Network.

Luckett, B.G., et al., 2015. Application of the Nutrition Functional Diversity indicator to assess food system contributions to dietary diversity and sustainable diets of Malawian households. Public Health Nutr. 18 (13), 2479–2487. http://dx.doi.org/10.1017/S136898001500169X.

M'Kaibi, F.K., et al., 2015. Effects of agricultural biodiversity and seasonal rain on dietary adequacy and household food security in rural areas of Kenya. BMC Public Health 15, 422. http://dx.doi.org/10.1186/s12889-015-1755-9.

Malapit, H.J.L., et al., 2015. Women's empowerment mitigates the negative effects of low production diversity on maternal and child nutrition in Nepal. J. Dev. Stud. 51 (8), 1097–1123.

Murshed-e-Jahan, K., et al., 2015. Aquaculture technologies in Bangladesh: An assessment of technical and economic performance and producer behavior. WorldFish, Penang, Malaysia.

National Health and Medical Research Council, 2013. Australian Dietary Guidelines: Providing the scientific evidence for healthier Australian diets. National Health and Medical Research Council, Canberra.

NIPORT, et al. 2015. Bangladesh demographic and health survey 2014. Dhaka, Bangladesh; Maryland, USA: National Institute of Population Research and Training, Mitra and Associates, ICF International.

Nugent, R., 2011. Bringing Agriculture to the Table: How Agriculture and Food can Play a Role in Preventing Chronic Disease. The Chicago Council on Global Affairs, Chicago, USA.

Remans, R., et al., 2015. Expanding the view on the production and dietary diversity link: scale, function, and change over time. Proc. Natl. Acad. Sci. USA 112 (45). http://dx.doi.org/10.1073/pnas.1518531112. (E6082-E6082).

Remans, R., et al., 2011. Assessing nutritional diversity of cropping systems in African villages. PLoS One 6 (6). http://dx.doi.org/10.1371/journal.pone.0021235.

Remans, R., et al., 2014. Measuring nutritional diversity of national food supplies. Glob. Food Secur. 3 (3–4), 174–182. http://dx.doi.org/10.1016/j.gfs.2014.07.001.

Roos, N., 2001. Fish Consumption and Aquaculture in Rural Bangladesh: Nutritional Impact and Production Potential of Culturing Small Indigenous Fish Species (SIS) in Polyculture with Commonly Cultured Carps (Ph.D. Thesis). The Royal Veterinary and Agricultural University, Copenhagen, Denmark.

Sibhatu, K.T., et al., 2015. Production diversity and dietary diversity in smallholder farm households. Proc. Natl. Acad. Sci. USA 112 (34), 10657. http://dx.doi.org/10.1073/pnas.1510982112.

Sobal, J., et al., 1998. A conceptual model of the food and nutrition system. Soc. Sci. Med. 47 (7), 853–863. http://dx.doi.org/10.1016/S0277-9536(98)00104-X.

Torheim, L.E., et al., 2004. Nutrient adequacy and dietary diversity in rural Mali: association and determinants. Eur. J. Clin. Nutr. 58 (4), 594. http://dx.doi.org/10.1038/sj.ejcn.1601853.

United Nations, 2015. Transforming Our World: The 2030 Agenda for Global Action. United Nations, New York.

Wood, S., 2017. Crop functional trait diversity and human nutrition in southeastern Senegal. J. Appl. Ecol (Forthcoming).