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Assessing nutritional, health, and environmental sustainability dimensions of agri-food production

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ABSTRACT

Agri-food production systems are major drivers of global sustainability challenges including climate change, freshwater scarcity, micronutrient deficiencies, and cardiovascular disease. There is an urgent need for more robust methods (e.g., life cycle assessment, system-based modelling) and metrics (e.g., Disability-Adjusted Life Years, nutrient diversity indicators) to quantitatively assess the sustainability of these production systems on a joint nutritional, health, and environmental basis. Creating a sustainable future will require actors to co-develop and co-implement interventions across these groups; presently, however, these fields are misaligned. Current methods are siloed, qualitative, and calorie- or food- based, and they should be developed in a more holistic, quantitative, and nutritionally-focused manner. Developing data-driven and interdisciplinary approaches can help to alleviate food security and sustainability challenges.

1. Introduction

Agri-food production systems, defined as the inputs, processes, and infrastructure needed to produce and distribute food, are inextricably linked with nutritional, health, and environmental sustainability. Agri-food systems, for instance, are key drivers of climate change (Campbell et al., 2017), dietary diseases (Afshin et al., 2019), and our food supply's nutrient-content (Fig. 1). Accordingly, more studies of food production systems should jointly assess environmental dimensions with nutritional and/or health dimensions; we term such studies nutritional-health-environmental (NHE) sustainability assessments. This paper provides an overview of NHE metrics and methods, along with a discussion of future NHE research areas to target.

Our focus is on food production for two primary reasons. First, many of our current and envisioned challenges are intertwined with production. Agricultural and processing practices can influence nutrition and the environment by altering nutritional compositions of foods, reducing yields, and engendering environmental degradation (Poore and Nemecek, 2018; Weyant et al., 2018). Fig. 1 and the accompanying legend illustrate that various factors like biofortification can increase or decrease nutrient-contents in foods. Additionally, the diversity of our food and nutrient supply is changing due to elements such as climate change, increasing homogeneity among food groups, and an over-reliance on a few staple crops (Alston and Pardey, 2008; DeFries et al., 2015; FAO, 2018; Khoury et al., 2014; Myers et al., 2014). This could lead to unknown micronutrient deficiency risks. Moreover, global preferences are changing, and as new food items (e.g., protein-rich grains, insects, algae, and cultured meat) are considered for market integration, farmers and industry will need to develop methods to compare the sustainability of those products to that of status-quo products. The second reason is that many recent studies have been consumption-oriented, meaning they focus on dietary patterns and demand-side interventions (Chaudhary et al., 2018a; Jones et al., 2016; Springmann et al., 2018; Willett et al., 2019). Despite the high prevalence of the consumption-perspective in the literature, studies (Springmann et al., 2016b; Willett et al., 2019) recognize that production-side interventions will be key in developing optimal food systems inclusive of sustainable diets.

For sustainability studies on agri-food production systems, there is a need to move from (i) siloed to more holistic analyses, (ii) qualitative to quantitative approaches, (iii) food quantity or calorie-based studies to nutrient-focused ones, and from (iv) ad-hoc applications of metrics to a

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more structured understanding of their use. With respect to the first point, many studies use a siloed approach and analyze nutritional and health dimensions separately from the environmental dimension. Holistic studies, however, are needed to identify trade-offs and synergies amongst NHE sustainability dimensions because optimizing production systems on all dimensions is impractical. NHE dimensional trade-offs arise, for example, when transitioning from conventional to organic agricultural practices. One instance of such a trade-off occurs because organic systems have higher land use impacts due to lower yields but lower energy use and can produce foods with higher antioxidant contents that have the potential to influence health outcomes (Clark and Tilman, 2017; Hunter et al., 2011). Second, a common method of assessing the NHE sustainability of food items or food systems is to use a qualitative, comparative approach, meaning researchers assess the environmental impacts of a status-quo product or process to an alternative deemed to be 'health promoting' or nutrient-enriched. These studies could be more robust by quantifying the nutritional differences between these products. Third, many studies assess nutrition via available calories or food quantity, with a particular emphasis on staple crops, (Nelson et al., 2018; van Dijk and Meijerink, 2014). While hunger and food availability are critical issues, nutrients play a vital role in human health. In relation to the last point, we establish differentiating criteria for metrics (Table 1, Table 2, Table 3), when applicable. These criteria can help elucidate the type of metric most appropriate for a study.

For the aforementioned reasons, the aim of this paper is to provide an overview of NHE metrics and approaches that actors in the agri-food production sector may use to quantitatively assess the sustainability of food production. Past reviews have focused on metrics of dietary quality (Drewnowski and Fulgoni, 2008; Hallström et al., 2018). Here, we discuss the use of these metrics for the production-perspective, based on differentiating criteria that we identified from the review. We expand upon nutrient diversity work (Bogard et al., 2018), by exploring how these metrics relate to human health and environmental sustainability. Finally, we build upon previous reviews that discuss the integration of nutrition into LCA (McAuliffe et al., 2019; Saarinen et al., 2017), by addressing multiple LCA phases (i.e., goal and scope, impacts) and proposing alternative nutrient-based approaches that future LCA studies can employ.

The paper is structured into three main parts. We first discuss health [e.g., Disability Adjusted Life Years (DALYs)] and nutritional metrics for which we define three facets used in sustainability analyses: (i) nutrient quantity (e.g., Nutrient-Rich Food Index (NRF) 9.3), (ii) nutrient diversity (e.g., Rao's Quadratic Entropy), and (iii) nutrient quality [e.g., Digestible Indispensable Amino Acids Score (DIAAS)]. We devote limited space to environmental metrics because their use in sustainability analyses is extensively documented. In the second part, we examine the current use, limitations, and advantages of methods that use these metrics in NHE analyses. We place a particular focus on LCA because it is an ISO standardized (Finkbeiner et al., 2006) and widely used (Heller et al., 2013; Hellweg and Milà i Canals, 2014) method for estimating environmental impacts of products and processes. Moreover, researchers frequently use LCA to evaluate dietary patterns (Jones et al., 2016) and the LCA community is making a concerted effort to quantitatively integrate nutrition into analyses. In addition to LCA, we examine other methods (e.g., systems dynamics models (SD), optimization algorithms), which are relatively less used in NHE production studies, because these methods can offer alternative viewpoints

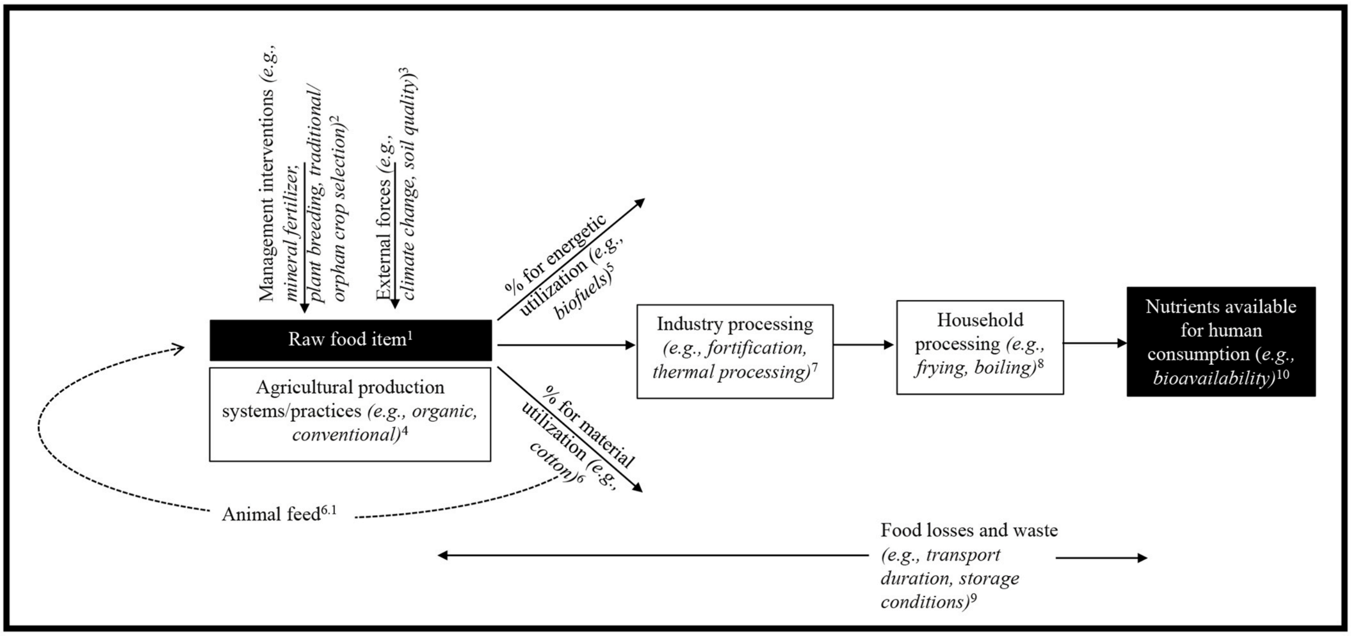

Fig. 1. Factors that alter the nutritional composition of food items and our food supply: (1) Raw food items have a base nutritional composition, which is defined as the ratio of nutrients to one another or to the energy content (i.e., it measures if a food becomes more nutrient-dense or more energy-dense relative to its previous state). Examples of factors that can alter these compositions are provided in the Figure. (2) Management interventions: biofortification such as mineral fertilizer (Bouis and Saltzman, 2017; de Valença et al., 2017), variety selection or plant breeding (Welch and Graham, 2004), animal diets (Clark and Tilman, 2017), orphan/traditional crop selection (Mabhaudhi et al., 2019). (3) External factors: climate change (Myers et al., 2014), site conditions [e.g., soil quality (Welch et al., 2013)]. (4) Agricultural production practices: N-fixing crop rotations (Bedoussac and Justes, 2010), organic or conventional practices (Hunter et al., 2011). (5) A proportion of food is diverted from human consumption purposes to energetic utilization (e.g., biofuels). (6) A percentage of food production is allocated to material use (e.g., fibers). (6.1) A percentage of food production is also allocated to feed, which results in substantial nutrient losses because there is a low conversion efficiency for nutrients in the crop-animal-human chain. (7) Industry processing practices: thermal processing, fortification (Kessler, 2002). (8) Household cooking methods: frying, boiling (Kessler, 2002). (9) Food losses and waste will result in nutrient losses throughout the supply chain due to storage conditions, transport duration, etc. (Parfitt et al., 2010). Additionally, certain parts of food are inedible. (10) Bioavailability further affects the nutrients absorbed and utilized by humans (Gibney et al., 2013).

Table 1
Nutrient indices and included nutrients.

	Points of differentiation: included nutrients				
Nutrient Index[1]	Macronutrients	Vitamins	Minerals	Disqualifying nutrients	Other[2]
ONQI[3] (Katz et al., 2010)	Fiber, omega 3 (n-3) fatty acids, protein quality, fat quality	Folate, A, C, D, E, B-12, B-6	K, Ca, Zn, Mg, Fe	Saturated fat, trans fat, sodium, total/added sugar, cholesterol	Total bioflavonoids, total carotenoids
WNDS[4] (Arsenault et al., 2012)	Protein, fiber, unsaturated fat	C	Ca	Saturated fat, sodium, added sugar	None
NRF9.3[5] (Fulgoni et al., 2009)	Protein, fiber	A, C, E	Mg, Ca, Fe, K	Saturated fat, added sugars, sodium	None
NRF9[5.1]	Protein, fiber	A, C, E	Mg, Ca, Fe, K	None	None
LIM3[5.2]	None	None	None	Saturated fat, added sugars, sodium	None
NBC[6] (Fern et al., 2015)	Fiber, protein, linoleic acid, α-linolenic acid, choline	Folate, niacin, riboflavin, thiamin, pantothenic acid, A, B-12, B-6, C, D, E, K	Ca, Cu, Fe, Mg, Mn, P, K, Se, Zn	Total fat, saturated fat, trans fat, cholesterol, total sugar, sodium	Water
QI[6.1]	Fiber, protein, linoleic acid, α-linolenic acid, choline	Folate, niacin, riboflavin, thiamin, pantothenic acid, A, B-12, B-6, C, D, E, K	Ca, Cu, Fe, Mg, Mn, P, K, Se, Zn	None	Water
DI[6.2]	None	None	None	Total fat, saturated fat, trans fat, cholesterol, total sugar, sodium	None
DNS[7] (Chaudhary et al., 2018a)	None	None	None	Sugar, cholesterol, saturated fat, total fat	None

[1] See sources for full information on nutrients; multiple variations of a specific index, which differ by the included nutrients, can exist.
[2] E.g., other antioxidants, phytochemicals.
[3] Overall Nutritional Quality Index (ONQI).
[4] Weighted Nutrient Density Score (WNDS).
[5] Nutrient Rich Foods Index (NRF9.3); composed of the NRF and LIM.
[5.1] Nutrient Rich Foods (NRF).
[5 2] Limiting Nutrient (LIM).
[6] Nutrient Balance Concept (NBC); composed of the QI and DI.
[6 1] Qualifying Index (QI).
[6 2] Disqualifying Index (DI).
[7] Disqualifying Nutrient Score (DNS).

including more dynamic, systems-oriented, and holistic perspectives compared to standard LCA studies. Finally, in the third section, we detail seven key gaps for future research to target.

Table 2
Nutrient indices (from Table 1) and other points of differentiation.

	Additional points of differentiation		
Nutrient Index[1]	Weighting basis	Capping basis	Group-specific or across-the-board
ONQI[3] (Katz et al., 2010)	Proprietary; based on relationship between nutrients and health outcomes.	Nutrients in fortified and processed foods are capped; nutrients from raw food products are uncapped.	Across-the-board
WNDS[4] (Arsenault et al., 2012)	Based on regression coefficients estimated by the relationships between nutrients and the Healthy Eating Index.	Qualifying nutrients are capped at 100% of recommended intake.	Across-the-board
NRF9.3[5] (Fulgoni et al., 2009)	None	Nutrients are capped at 100% of daily values.	Across-the-board
NRF9[5.1]	None	Nutrients are capped at 100% of daily values.	Across-the-board
LIM3[5.2]	None	None	Across-the-board
NBC[6] (Fern et al., 2015)	See QI	Capped if QI is above 1	Across-the-board
NBC- QI[6.1]	By energy needs of population / energy in food or meal	Capped if above 1	Across-the-board
NBC- DI[6.2]	By contribution to total energy	None	Across-the-board
DNS[7] (Chaudhary et al., 2018a)	None	Capping is optional	Across-the-board

2. Methods & environmental metrics

For this study, we carefully evaluated publications found through keyword searches in Web of Science; Fig. 2 details our protocol and exclusion criteria. For details of the method protocol, see the supplementary material. Of the 774 papers that were identified, 25 were NHE studies that were directly relevant the production-perspective. However, we also include information from NHE consumption-based studies when their metrics and methods are pertinent.

As mentioned, we focus on nutritional and health metrics because their use in sustainability analyses is relatively new. Briefly, however, we provide an overview of key information related to the environmental dimension. Most studies include impacts related to GHG emissions and biogeochemical flows (i.e., eutrophication and acidification potentials). However, agri-food production contributes to other environmental impacts (Campbell et al., 2017). Fully identifying synergies and trade-offs amongst sustainability dimensions, therefore, requires the inclusion of these other impact categories. Unfortunately, the spatially-explicit nature and lack of underlying data for some of these (e.g., freshwater use, biodiversity loss) limit their use (Chaplin-Kramer et al., 2017). Regardless, recognizing these gaps minimizes the risk of unknowingly sub-optimizing production systems. For example, nuts are viewed as a sustainable protein-alternative to meat, based on their GHG emissions and health attributes; however, on average, their production causes significantly more water scarcity (Aune et al., 2016; Poore and Nemecek, 2018; Vanham et al., 2020).

Table 3
Nutritional diversity metrics and points of differentiation.

		Points of differentiation			
Metric[1]	Description	*Nutrient diversity*	*Food quantity*	*Relation to human health*	*Relation to environmental sustainability*
Functional diversity (FD)	Calculates diversity based on nutrient content and the weighted deviance from the center of gravity.	Yes	No	FD accounts for human nutrient requirements.	A higher FD can mean more species traits. This is indicative of a more resilient system (Liu et al., 2018).
Potential nutrient adequacy (PNA)	Weights percent of population potentially nourished by nutrient evenness.	Yes	Yes	The percent undernourished represents potential micronutrient deficiencies.	None
Modified functional attribute diversity (MFAD)	Assesses functional differences.	Yes	No	No	A higher MFAD can mean more species traits. This is indicative of a more resilient system (Liu et al., 2018).
Rao's quadratic entropy (Q)	Weights nutrient diversity by relative food quantities.	Yes	Yes	No	A higher Q can mean more species traits. This is indicative of a more resilient system (Liu et al., 2018).

[1] The selected metrics are from Bogard et al., (2018); here, we explain their relation to human health and the environment.

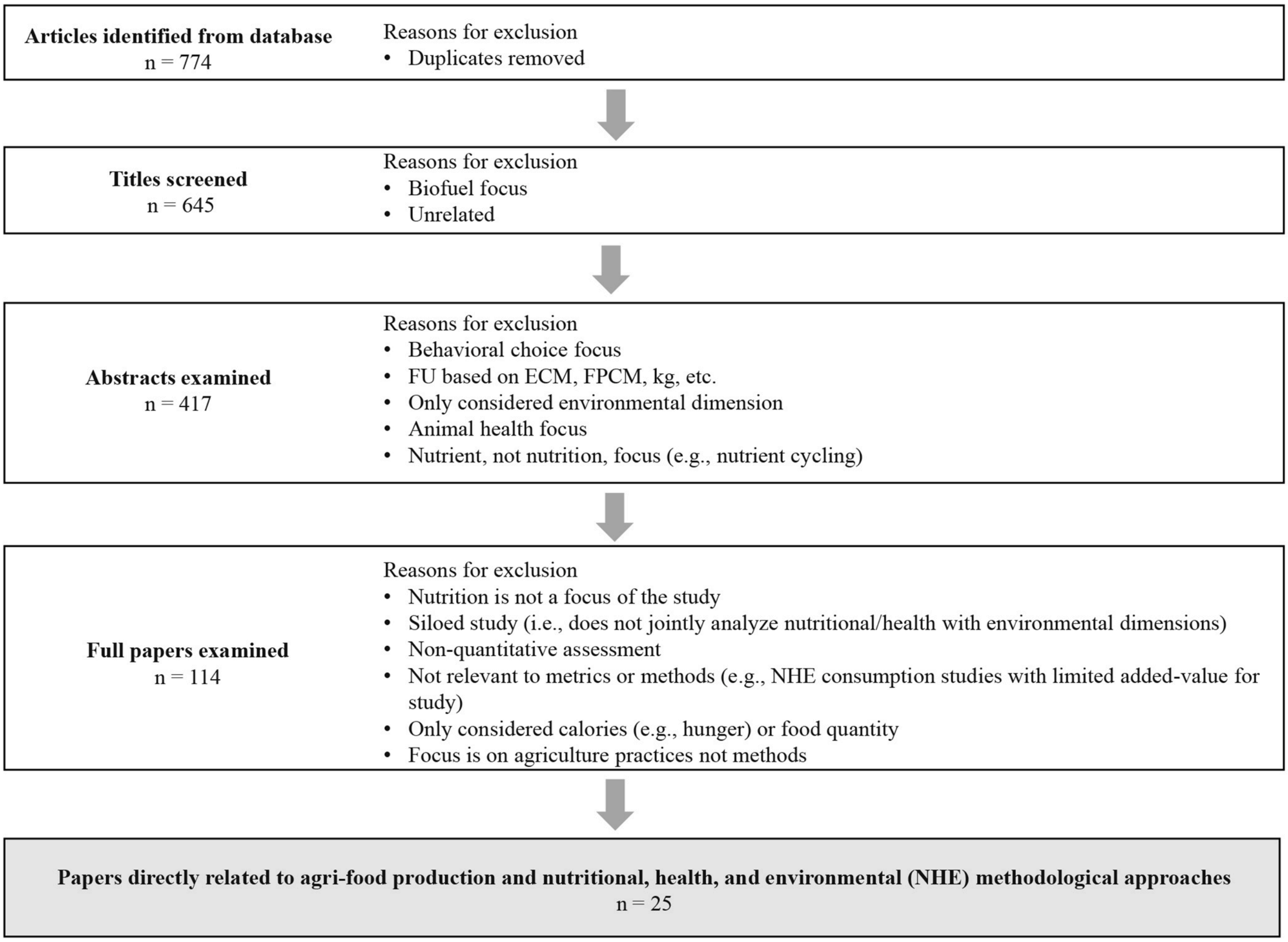

Fig. 2. Method Protocol. This diagram illustrates our exclusion criteria.

3. Nutritional & health metrics

Here, we discuss nutritional and health metrics that have been used in sustainability analyses. We classify nutritional metrics into three categories; namely, nutrient quantity, nutrient quality, and nutrient diversity. Quantity-based metrics measure the amount of nutrients present in different food levels, which we define to include food supply, diets, meals, food groups, food items, and production/processing systems. Nutrient quality metrics assess the differences within nutrients (e.g., amino-acid profiling), and nutrient diversity metrics evaluate the heterogeneity of aggregate food levels. Finally, health metrics evaluate the impacts of food and nutrients on health.

3.1. Nutrient quantity metrics

The most frequently used category of nutrition metrics in sustainability assessments is that of nutrient quantity. These metrics measure nutrient amounts, and data for these are easily attainable from food composition databases [e.g., USDA (USDA, 2020)]. However, these databases contain different foods and nutrients that vary due to regional differences and data quality, and this creates data harmonization issues. Nutrient quantity metrics are useful in estimating if food levels are able to provide adequate nutrients of interest for a population. These metrics are applied as single nutrients or as nutrient indices.

Nutrient indices rank and compare food items based on their nutrient contents, and are composed of qualifying [i.e., health promoting (Fern et al., 2015)] nutrients with defined lower limits and disqualifying nutrients [i.e., nutrients detrimental to health (Fern et al., 2015)] with defined upper limits. They are expressed relative to Daily Reference Intake (DRI) measures [e.g., serving sizes, Recommended Dietary Allowances (RDA), and Maximal Reference Values (MRV)] that vary nationally. Additionally, indices can be validated against objective measures of diet quality, such as the Healthy Eating Index, to determine if the nutrient index is reflective of health outcomes; however, these indices have been criticized as lackluster predictors of health (Heller et al., 2013).

No perfect algorithm exists to inform users on the types and amounts of nutrients to consume for optimal health. Understanding the points of differentiation, which we identified from the review, amongst nutrient indices, is therefore important. Moreover, these points also influence study outcomes, as explained in the following sections. Tables 1 and 2 provide a list of indices and their associated points of differentiation (i.e., included nutrients, weighting, capping, and across-the-board vs. group-specific). The tables are not exhaustive because we only present a representative list of indices that illustrates the variety of index types relevant to production.

3.1.1. *Included nutrients*

The choice of nutrients will affect the end index value (Saarinen et al., 2017). For example, using fat instead of differentiating between qualifying and disqualifying fats will penalize foods that are a healthy source of fatty acids by assigning them a lower index score. In theory, one could use an algorithm inclusive of all nutrients relevant to human health. However, this increases the data collection burden. Furthermore, many nutrients are correlated; this point is particularly relevant to validated indices because incorporating additional nutrients into these indices does not offer additional insights with regards to health outcomes (Arsenault et al., 2012). Nevertheless, there should be a rationale for excluding nutrients. The Disqualifying Nutrient Score, for example, excludes salt because the values in food databases are often incorrect since consumers add salt during the household preparation phase (Chaudhary et al., 2018a). The choice of DRI is also important. For example, disqualifying nutrients should be included with their MRV, since consuming them in limited amounts is not necessarily detrimental to health (Saarinen et al., 2017) and recommending that individuals fully eliminate their consumption is unrealistic.

3.1.2. *Weighting*

Another question is whether to weight indices and, if so, on what basis? There is no scientific agreement on how to weight nutrients (e.g., we cannot measure the relative importance of protein to carbohydrates) (Schaubroeck et al., 2018). Due to this, most indices do not apply weighting, but this assumes that all nutrients are equally important. Some studies, however, use weighted nutrient indices based on criteria such as bioavailability, nutrient quality, or nutrient distributions (Fulgoni et al., 2009). For example, due to nutritional deficiencies in the population, a Peruvian study assigned a higher weighting to omega-3 (Avadí and Fréon, 2015).

3.1.3. *Capping*

The primary reason for capping is to ensure that foods do not receive higher index scores because they have an excess of qualifying nutrients (i.e., they provide more than 100 percent of an individual's DRI). Consuming nutrients in excess does not create additional health benefits and can be detrimental (Fern et al., 2015). The choice of capping largely depends on the type of nutrient. Qualifying nutrients are often capped for raw food items. An alternative option is to only cap nutrients in foods that are processed or fortified (Katz et al., 2010). Disqualifying nutrients, on the other hand, are often uncapped because indices should penalize foods high in nutrients that are harmful to health if overconsumed.

3.1.4. *Across-the-board vs. food-group-specific*

Indices are either across-the-board or food-group-specific, but the former categorization is more common. For across-the-board indices, all foods are measured against the same index unlike food-group-specific indices in which different indices are applied to different food groups. For example, one study proposed an index comprised of antioxidants specific to the berry food group (Saarinen et al., 2017). Food-group-specific indices can compare substitute products within a food group on a more representative basis because they align with the substitution method (Scarborough et al., 2010). For this, one food is produced over another within a food group, based on sustainability criteria. For example, quinoa could be substituted for wheat. Across-the-board indices, in contrast, align with the displacement approach (Scarborough et al., 2010) wherein one food group, such as plant-based protein, is produced in place of another like animal-sourced food (ASF)-protein.

3.2. *Nutrient quality metrics*

Nutrient quality metrics differentiate between nutrient types because various factors can alter the quality of nutrients. For example, proteins vary in quality due to differences in amino-acid composition and digestibility. Consequently, ASF-proteins are of a higher quality than plant-based proteins like legumes or nuts (Loveday, 2019). Processing practices can further alter these quality values; for instance, autoclaving and extruding food items can reduce and increase digestibility, respectively (Loveday, 2019).

Few metrics exist to account for protein quality; the most accepted one is FAO's DIAAS. This score is calculated for each amino acid, and the lowest number becomes the chosen DIAAS value. However, because this indicator is based on the limiting nutrient, it can be argued that it is not a comprehensive measure of quality. Overall, there is limited literature data on nutrient quality because it is difficult and expensive to measure. Accordingly, few studies (Sonesson et al., 2017; Tessari et al., 2016) include this category in sustainability analyses. Furthermore, when included, most studies assess the quality of protein instead other nutrients such as iron.

3.3. *Nutrient diversity metrics*

Nutrient diversity metrics measure the diversity of nutrients within a food supply or production system. Currently, diversity metrics are infrequently used in NHE sustainability assessments. Data for these metrics come from on-farm surveys (Remans et al., 2011), databases and literature with yield data (Bogard et al., 2018), or food composition databases. They vary greatly in computational complexity and can require significant data collection efforts (Bogard et al., 2018). While researchers strive to further develop these metrics, poor data and methods hinder these endeavors (Herforth and Ballard, 2016).

As mentioned, global nutrient diversity is changing, and diversity metrics can support targeted production-side interventions that account for nutritional impacts in addition to yield, mass, or economic impacts. These metrics are indicative of supply diversity (and thus nutrition) in Low-Income Countries (LIC) wherein market access to purchase other goods is limited, unlike in High-Income Countries (HIC) that have more access to imports (Remans et al., 2014). Nevertheless, HIC can still use these metrics to assess their self-sufficiency.

While diversity is an important aspect of sustainable agri-food

Table 4
Examples of studies that use nutritional, health, and environmental (NHE) assessment methods.

Method	Study descriptions
Eco-efficiency composite indicators	- Used an indicator (vitamin C-content / CO_2 emissions) to estimate the impact of elevated CO_2 treatment in greenhouses on the nutrient-content of spinach and compared this to conventional growing methods (Seo et al., 2017). - Calculated the Nutrition Carbon Footprint Score [Nutrition Balance Concept (i.e., a nutrient index) / carbon footprint] to assess the feasibility of reformulating grain products by incorporating yellow pea flour (Chaudhary et al., 2018b).
Scoring composite indicators	- Scored how changes in farm management affect sustainability, using 19 diverse metrics related to animal welfare, nutrient-contents, the environment, economics, and food safety (Zucali et al., 2016). - Assessed the sustainability of canteen meals by developing a scoring system based on nutritional requirements, environmental impacts, as well as management and production practices (Schaubroeck et al., 2018). - Compared the sustainability of omnivore and vegan/vegetarian diets differentiated by organic and non-organic production systems on a health and environmental basis (Baroni et al., 2007). - Compared food items on the basis of IPCC generated GHG emission values per kg protein, nutrient density, GJ, and ton of product (Doran-Browne et al., 2015). - Developed the Nutritional Footprint, which scores foods based on environmental and nutritional parameters (Speck et al., 2013).
Classification composite indicators	- Classified food items into three sustainability groups based on GHG emissions and the nutrient quantities of six nutrients (van Dooren et al., 2017).
Scaled composite indicators	- Developed a sustainability index by converting different metrics to a common scale (i.e., 0–10) (Müller-Lindenlauf et al., 2010). They evaluated organic farms differentiated by grassland percentage and feed intensity. They included environmental, animal welfare, and milk nutrition (i.e., omega-3 fatty acids, conjugated linoleic acids, and antioxidants) metrics.
System-based models	- Modeled the food system with a systems dynamic (SD) model (Sabaté et al., 2016) by including drivers of nutrient-contents, health outcomes, and environmental degradation, in addition to more social concerns such as food sovereignty and governance. - Explored the environmental and socioeconomic changes of food systems, with a SD model, impacted by resilience factors, with food and nutrition security as outcomes (Allen and Prosperi, 2016). - Linked the International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT), which is a partial equilibrium model to a comparative risk framework to understand the risk to health based on changes in agricultural production (Springmann et al., 2016b). - Used IMPACT with nutritional analyses (calculated via nutrient indices) to evaluate changes in nutrient availability based on future climate scenarios (Beach et al., 2019; Nelson et al., 2018).
Optimization algorithms	- Used a linear programming model to simulate the Swiss food supply, comprised of agricultural production, food processing, external trade, and food stock management components and linked it to environmental indicators and nutritional requirements to optimize the food supply (von Ow et al., 2020).
Nutritional-LCA	- Measured the nutrient quantity of antioxidants in cauliflower, based on varying levels of mineral fertilizer added to compost, for the functional unit (FU) (Martínez-Blanco et al., 2011). - Estimated omega-3 contents in livestock systems (e.g., beef-concentrate vs beef-forage, chicken-intensive vs. chicken-extensive) to be used as FUs (McAuliffe et al., 2018). - Developed the Combined Nutritional and Environmental-LCA framework, which uses epidemiological studies to compare the dietary risks (e.g., stroke, colorectal cancer) and environmentally-driven health impacts (e.g., asthma from particulate matter emissions) of food items like milk (Stylianou et al., 2016). - Compared pork items produced under different production scenarios (e.g., organic vs. conventional), while using different FU (e.g., protein) (Teixeira et al., 2013). - Defined nutrient equivalent units (NE) as the FU, to compare vegetables in a multi-cropping system. NE was defined as the mean of the ratios between the nutrients present in a food to the DRI (Li et al., 2018).

production, many metrics calculate diversity based on differences in food quantity instead of nutrients (Bogard et al., 2018). Table 3 presents nutrient-based diversity metrics that we selected from Bogard et al. In this table, we explain how each diversity metric relates to human health and environmental sustainability. For example, a greater nutrient diversity, and thus number of crop traits, can increase resilience to environmental pressures like pests and diseases (Liu et al., 2018). Environmental resilience is an important aspect of sustainable food systems but is often ignored because measuring it is challenging.

3.4. Human health metrics

Within sustainability studies, the most commonly used metric is the DALY. It measures years of healthy life lost due to premature death, disability, or illness (WHO, 2018). DALYs are useful in NHE analyses because DALYs consequent from food intake, like colorectal cancer, are directly comparable to those caused by pollution and other environmental factors such as asthma or heat-induced mortality. Other metrics include the: (i) cox proportional hazard ratio, which estimates the chance of surviving based on survival factors like food intake and other predictor variables (Biesbroek et al., 2014; Segovia-Siapco and Sabaté, 2019), (ii) comparative risk assessment framework that estimates mortality and disease burden (Springmann et al., 2018, 2016a) based on population attributable fractions, relative risk (RR) ratios, and disease-specific death rates differentiated by region, and the (iii) DIETRON model, which uses age and sex specific RR to estimate mortality from food consumption (Briggs et al., 2013; Scarborough et al., 2011). National mortality data (Scarborough et al., 2011) or Global Burden of Disease studies (Afshin et al., 2019) often provide data for these metrics.

While these metrics are useful, some limitations exist, as detailed in a recent viewpoint paper (Ioannidis, 2018). Summarily, isolating the health effects of a single food or nutrient is a complex endeavor. Nutrients are often correlated with one another, and it is challenging to account for behavioral factors like cooking practices that alter nutrient-contents. Bioavailability adds another layer of complexity as the intake of nutrients is not equivalent to the nutrients absorbed (Gibney et al., 2013); moreover, we do not consume foods in isolation and factors like phytic and ascorbic acid can inhibit or enhance the absorption of nutrients like iron (Hunt, 2003). There are no standardized ways to account for bioavailability, but certain formulas can approximate it. Finally, genetics, fitness levels, and metabolic profiles also contribute to dietary health (Ioannidis, 2018).

4. Methodological approaches to combine nutritional, health, and environmental sustainability dimensions

This section discusses methods for combining nutritional and health metrics with environmental metrics to simultaneously evaluate NHE dimensions of agri-food production systems. These approaches include composite indicators, defined as the combination of two or more metrics, LCA, optimization algorithms, Geographic Information Systems (GIS), econometric models (EC) and system-based models, which we define as quantitative models that approach sustainability problems from a systems or dynamic perspective. This group includes SD, Partial

Equilibrium Models (PEQ), and Integrated Assessment Models (IAM). These methods are not mutually exclusive; for example, LCA results are often the basis for environmental parameters in other approaches (e.g., composite indicators, optimization algorithms (von Ow et al., 2020). Additionally, IAM can encompass many different methods such as PEQ (Nikas et al., 2019). Table 4 describes studies that use these methodological approaches.

4.1. Composite indicators

Composite indicators combine nutritional and health metrics with environmental metrics; for example, for a food item, a composite indicator can measure the amount of protein (g) per kg of CO_2 produced. These indicators are relatively simple to calculate when compared to other approaches. They are also easy to communicate to actors outside of research, and this increases their effectiveness and likelihood of implementation. We classify these indicators into four types (i.e., eco-efficiency, scoring, classification, scaled), based on their usefulness to different actors.

Eco-efficiency indicators, frequently used by industry, estimate efficiency by measuring the value (e.g., nutrition, health) of a food level against its environmental impact. Scoring systems rank food levels based on differences between individual nutritional, health, and environmental measures, and can be useful in policy-settings and have been used to optimize farm management practices. Classification indicators, similarly, allow actors to classify various food levels into different groups based on differences between sustainability categories; they are easy to communicate to policy stakeholders and can contribute to setting targets. For example, food items can be categorized into red-, yellow-, or green- light sustainability groups. Such classifications, however, are subject to weighting bias, which makes their interpretation difficult. Scaled indicators translate disparate metrics onto a common scale for an overall index of sustainability. Despite being easy to communicate to outside stakeholders, scaled indicators are, generally, more context-specific with limited applicability beyond case studies. Consequently, they are most relevant to microscale actors such as farmers, companies and researchers.

4.2. Life cycle assessment

LCA assesses multiple environmental impacts of products and processes over a life cycle. Below, we outline three key options for streamlining nutritional and health metrics into environmental LCA (n-LCA). Summarily, a practitioner can i) incorporate nutrients into the functional unit (FU), ii) use an allocation or systems expansion approach on a nutritional basis, or iii) define nutrients as inventory flows and health as an impact. Life cycle inventory databases such as ecoinvent (Ecoinvent, 2020) and Agri-footprint (Agri-footprint, 2020) are the biggest providers of LCA data, while literature is an alternative source. Data is often decentralized and issues of data harmonization pose a significant issue (Nemecek et al., 2016). Moreover, the majority of data comes from HIC, partly because financial constraints hinder such data collection in LIC.

Here, we focus on LCA, but the issues discussed in the FU section are also relevant to footprints, which differ from LCA because footprints only assess one environmental impact at a time. Previous studies (Sokolow et al., 2019) have compared environmental footprints (e.g., water, CO_2) to nutrient indices. Other environmental impact assessment methods such as input-output analyses (Reynolds et al., 2015) predominately use a consumption-perspective or siloed approach.

4.2.1. Functional unit

Incorporating nutrition into the FU, to achieve functional equivalency, is the most widely used option to integrate nutritional and health metrics into LCA. The FU is the unit against which environmental impacts are estimated and should be representative of the product or service. Although absolute values of environmental impacts remain the same irrespective of FU choice, relative impacts vary according to the FU. Therefore, we define functional equivalency as a more representative estimation of environmental impacts because the relative impacts per FU (e.g., 1 kg food item) are determined by the actual benefits or functions, in this case nutrition, that foods provide. While these studies account for nutrition, they do not directly assess health. However, by weighting environmental impacts against the proper ‘value’ of the product, the study indirectly accounts for the health-environment benefit to society and avoids undervaluing the product.

Prior to the introduction of n-FU, most studies used a mass or kcal basis (Notarnicola et al., 2016). Using kcal can bias results because foods may have similar caloric contents but different nutrient densities (Sonesson et al., 2017). Moreover, mass does not represent the true function of food. When estimated on a mass basis, ASF have higher environmental impacts compared to plant-based products; this difference decreases when impacts are evaluated on a protein basis (Sonesson et al., 2017). Arguably, single nutrients are only informative when the research question relates to nutrient deficiencies and associated diseases. Previous production-oriented studies have included single nutrient quantities like protein (Halloran et al., 2016; Smetana et al., 2019, 2015), antioxidants (Martínez-Blanco et al., 2011), omega-3 (McAuliffe et al., 2018), and protein quality (Sonesson et al., 2017; Tessari et al., 2016).

Other studies have used nutrient indices (Chaudhary et al., 2018b; Doran-Browne et al., 2015; Li et al., 2018), which poses two methodological challenges. First, some argue that disqualifying nutrients are not a function of food; additionally, indices with these nutrients can generate a negative FU with subsequent negative environmental values that could be misinterpreted as beneficial outcomes (Saarinen et al., 2017). The second issue pertains to capping FU values. Environmental impacts are lower when evaluated against an uncapped-FU because impacts are allocated over excess, or uncapped, nutrients (Van Kernebeek et al., 2014). Capping is valid for food levels that can be linked to a nutrient budget that dictates, for example, how much calcium to produce globally, nationally, and individually. For instance, capping is applicable to food groups because actors can develop a vitamin C budget for the fruits food group. At the micro scale (e.g., farm), however, there is no basis on which to cap an individual sugar beet farm that produces liberal amounts of sugar because a neighboring farm may be producing very little.

4.2.2. Allocation & systems expansion

With multi-product systems, such as a milk and beef system, the main or most economically relevant product becomes the FU; the other products are defined as co-products to which environmental impacts are assigned via allocation or systems expansion. Traditionally, LCA has used an economic or mass-based allocation. Economic allocation, however, may suffer from bias due to distortion factors such as food subsidies (Schau and Fet, 2008). As with the FU, using a nutritional basis [e.g., macronutrients (Aguirre-Villegas et al., 2012; Bava et al., 2018)] for allocation can minimize the risk of undervaluing food. Future approaches could define qualifying micronutrients as co-products. For example, when comparing a legume to a beef production system, protein could be the FU with unsaturated fatty acids and iron as co-products. Alternatively, one could employ a nutritionally-based systems expansion approach (Tyszler et al., 2014).

4.2.3. Impacts

Incorporating nutrition into this phase allows one to examine the impacts of disqualifying nutrients and to evaluate trade-offs between environmental and health outcomes. Studies can create models to estimate LCA characterization factors that link nutrients (i.e., inventory flows) to dietary risks (i.e., impacts) via epidemiological studies (Stylianou et al., 2016) or RR ratios. These studies can then examine trade-offs between health impacts due to environmental and dietary risks.

4.3. System-based models

While composite metrics and LCA are useful approaches, a key drawback is their static nature and more narrow view of the system, meaning they do not analyze sustainability questions through a dynamic, temporal, or systems-oriented approach. We name the broad group of models that do this, 'system-based models.' Such models are better equipped to analyze complex causal pathways, secondary impacts, spatial-fixes, resilience, time, and feedback loops within the food sector. Despite these advantages, relatively few NHE production studies use these models. As identified in this review and other studies (van Dijk and Meijerink, 2014), these models, generally, assess nutrition and health from a calorie or food quantity perspective.

SD studies (Allen and Prosperi, 2016; Sabaté et al., 2016) can map the relationships amongst NHE dimensions to determine how changes in one affect another. One example of such a relationship is the negative impact of rising temperatures on nutritional compositions overtime (Weyant et al., 2018). In general, most studies exclude dynamic relationships but they can greatly influence production systems. As an example, climate change negatively affects agricultural productivity and in response actors intensify agricultural practices, which lead to more climatic impacts and an eventual positive feedback loop (Bajželj and Richards, 2014). NHE studies also use IAM, which combine models from different disciplines, such as the International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT) model, which is a well-known and used PEQ; the use of this model is well documented elsewhere (Mason-D'Croz et al., 2019; Robinson et al., 2015). Summarily, it links economic, crop, and water models, to assess outcomes such as hunger, and is being updated to include nutritional deficiencies and health (Robinson et al., 2015). Previous studies have used the IMPACT model in conjunction with nutritional analyses [e.g., nutrient indices (Beach et al., 2019; Nelson et al., 2018)] and comparative risk frameworks to measure health outcomes (Springmann et al., 2016b). Limitations and advantages of PEQ include their narrower but more detailed scope because they only model interactions within the sector of interest (e.g., food) (van Dijk and Meijerink, 2014). Many IAM studies, however, assess nutrition as a function of calories (Hasegawa et al., 2018).

System-based models can, in theory, more seamlessly integrate social and economic dimensions, which enables them to identify trade-offs and synergies in a more comprehensive manner. These models are also more adept at integrating the systemic issues described earlier. Drawbacks of these models include the large data requirements for their parametrization and the complex techniques needed to use and interpret these models.

4.4. Optimization algorithms, geographic information systems, and econometric models

Mathematical optimizations determine the best alternative option, by minimizing or maximizing an objective function (i.e., goal or research question) under different constraints. These algorithms are needed to compare the impacts of substitute products under different production scenarios (von Ow et al., 2020). To date, however, this method has been predominately used to determine optimal dietary patterns (Gazan et al., 2018; van Dooren, 2018). GIS studies are used for spatial analyses of food systems; however, many studies do not jointly assess NHE dimensions of production systems. For example, they evaluate biodiverstiy losses driven by crop production (Geyer et al., 2010), obesity (Thornton et al., 2011a), or the impact of yield loss on food availability (Senay and Verdin, 2003). EC are widely used in food sector analyses. However, many EC studies use a siloed approach (Basu et al., 2013; Seo, 2010) or demand-side interventions such as taxes on nutrients (e.g., sodium, saturated fat) or food. One study included the environmental dimension by internalizing the cost of GHG emissions in the form a tax and subsidy to estimate changes in chronic disease (Briggs et al., 2013).

4.5. Discussion and future areas of research

Optimizing agri-food production systems will require developing metrics and methods that quantitatively analyze trade-offs and synergies amongst NHE dimensions. Based on the review, we identified seven key gaps in this field. Future research should focus on: (i) standardizing methods and streamlining the integration of nutrition into LCA; (ii) including dynamic and systemic aspects of food production; (ii) improving data availability, including the quantification of changes in nutrient amounts due to production and processing practices (Fig. 1); (iv) incorporating production-oriented, food-group specific, nutrient diversity, and nutrient quality metrics; (v) creating robust metrics inclusive of bioavailability aspects; (vi) understanding limitations of health metrics; and (vii) broadening the range of environmental impacts.

4.6. Standardized and enhanced methods

Standardizing methods is needed so that underlying assumptions are transparent, unknown biases are minimized, and results across studies are more comparable and interpretable. With respect to n-LCA, we explored best practices and novel methodological issues. We also discussed the points of differentiation for nutritional metrics to help streamline their integration into environmental LCA. Finally, we recognized the importance of methods that include the dynamic, circular, and temporal nature of NHE dimensions in food production. Improved methodological approaches, however, are only as useful as their underlying data and metrics.

4.7. Increased data availability and quality

We described where to access data for the various metrics and methods. Overall, however, data collection across sustainability dimensions remains challenging. Data harmonization across databases is a significant constraint and collection efforts are time-intensive and financially prohibitive, particularly in LIC; thus, studies often use globally-averaged data that obscure regional variations and this makes targeted solutions unattainable. For environmental data, these global averages are often based on data from HIC regions, thus these values are even less representative for LIC areas. Additionally, many food items do not have environmental data so studies must assign proxies. For some foods, the use of proxies is warranted, particularly if the foods are produced in standardized manners under similar conditions (e.g., akin energy mixes). In Fig. 1, we presented the influence of factors, such as agricultural and processing practices, on the nutrient contents of food items. Most food composition databases do not capture this variability and only present the average nutrient content per food item. Researchers should, therefore, focus on quantifying the impact of these production-side interventions.

4.8. Robust and targeted metrics

As discussed, health and nutritional metrics that include functionality aspects such as bioavailability and nutrient quality can avoid undervaluing food products in sustainability assessments. These issues are particularly important when linking the production to the consumption-perspective because people do not consume foods in isolation. Nutrient diversity metrics show significant promise in enhancing sustainability assessments and should be integrated into analyses more frequently. With respect to the environmental dimension, assessments that include a broader range of environmental metrics (e.g. biodiversity, water scarcity) will be more effective in identifying trade-offs to avoid sub-optimizing production systems. Currently, a lack of data limits the use of such metrics.

Introducing sustainable foods into the food supply is another option to concurrently improve NHE dimensions. For this, researchers need food-group specific methods to clarify substitution potentials. Cultural preferences and taste are significant drivers of food consumption; accordingly, producing foods within the confines of food groups, or like-products, reduces the risk that sustainable alternatives will be rejected. Finally, researchers should develop metrics specific to production aspects of food systems (i.e., yields and carbon sequestration). One such metric is the Nutritional Yield metric that estimates the number of adults who can satisfy their DRI of a nutrient for one year from a food item produced on one ha annually (DeFries et al., 2015).

5. Conclusion

For agri-food systems, optimizing NHE dimensions will require the adoption of emerging technologies (e.g., sustainable aquaculture farms, enhanced food processing techniques, regenerative agriculture, or sustainable intensification) and alternative foods (e.g., cultured meat, traditional crops, or insects). To this end, as demonstrated in this paper, we will need more robust metrics and methodological approaches to identify and compare these foods and technologies. Future studies can build on this work by incorporating the economic dimension to more effectively assess trade-offs. For example, sustainable diets are unaffordable for certain income groups (Headey and Alderman, 2019; Hirvonen et al., 2020) and their implementation can interfere with established livelihoods (Thornton et al., 2011b). Consumption-based studies and demand-side interventions are important but can place undue burdens on consumers to change their behavior; thus, we need a more concerted effort to improve the production-side of agri-food systems.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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