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Author(s):
Green, Ashley; Nemecek, Thomas; Smetana, Sergiy; Mathys, Alexander

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Reconciling regionally-explicit nutritional needs with environmental protection by means of nutritional life cycle assessment

Ashley Green[a,b,*], Thomas Nemecek[b,**], Sergiy Smetana[c], Alexander Mathys[a]

[a] ETH Zurich, Laboratory of Sustainable Food Processing, Schmelzbergstrasse 9, Zurich, 8092, Switzerland
[b] Agroscope, Agroecology and Environment Research Division, Life Cycle Assessment Research Group, Zurich, Switzerland
[c] German Institute of Food Technologies (DIL e.V.), Quakenbrück, Germany

A R T I C L E I N F O

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A B S T R A C T

Nutritional life cycle assessment integrates nutrition into environmental life cycle analysis to comprehensively account for agri-food sustainability challenges including micronutrient deficiencies, nutrient diversity, and environmental impacts like climate change or freshwater scarcity, when compared to traditional life cycle assessment. We use regionally-explicit nutritional and environmental data at the food product and country levels to calculate environmental impacts, nutritional adequacy (e.g., Nutrient Rich Food Indices), and nutritional diversity (e.g., Rao's Quadratic Entropy). We first discuss various reasons for the differences in nutritional and environmental sustainability metrics for the various food products and countries. We then present nutritionally-invested environmental impacts. Here, because nutritional life cycle analysis is a nascent method, we explore the influence of methodological choice (e.g., capped versus uncapped metrics, energy standardization, contingent versus non-contingent measures) on results. We find using nutritionally-invested environmental impacts change the relative sustainability rankings of foods and countries, regional variability in nutritional profiles and environmental footprints of food products influence results, methodological choice alters nutritional metric scores, and food products can cover nutritional deficiencies in an environmentally-friendly manner. Our study contributes to research on the joint accounting of nutritional and environmental food system outcomes.

1. Introduction

Understanding the interconnectedness between nutritional and environmental dimensions of food production is crucial to the progress of sustainability initiatives as the impacts of climate change, environmental degradation, and hidden hunger become ever-present in our daily lives (Field et al., 2014; Springmann et al., 2018; von Grebmer et al., 2014; Willett et al., 2019). Our production system is highly interlinked yet greatly locally-dependent. Nutritional and environmental dimensions vary by region because of soil conditions, agricultural practices, and fortification policies (Green et al., 2020; Poore and Nemecek, 2018a; Thompson and Amoroso, 2011). Overall, this interconnectedness and regional variability make optimizing 'the global food system' a difficult endeavor.

Newer challenges to improving our agri-food production system include increased recognition for producing nutritious foods as opposed to enough food (Ingram, 2020; Nelson et al., 2018; Smetana et al., 2019). For such nutrition security analyses, actors need proper metrics to assess nutritional diversity and nutritional adequacy. With respect to diversity, the world relies on only 30 crops for the majority of our food supply and 40 percent of our calories come from three crops; namely, wheat, rice, and maize (FAO, 2018). Minimal food diversity can have negative repercussions because diversity is important for the environmental resilience of agricultural systems (Tscharntke et al., 2012) as well as for improving human health (Chen et al., 2018). Our primary metric for nutrient diversity is Rao's Quadratic Entropy (Q); however, we also discuss other diversity metrics for comparison purposes. For nutritional adequacy, we use metrics from the Nutrient Rich Food Index (NRF) family; namely, the regionally-explicit NRF21.2 and the $NRF_{protein\text{-}sub}$ score; we developed the latter to elucidate differences between

Abbreviations: (n-LCA), nutritional-Life Cycle Assessment; (n-FU), nutritional-functional unit; (LNS), legumes, nuts, and seeds; (RT), roots and tubers; (DE), dairy and eggs; (OFS), oils, fats, and sugars; (NA), North America; (SCC), South and Central America and the Caribbean.

* Corresponding author. ETH Zurich, Laboratory of Sustainable Food Processing, Schmelzbergstrasse 9, Zurich, 8092, Switzerland.
** Corresponding author.
E-mail addresses: greenas@hest.ethz.ch (A. Green), thomas.nemecek@agroscope.admin.ch (T. Nemecek).

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vegan and vegetarian products when considering micronutrients of concern for non-omnivores.

Core to the issue of sustainable optimization is the question of best practices for merging nutritional and environmental sustainability methods to more holistically assess the food production system. One answer to this is nutritional-Life Cycle Assessment (n-LCA), which is defined as the integration of nutrition into environmental LCA (Green et al., 2020; Saarinen et al., 2017). Currently, mass-based FUs are more common, but these do not reflect the nutritional benefits that foods provide for society. Integrating nutrition into the functional unit (FU) to estimate nutritionally-invested environmental impacts will help actors compare impacts in a less biased manner.

This analysis provides additional insights to the literature in four key areas. First, we explore regional differences. Many studies use globally-averaged data (Chaudhary et al., 2018; Nelson et al., 2018). Here, however, we use regionally-explicit nutritional (Smith et al., 2016) and environmental data at the continental level that were calculated from a recent meta-analysis (Poore and Nemecek, 2018a). Second, many n-LCA studies focus on greenhouse gas (GHG) emissions; however, it is important to identify tradeoffs between nutritional and other environmental outcomes. For instance, nuts are sustainable from a GHG but not water use perspective (Vanham et al., 2020). This study includes four environmental impacts; namely, GHG emissions, water use, eutrophication, and land use. Within the latter, we further distinguish between arable land use and pasture land use. Third, for the first time, we apply nutrient diversity within the context of LCA. Fourth, we discuss novel methodological issues (e.g., contingent versus non-contingent measures, energy standardization), and expand on other matters (e.g., capping metrics, disqualifying nutrients) as they relate to n-LCA.

The first research objective separately assesses the environmental impacts and nutritional contributions of food production at the food product and food supply levels, with the metrics described earlier. As a sub-objective, we illustrate how sustainably produced foods can alleviate micronutrient deficiencies in an environmentally-responsible manner. With respect to n-LCA, the inclusion of nutrition into the FU and the subsequent changes in environmental impacts encompasses our second objective. Here, we show that new tradeoffs are revealed when measuring environmental impacts on a nutritional basis versus a mass basis. Relatedly, the third objective examines the influence of methodological choice when integrating nutrition into the FU. The aforementioned methodological issues will influence study results and consequent messages to society dictating best practices for optimizing food systems. Accordingly, we explore the inclusion or exclusion of disqualifying nutrients in the FU, depending on the type of nutrition metric used (i.e., quantity vs. diversity). We also detail issues associated with the energy standardization of nutrient indices, data selection, nutrient inclusion, scaling, and interpretability issues surrounding capped versus uncapped and contingent versus non-contingent nutritional measures.

2. Methods

2.1. Food supply analysis

We calculated average food supply values based on the years 2014–2017 to avoid yearly fluctuations in production by using the Food Balance Sheets (FBS) of FAOSTAT (FAOSTAT, 2020); at the time of writing, 2017 was the year with the most recent data. FAO calculated the data for these years using their new methodology. FAO calculates food supply as Production+Imports-Exports-Losses (pre-farm losses including Feed, Seeds, 'Other use', and post-farm losses such as processing excluding household waste). Before calculating the nutrient content of each food item, we converted available food in FBS units into available edible food. We used data from the USDA (USDA, 2020) to convert meats and seafood from FBS units to edible units. We then converted all other food items into edible form using the given values from the GENuS nutrient database (Smith et al., 2016). We did not consider household waste because data for this is highly variable and our focus is on production.

2.2. Nutritional analysis

FAO FBS are the best available and centralized source at the country level, on a global scale. However, their use for detailed analyses is limited. All food items are categorized into 80 broad groups, and, for example, apples and bananas have their own groups while the other fruits are grouped into one category. To more accurately reflect the nutrient content of a food supply we used the weighted average of individual food items that we calculated based on production and EXIM data from FAO, when calculating the nutrient content of aggregate FBS groups. For this, we followed the method of a previous study (Arsenault et al., 2015; Chaudhary et al., 2018). For example, for 'Fruits, other' we used the weighted average of nutrients for pears, apricots, etc. Table B1 (Appendix B) presents the disaggregation of the FBS groups into individual commodities. Another option is to use an unweighted matrix (Arsenault et al., 2015; Wood et al., 2018) in which pears and apricots are weighted equally.

As mentioned, we used regionally-explicit nutrient datasets from the GENuS database. To avoid bias from combining different data sources, we did not supplement this database with others. The GENuS database was derived to be aligned with the FBS; thus, we were able to match their nutrient values to the FBS groups. The database was created based on primary commodities and selected secondary ones such as flours. For food items that did not have nutrient values, we assigned the primary commodity values as determined by the FAO commodity trees (FAO, 2009). Table B1 lists how we matched food items with GENUS nutrients. For nutrients that were missing, and not zero, we filled these in with the median nutrient values of that food item from other regions.

2.3. Nutrition metrics

In n-LCA, NRF metrics are the most commonly used type of nutrient index (Green et al., 2020), which is an established measure for ranking food items based on their nutrient content. NRF indices (Drewnowski and Fulgoni, 2008) assess this by measuring the nutrient-content in foods relative to nutrient needs (i.e., Daily Recommended Intake [DRI]) and are composed of qualifying or nutrient-rich (NR) and disqualifying (LIM) nutrients.

For nutrient diversity, we used Q; however, we also considered the Shannon-Wiener diversity index (H) (Bogard et al., 2018), which only assesses diversity on a quantity and not nutrient basis. The concept of diversity is derived from the field of ecology; here, instead of species diversity, we analyzed nutrient diversity. There are three main facets of diversity that would be applicable to nutrients— evenness, richness, and divergence. Richness does not consider abundance and assumes the distribution of species is uniform (Botta-Dukát, 2005). This would result in bias against foods that supply large amounts of particular nutrients, and evenness is antithetical to our aims because it measures how similar a food supply is. Consequently, the latter aspect of divergence is most relevant for our purposes; for this, we used Q because it has been suggested in previous nutritional analyses (Bogard et al., 2018). Moreover, Q is correlated with functional dispersion (Fdis), which is another frequently used measure of divergence; we calculated a Spearman rank correlation of 0.852. Such a finding is consistent with the literature (Karadimou et al., 2016).

For all nutrient indices, we calculated the nutritional composition of each food item for every country by using the GENuS nutrient datasets. Our NRF metrics were standardized to energy content at the product level and scaled to 100 at the supply level. For these NRF metrics we included 21 NR and 2 LIM that are present in the GENuS database. The NR is comprised of Protein, Calcium, Zinc, Folate, Vitamin C, Iron, Vitamin A, Carbohydrates, Potassium, Phosphorus, Copper, Fiber, Riboflavin, Vitamin B6, Thiamin, Niacin, Vitamin B12, Polyunsaturated fat, Choline, and Manganese, and Magnesium. The LIM is comprised of Sodium and Saturated fat. To preserve the regional variability of our data, we did not supplement our data with nutrients from other databases.

We calculated the NRF (Eqns. (1)–(3)) at the product level and we applied it for the first time at the supply level (Eqn. (5)). This NRF was adapted from a previous study (Vieux et al., 2019). For the latter, food supply for a given year in a country was converted to daily per-capita values. As done in Wood et al. (2018), we calculated age-sex specific DRI values for each country by combining 2017 UN population data (UN, 2017) on sex and age with Recommended Dietary Allowances (RDA), Adequate Intakes (AI), and Maximal Reference Values (MRV) (Institute of Medicine, 2019). For the LIM, we subtracted 1 to avoid penalizing foods that did not exceed MRV (Vieux et al., 2019). For LIM, we set the minimum value to zero because negative values would erroneously result in higher final NRF values. Moreover, we scaled this metric against the number of nutrients in the index, and in instances where NR-LIM was negative, we set the value to 1 to avoid negative and fractional scores as described earlier. For a capped NRF (i.e., $NRF21.2_{supply}$), a maximal metric value of 100 indicates that qualifying nutrient needs are fully met for all nutrients and disqualifying nutrient production does not exceed MRVs.

Finally, we developed the $NRF_{protein\text{-}sub}$ score (Eqn. (4)) because metrics are needed in LCA to address questions specific to the debate of animal- and plant-based protein. Often, the reported deficiencies for vegan and vegetarian diets will vary depending on the population (e.g., inclusion of women or pregnant women), region or country, data type (e.g., globally-applicable FAO aggregated data versus more localized data that better differentiates between food types and thus nutritional differences, or supplements), and study type (e.g., blood sample or food composition data). With respect to the nutritional dimension, animal-based foods are better sources of protein quality, vitamin B12, riboflavin, calcium, and iron quality; heme iron, predominately found in animals, is better absorbed by humans than nonheme iron which is common in plants (Hooda et al., 2014; Springmann et al., 2018). Accordingly, we defined the $NRF_{protein\text{-}sub}$ score to be representative of these nutrients commonly lacking in non-omnivore diets, in addition to saturated fat because meats and dairy are linked to worsened health outcomes due to their higher saturated fat content (Siri-Tarino et al., 2010). Eqn. (4) holds the same assumptions as Eqns. (2) and (3).

As mentioned, our primary diversity measure is Q (Eqn. (6)), which measures nutrient diversity based on a pairwise distance matrix of nutrients, and we weighted this by the quantity of each food item present in the supply. We calculated Q by using the FD package in R (Lalibertè et al., 2014) and H with the 'vegan' package in R (Dixon, 2003). We used six trait matrices for Q reflective of the six GENuS nutrient datasets; the GENuS regions are the United States, India, North-East Asia, Latin America, South-East Asia, and West Africa. For these trait matrices, we calculated unweighted nutrient compositions for the FBS groups. As explained in the discussion, we scaled Q by a theoretical maximal Q so that the maximum value of the scaled Q was 100. This theoretical Q was calculated with a trait matrix that used the highest nutrient value for each food item as determined from the other trait matrices.

$$\text{Nutrient}-\text{rich (NR)} = \sum_{i=1}^{n=21} \frac{\left(\text{nutrient}_i/\text{calories}_j\right) \times 2000}{\text{RDA}_i \text{ or AI}_i}; \tag{1}$$

where: i = nutrient, j = food item.

$$\text{Limiting nutrients (LIM)} = \sum_{i=1}^{n=2} \frac{\left(\text{nutrient}_i/\text{calories}_j\right) \times 2000}{\text{MRV}_i} - 1; \text{if LIM} < 0 \text{ set LIM} = 0. \tag{2}$$

$$\text{NRF21.2}_{food} = (\text{NR} - \text{LIM});\ \text{if NR} - \text{LIM} < 1,\ \text{set NR} - \text{LIM} = 1 \tag{3}$$

$$\text{NRF}_{protein-sub} = \sum_{i=1}^{n=4} \frac{\left(\text{nutrient}_i/\text{calories}_j\right) \times 2000}{\text{RDA}_i \text{ or AI}_i} - \left(\frac{\left(\text{nutrient}_i/\text{calories}_j\right) \times 2000}{\text{MRV}_i} - 1 \right) \tag{4}$$

$$\text{NRF21.2}_{supply} = \left(\frac{\sum_{i=1}^{n=21} \frac{\text{nutrient}_i}{\text{RDA}_i \text{ or AI}_i} - \sum_{i=1}^{n=2} \left(\frac{\text{nutrient}_i}{\text{MRV}_i} - 1 \right)}{n = 21} \right) \times 100;\ \text{if} \left(\frac{\text{nutrient}_i}{\text{RDA}_i \text{or AI}_i} \right) > 1,\ \text{set} = 1 \tag{5}$$

$$Q = \sum_{q=a+1}^{s-1} d_{aq}\ p_a\ p_q; \tag{6}$$

where: s = total food richness, a = $food_n$, q = $food_{n+1}$, p = relative abundance of food items, d = the dissimilarity between foods a,q measured by differences in nutritional composition via a Euclidean distance measure.

$$\text{Environmental impact}_{nutritionally-invested} = \frac{\text{Impact}}{\text{Nutrition metric}} \tag{7}$$

From the given food supply values, before conversion to edible weights, we calculated environmental impacts of food supply using regionalized environmental impacts of food products. For imports, the data on country of origin was limited; therefore, from the given supply values, we found the fraction of imported food (FBS Imports/FBS Supply) and attributed globally-averaged impacts to these items. Regional environmental values of production were calculated by Joseph Poore based on a recent Science paper (Poore and Nemecek, 2018a) and is available in an online repository (Poore and Nemecek, 2018b). This repository contains original inventory data, regional data, and final impact results for all disaggregated food products used in Poore and Nemecek (2018a). We supplemented this data with economically re-allocated environmental impacts to obtain more granular data (e.g., cassava and cassava leaves, seeds and oils). Economic allocation is accomplished by assigning price values to food items and their co-products; based on this, environmental impacts are re-allocated between the products and co-products (Chomkhamsri et al., 2011). These additional calculations can be found in Table 1. Most LCA studies are conducted at country or production-scales. Thus, regional as well as global values are weighted averages of these country production values. For all products, we used regional values with the exception of 'butter cream and ghee', honey, and animal fats; for these, we used global impacts because regionalized data for these groups was poor.

As with the nutritional analysis, we calculated weighted environmental impacts for each FBS group using FAOSTAT trade data on disaggregated commodities. We first assigned environmental impacts to these disaggregated food items, based on the food groups in Poore and Nemecek (2018a); for smaller food items not included in this paper (e.g., 'okra', 'fruit pome, nes', 'horse meat') we used, for example, the average environmental impacts of vegetables, fruits, and mono-gastric meat, respectively. For processed items such as tomato juice we attributed environmental impacts of the primary commodity. We excluded less important food items that constituted a minimal portion of food supply for which there was subpar proxy data (e.g., 'fish, liver oil'). Finally, we calculated nutritionally-invested environmental impacts (Eqn. (7)) by dividing the environmental impacts on a kg basis by the NRF or Q metric.

Table 1
Economically re-allocated environmental impacts. Additional calculations for environmental impacts. North America (NA); South and Central America and the Caribbean (SCC); Greenhouse gases (GHG). Pasture values all zero and excluded.

Food product	Region	Land Use (m^2)	Arable (m^2)	GHG (kg CO_2eq)	Eutrophication (g PO_4^{3-}eq)	Water Use (L)
Cassava leaves	Global	0.85	0.85	0.67	0.38	0.00
Cashewapple	Global	2.53	2.53	0.14	4.38	951.18
Sunflower seeds	Global	8.40	8.40	1.76	24.73	460.93
Soybeans	Global	3.12	3.12	1.87	3.44	128.15
Mustard and rapeseed	Global	17.26	17.26	6.26	31.73	382.43
Cassava leaves	NA	1.06	1.06	0.81	0.46	0.00
Cashewapple	NA	1.58	1.58	−0.19	3.44	1390.14
Sunflower seeds	NA	8.40	8.40	1.76	24.73	460.93
Soybeans	NA	3.75	3.75	1.00	4.99	296.00
Mustard and rapeseed	NA	25.72	25.72	6.08	30.82	71.03
Cassava leaves	Europe	1.06	1.06	0.81	0.46	0.00
Cashewapple	Europe	3.75	3.75	−0.06	8.90	390.66
Sunflower seeds	Europe	6.61	6.61	1.57	42.00	705.78
Soybeans	Europe	4.99	4.99	2.84	18.41	211.02
Mustard and rapeseed	Europe	10.26	10.26	5.83	33.37	46.22
Cassava leaves	SCC	0.85	0.85	0.67	0.38	0.00
Cashewapple	SCC	5.54	5.54	3.17	4.26	2.72
Sunflower seeds	SCC	6.49	6.49	1.22	6.40	797.19
Soybeans	SCC	2.18	2.18	2.25	3.17	0.48
Mustard and rapeseed	SCC	15.23	15.23	6.67	25.02	1193.94
Cassava leaves	Africa	1.06	1.06	0.81	0.46	0.00
Cashewapple	Africa	3.75	3.75	−0.06	−1.92	390.66
Sunflower seeds	Africa	24.16	24.16	1.74	7.04	1.43
Soybeans	Africa	4.99	4.99	2.84	3.62	211.02
Mustard and rapeseed	Africa	74.31	74.31	5.95	21.91	2.40
Cassava leaves	Oceania	0.85	0.85	0.67	0.38	0.00
Cashewapple	Oceania	2.53	2.53	0.14	10.24	951.18
Sunflower seeds	Oceania	8.40	8.40	1.76	24.73	460.93
Soybeans	Oceania	3.12	3.12	1.87	3.44	128.15
Mustard and rapeseed	Oceania	41.33	41.33	8.76	16.45	48.92
Cassava leaves	Asia	0.46	0.46	0.52	0.38	0.00
Cashewapple	Asia	3.20	3.20	0.60	8.86	164.47
Sunflower seeds	Asia	8.40	8.40	1.76	24.73	460.93
Soybeans	Asia	4.99	4.99	2.84	1.70	211.02
Mustard and rapeseed	Asia	74.31	74.31	5.95	32.88	2.40

3. Results

3.1. Nutritional and environmental sustainability results for food products and food supply

3.1.1. Regional differences in environmental and nutritional outcomes for food products

Fig. 1 shows the NRF21.2_{food} scores (Eqn. (3)) and environmental impacts of food groups. Vegetables are the most nutrient-dense group followed by seafood. As these results are uncapped, their decisively higher scores are likely owed to the considerably higher concentrations of vitamin C and vitamin A in vegetables and vitamin B12 in seafood relative to other food groups (Fig A.1). A more detailed discussion of this is presented in the capping section. On average, legumes, nuts, and seeds (LNS), fruits, and meats have the next highest scores followed by roots and tubers (RT), dairy and eggs (DE), and cereals. As expected, oils, fats, and sugars (OFS) are the least nutrient dense. Regional variation also influences nutrient density. For example, South and Central America and the Caribbean (SCC) has higher scores for vegetables and fruits while Asian DE is more nutrient dense than its counterparts in other regions. Overall, regional variation plays a relatively greater role for the groups of vegetables, seafood, DE, and meat. This has implications on how food should be nutritionally optimized. For example, adopting a higher use rate of mineral fertilizer or implementing food substitution in Europe could improve the region's nutrient density of vegetables.

For eutrophication and GHG impacts, the relative relationships between food groups are similar, except meat has a higher GHG footprint than seafood. In general, vegetables, fruits, and RT have the lowest footprints across all environmental categories. Cereals have moderate impacts while LNS and OFS have moderate to high impacts. Relative to other food groups, meats have similar arable land use values to LNS and OFS while DE have lower values; on an overall land use basis, meats have much higher use values as evidenced by their higher pasture use. We see that regional variations exist for many food groups under different impact categories (e.g., pasture use of meat and DE or eutrophication emissions of seafood). However, the influence of regional variation is strongest for water use (e.g., RT, cereals).

3.1.2. Meat products and sustainability comparisons

A key sustainability question, illustrated in Fig. 2, is that of meat consumption. Here, we see nutritional and environmental differences between pig, goat and sheep, poultry, and bovine meat. Overall, regional variations obscure differences between product groups, and groupings are not well defined. For the NRF21.2_{food} of meat products, there are high regional variations for bovine, pig, and poultry meat. On average, bovine meat scores the highest followed by the goat and sheep group, however, this is a result of their high vitamin B12 content (Fig A2). The implications of this are discussed in the methodological section on capping. Poultry meat scores the next highest and pig meat is the least nutrient dense. While bovine and goat and sheep product groups have higher nutritional profile scores, they also have higher footprints on average for all environmental categories.

3.1.3. Vegetarian and vegan product sustainability differences as determined by key micronutrients of concern for non-omnivores

The $NRF_{protein\text{-}sub}$ score (Eqn. (4)) was derived to contribute to the debate of reducing animal-protein production to stay within planetary boundaries (Poore and Nemecek, 2018a; Springmann et al., 2018). For reasons explained in the methods section, we define the $NRF_{protein\text{-}sub}$ to include protein, vitamin B12, calcium, iron, riboflavin, and saturated fat.

Fig. 3 shows that of the protein-rich, plant-based alternatives,

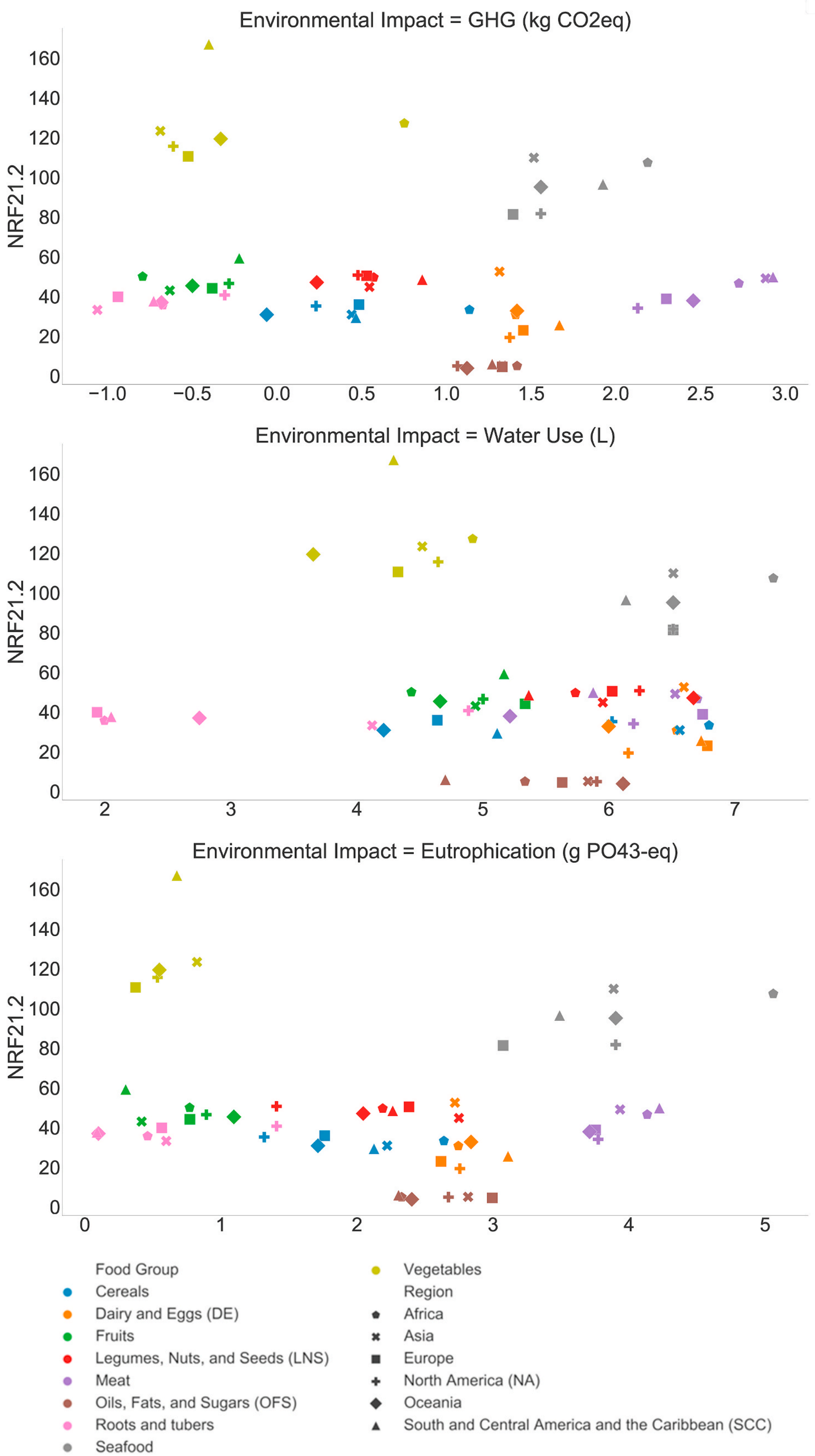

Fig. 1. Nutritional scores ($NRF21.2_{food}$) and mass-based environmental impacts of food groups. Environmental impacts presented on a natural log basis and calculated against a 1 kg functional unit. NRF scores uncapped. Food groups denoted by colors and regions by shapes.

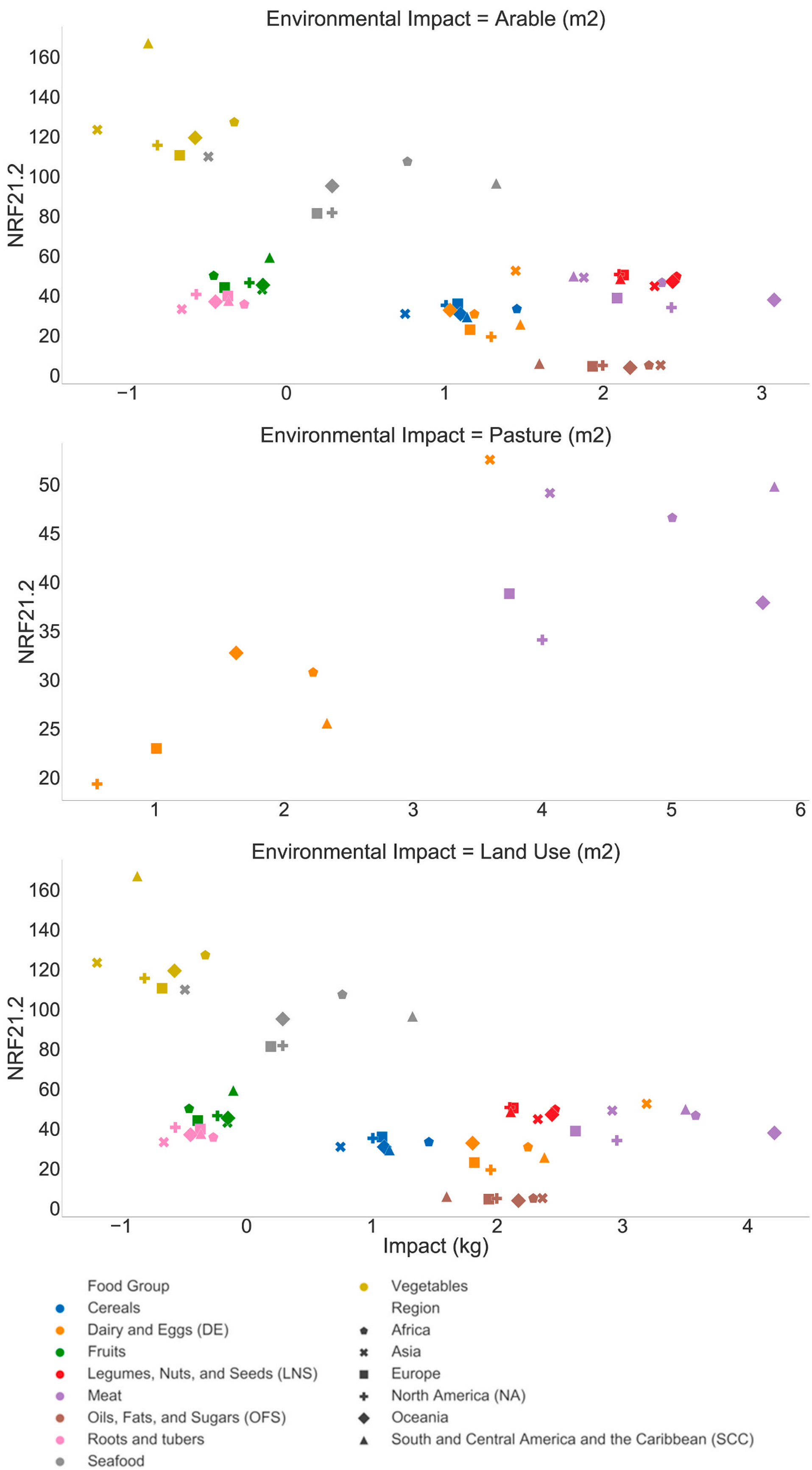

Fig. 1. (*continued*).

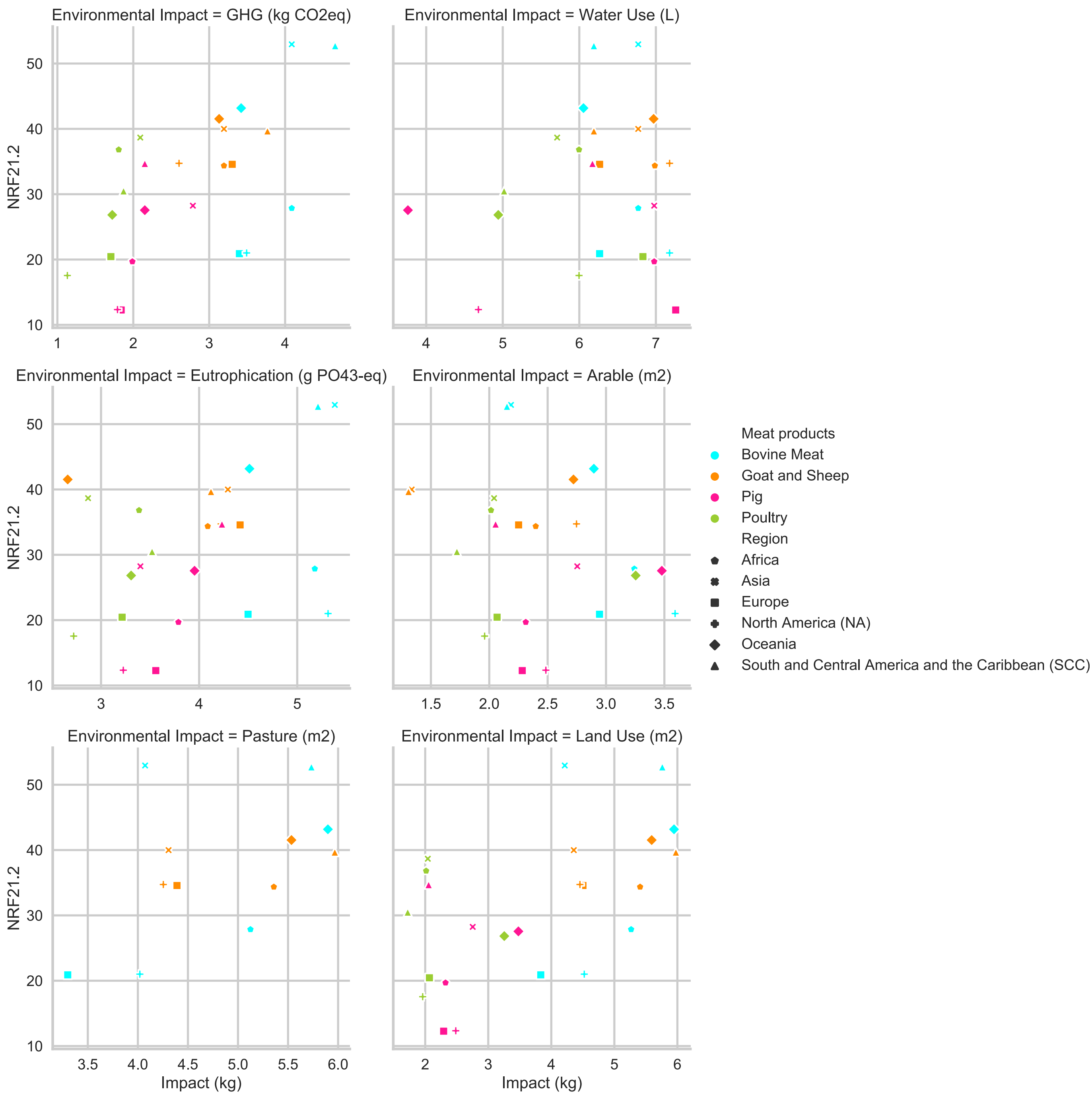

Fig. 2. Environmental impacts and NRF21.2$_{food}$ scores of meat products. Colors represent food items; shapes represent regions. Environmental impacts are presented on a natural log basis.

vegetarian products, on average, have a higher NRF$_{protein\text{-}sub}$ score than vegan products. Of the vegetarian products, eggs do the best nutritionally followed by cheese and milk. However, cheese has higher environmental impacts than eggs and milk. Of the vegan foods, legumes and seeds are the most nutrient dense. Starch-rich crops have the lowest environmental footprints, but their nutritional densities are not as high as legumes or seeds. Of the LNS category, seeds have the highest GHG, land use, and eutrophication footprints while nuts have a much higher water footprint and the lowest nutritional density. This figure also illustrates that global staple grains (i.e., wheat, rice, maize) have lower nutritional scores than their traditional counterparts or crops that are widely eaten in low-income countries but largely overlooked in high-income ones. This suggests that we could produce more traditional and orphan crops or fortify our staple crops to improve our overall nutritional supply. Both options have been examined (FAO, 2018, 1995; Garg et al., 2018; Khush et al., 2012; Pingali, 2015), although the former to a lesser extent.

3.1.4. Environmental impacts of food supply

Two drivers that influence the environmental impacts of food supply include food choice, which is what foods people consume and technological efficiency, which is how the agri-food sector produces foods. Fig

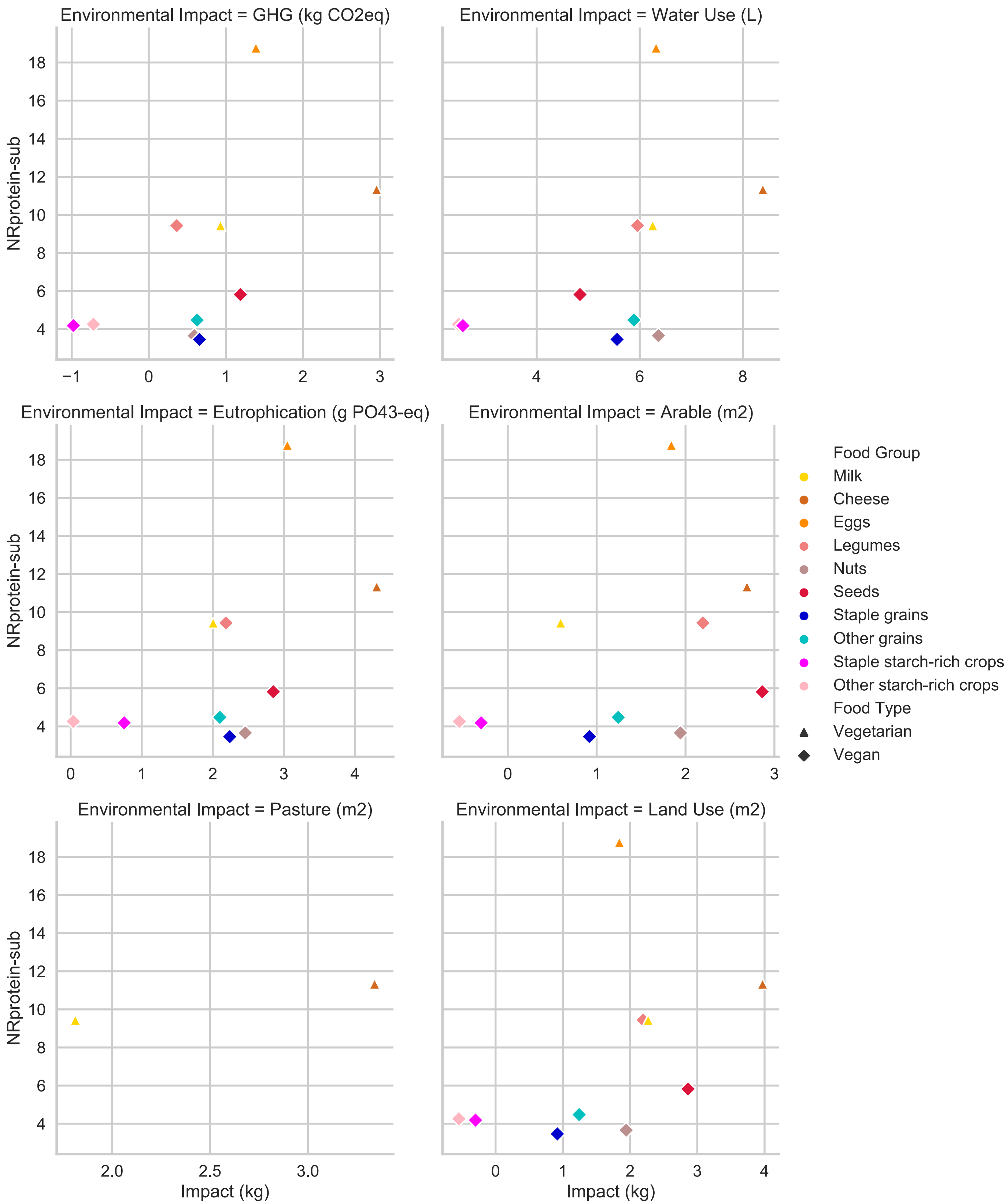

Fig. 3. Nutritional scores and environmental impacts of vegetarian and vegan products. Food types: Staple starch-rich crops include potato; staple grains include wheat, rice, and maize; Other grains— Sorghum, Rye, Oats, Millet, Buckwheat, Quinoa, Fonio, Triticale, Grain, mixed, Cereals nes, Barley; Other starch-rich crops—Yams, Taro, Roots and tuber nes, Yautia, Cassava. Environmental impacts are presented on a natural log basis.

A3 demonstrates that GHG emissions are highest in SCC, likely due to higher bovine meat consumption. Asia and Africa are the largest overall users of water; in Asia, this is likely driven by a higher rice consumption despite Asia's lower water use intensity (i.e., water use per kg of rice) when compared to North America (NA) and Oceania. Africa has the highest eutrophication potentials and Europe has the lowest. Foods with the largest eutrophication footprints include meat and seafood; for both categories, Africa generally has higher emission intensities while Europe has much lower values.

3.1.5. Country-level nutritional security

At the supply level, we calculated two FU metrics, the $NRF21.2_{supply}$ (Eqn. (5)) and Q (Eqn. (6)). Between these, we found a Spearman rank correlation of −0.00749, which implies the metrics are complementary and actors can use them in tandem to develop a more holistic picture of nutrition security. As explained in the methods section, both scores are scaled to 100. Nutrient adequacy scores of supply are higher compared to metric scores in previous analyses because of data and method choice. For example, our focus is production; consequently, our nutrient estimates are higher than those in other studies that account for losses and waste that occur during cooking or further processing foods (Chaudhary et al., 2018; Nelson et al., 2018). Table 2 shows results stratified by income and continental region; however, there are no clearly defined trends, which suggests that drivers of nutritional security operate at more localized levels. This is intuitive because within nations there is an unequal distribution of food and nutrients due to financial contraints (Hirvonen et al., 2020) and food deserts (Battersby and Crush, 2014; Beaulac et al., 2009), which are areas in which access to nutrient-dense foods is limited. Additionally, we know that individual households can be subject to both obesity and malnutrition.

For the $NRF21.2_{supply}$, values are fairly similar across income regions but across physical regions, Asia and Oceania have lower scores. We see a larger variation in scores when examining combined income-physical regions; for example, the Upper Middle Income Countries (UMIC) group in Europe also has a high score. However, the drivers and thus consequent interventions likely differ for these regions. For example, higher values in Lower Middle Income Countires (LMIC) and Lower Income Countries (LIC) in Africa or SCC may result from their limited market access to purchase traded commodities (Remans et al., 2014). It is possible that these regions rely on locally-produced and traditional foods that often have a higher nutrient density (FAO, 2018; Jacques and Jacques, 2012; Mabhaudhi et al., 2019). On the other hand, while higher income countries have trade access, relatively lower scores in High Income Countries (HIC) and UMIC could be attributed to foods high in limiting nutrients or foods subject to low-quality processing that leads to nutrient density losses. Proportions of these items are generally higher in a westerinzed or modernized food supply (Cordain et al., 2005; Hu, 2011).

For Q, LIC have the highest diversity scores; for physical regions, Oceania has the highest score and Europe the lowest. As with the NRF, there is a greater variation when examining combined physical-income regions. Similar to reasons before, LIC have more smallholder farms that provide foods higher in varietal diversity and micronutrient densities in comparison to large farms used by wealthier countries (Herrero et al., 2017; Jacques and Jacques, 2012). Thus, some LIC may have fewer but more micronutrient dense items. LIC may also have higher diversity scores because they rely on more traditional staples and crops instead of on a few traded staples. Nevertheless, their supply can still lack in diversity if their traditional food items and smallholder farms are nutritionally inadequate. On the other hand, HIC can use their trade purchasing power to avoid lower diversity scores (Kummu et al., 2020; Remans et al., 2014). This would increase their Q score as it is measured

Table 2
Regionally-differentiated nutritional scores for nutrient adequacy and nutrient diversity. Nutrient Rich Food Index (NRF); North America (NA); South and Central America and the Caribbean (SCC); Rao's Quadratic Entropy (Q).

$NRF_{supply}21.2$	High Income Countries (HIC)		Upper-Middle Income Countries (UMIC)		Lower-Middle Income Countries (LMIC)		Lower Income Countries (LIC)		Physical region
	mean ± std (n)	(min, max)	mean ± std (n)	(min, max)	mean ± std (n)	(min, max)	mean ± std (n)	(min, max)	
Africa			93.39 ± 3.44 (6)	(89.15, 98.33)	92.63 ± 4.49 (18)	(81.30, 97.28)	90.61 ± 5.59 (21)	(77.19, 96.28)	91.79
Asia	88.15 ± 5.00 (10)	(78.39, 93.80)	84.16 ± 6.22 (13)	(72.88, 97.66)	83.79 ± 7.61 (13)	(70.89, 94.49)	79.31 ± 9.82 (5)	(69.23, 92.22)	84.43
Europe	90.23 ± 1.81 (29)	(86.15, 92.81)	92.69 ± 2.47 (9)	(88.76, 96.54)	91.16 ± 6.71 (2)	(86.41, 95.91)			90.83
NA	90.76 ± 0.21 (2)	(90.61, 90.91)							90.76
Oceania	87.12 ± 2.68 (4)	(83.54, 89.63)	80.15 ± 10.67 (2)	(72.61, 87.70)	78.67 ± 7.70 (3)	(72.04, 87.12)			82.76
SSC	90.51 ± 4.02 (8)	(84.03, 94.66)	93.15 ± 3.29 (18)	(83.77, 98.25)	92.19 ± 1.93 (4)	(90.46, 94.37)	89.37 ± 0.00 (1)	(89.37, 89.37)	92.22
Income region	89.66		90.12		88.59		88.47		
Q	**HIC**		**UMIC**		**LMIC**		**LIC**		
Africa			35.90 ± 3.76 (6)	(31.84, 41.92)	36.27 ± 5.00 (18)	(28.35, 46.27)	44.54 ± 14.75 (21)	(22.95, 77.91)	40.08
Asia	45.45 ± 3.89 (10)	(39.17, 51.96)	39.43 ± 6.10 (13)	(34.05, 56.66)	37.49 ± 5.00 (13)	(25.39, 45.27)	34.05 ± 1.95 (5)	(31.78, 35.99)	39.63
Europe	35.83 ± 2.33 (29)	(29.83, 40.38)	33.94 ± 2.81 (9)	(29.80, 37.41)	33.15 ± 2.42 (2)	(31.44, 34.86)			35.27
NA	40.27 ± 2.55 (2)	(38.47, 42.07)							40.27
Oceania	42.38 ± 4.24 (4)	(36.90, 47.13)	45.43 ± 1.89 (2)	(44.10, 46.77)	40.62 ± 2.59 (3)	(37.63, 42.24)			42.48
SCC	38.55 ± 3.70 (8)	(34.18, 44.48)	40.74 ± 5.14 (18)	(31.78, 50.04)	41.73 ± 3.95 (4)	(36.43, 45.86)	43.60 ± 0.00 (1)	(43.60, 43.60)	38.72
Income region	38.72		38.7		37.38		42.56		

on both a food quantity and nutrient diversity basis. On the other hand, modernized countries have a more homogenous supply; for example, on a global scale, nutrient density in cereals has declined (DeFries et al., 2015). This could explain why some countries in UMIC and LMIC regions have moderate to low scores— their diets are modernizing but they do not have sufficient purchasing power to compensate for the lack of diversity in their food supply. For comparison purposes, we calculated H (Table A1). H is more frequently used in studies and it differs from Q because it measures diversity purely on a food quantity basis and does not account for nutrients. Between Q and H, we found a Spearmen rank correlation of 0.525. In general, there are some differences from the Q scenario; for example, we see that HIC have the highest scores and that Oceania has more moderate scores.

3.1.6. Nutritional deficiencies in food supply

To develop a more holistic picture of nutrition security, we calculated national nutrient adequacy ratios (Fig A4). Nutrient deficiencies that are common in most countries include calcium, vitamin A, potassium, and choline. Our adequacy values are based on food supply and ignores supplementation and bioavailability; the former does and can alleviate many deficiencies. On the other hand, minerals like zinc and iron would have much higher deficiency values if bioavailability were accounted for (Nelson et al., 2018). This analysis is for the production-perspective thus our nutrient adequacy ratios are higher than those in previous analyses that account for potential losses in processing and cooking (Nelson et al., 2018; Wood et al., 2018). For example, frying foods decreases nutrient contents. These higher values indicate that reducing food waste and processing losses (e.g., by using low thermal intensities) could reduce micronutrient deficiencies. Finally, while we used a different database, with different nutritional compositions; overall, we see similar trends for most nutrient deficiencies.

3.2. Nutritional-LCA results at food and country levels

3.2.1. Nutritionally-invested environmental impacts of food products

Table 3 demonstrates that different tradeoffs are revealed between food groups when comparing impacts measured on a purely kg basis versus when they are measured on a nutritional basis. For example, for eutrophication, under a FU of 1 kg, RT have the lowest potentials, however, with a nutritional FU (n-FU) — in this case, the NRF21.2$_{food}$— vegetables rank the lowest. Ranking spots refer to the environmental impacts of foods relative to one another. For all impact categories, the nutritionally-invested impacts of OFS are the highest because the nutrient-content of this group is relatively low as evidenced in Fig. 4 in the uncapped graph. Moreover, seafood has high water use impacts under a mass-based FU; however, when the value of nutrition is accounted for, seafood has a relatively low water footprint.

Fig. 5 shows how this picture varies when accounting for regional differences. For example, when using an n-FU, OFS, on average, have higher impacts than meat, but this is not the case for all regions. OFS and meat GHG footprints in SCC are very similar, and on a land use basis, meat has a higher impact than OFS in Oceania and SCC. Regional differences are also evident for water use for which meat is comparable to or higher than LNS for all regions except Oceania where LNS use more water. Additionally, for eutrophication potentials, meat ranks higher than seafood except for in the African region where the impacts are similar.

For meat items in Table A2, the NRF21.2$_{food}$ FU has little influence on the relative sustainability rankings. For example, despite the higher nutrient density of bovine meat, it still has the highest GHG and eutrophication footprints. Overall, this table suggests that if meat consumption is needed to meet amino acid or other nutrient requirements, the better option might be poultry because it has the lowest nutritionally-invested environmental footprints for all categories expect arable land use.

When impacts are measured with an NRF$_{protein\text{-}sub}$ FU, as shown in Table A3, we see new tradeoffs. Based on the changes in ranking spots, the n-FU has the largest impact on eggs and nuts as well as in the impact categories of GHG emissions and eutrophication. Despite the higher nutritional scores of legumes and cheese, their ranking spots remain largely unchanged. Finally, the rankings of staple grains increase for most impact categories while for eggs they decrease in all categories.

3.2.2. Nutritionally-invested environmental impacts of country and regional food supply

We classified the countries into percentile ranking groups. Overall, the stratification between some countries increases while in other instances it decreases. For instance, Burkina Faso has a high GHG footprint, but with the diversity FU it is categorized into the 'low' percentile. In general, the change in rankings when accounting for nutritionally-invested impacts has implications for which areas policies, interventions, and funding allocations should target for sustainability initiatives.

Based on Fig A5, at the continental level, the environmental impact rankings of regions are similar regardless of the FU used. We tested a kg,

Table 3
Differences in environmental impacts estimated with a baseline FU of 1 kg and with the NRF$_{food}$. Impacts calculated as average of regional values (e.g., average of African cereals, Asian cereals, etc). Values scaled against meat. Rankings in parentheses. Greenhouse gases (GHG); Nutrient Rich Food Index (NRF).

Food group	GHG (kg CO_2eq)		Water Use (L)		Eutrophication (g PO_4^{3-}eq)		Land Use (m^2)		Arable (m^2)		Pasture (m^2)		NRF$_{food}$ scaled
	kg	NRF$_{food}$	kg	NRF$_{food}$	kg	NRF$_{food}$	kg	NRF$_{food}$	kg	NRF$_{food}$	kg	NRF$_{food}$	
Vegetables	0.059 (7)	0.021 (9)	0.197 (8)	0.069 (8)	0.048 (7)	0.017 (9)	0.008 (9)	0.003 (9)	0.052 (9)	0.018 (9)			2.84
Seafood	0.301 (2)	0.137 (4)	1.178 (2)	0.536 (6)	1.116 (1)	0.508 (3)	0.026 (6)	0.012 (7)	0.182 (6)	0.083 (7)			2.20
Legumes, nuts, and seeds (LNS)	0.09 (6)	0.084 (6)	0.727 (6)	0.677 (5)	0.19 (5)	0.176 (6)	0.165 (4)	0.153 (4)	1.149 (2)	1.069 (2)			1.07
Fruits	0.033 (8)	0.031 (7)	0.223 (7)	0.208 (7)	0.033 (8)	0.031 (7)	0.012 (7)	0.011 (8)	0.085 (7)	0.08 (8)			1.07
Meat	1 (1)	1 (2)	1 (3)	1 (4)	1 (2)	1 (2)	1 (1)	1 (2)	1 (3)	1 (3)	1 (1)	1 (1)	1.00
Roots and tubers (RT)	0.024 (9)	0.029 (8)	0.036 (9)	0.045 (9)	0.024 (9)	0.03 (8)	0.011 (8)	0.013 (6)	0.075 (8)	0.093 (6)			0.81
Dairy and eggs (DE)	0.279 (3)	0.371 (3)	1.651 (1)	2.193 (2)	0.355 (3)	0.471 (4)	0.405 (2)	0.538 (3)	0.539 (4)	0.716 (4)	0.231 (2)	0.307 (2)	0.75
Cereals	0.096 (5)	0.131 (5)	0.923 (4)	1.257 (3)	0.149 (6)	0.203 (5)	0.046 (5)	0.062 (5)	0.318 (5)	0.434 (5)			0.73
Oils, fats, and sugars (OFS)	0.21 (4)	1.866 (1)	0.834 (5)	7.427 (1)	0.317 (4)	2.82 (1)	0.178 (3)	1.588 (1)	1.244 (1)	11.075 (1)			0.11

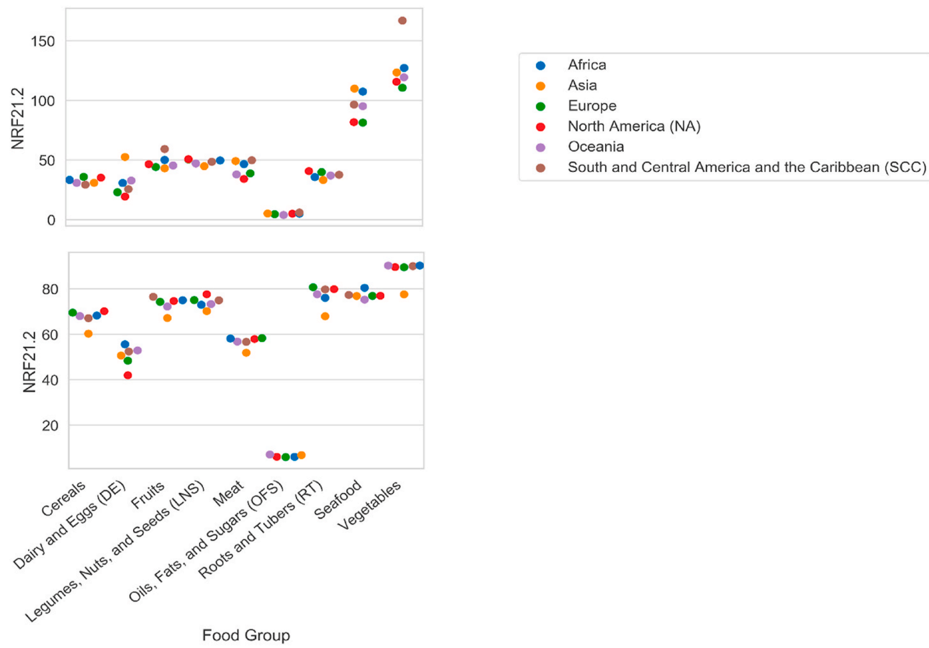

Fig. 4. NRF (Nutrient Rich Index) scores for food groups at the regional level. First graph on capped basis, second graph on uncapped basis.

Q, and NRF21.2_{supply} FU; the values were calculated in the same manner as for supply. This is because, for reasons described earlier, regions have similar averages for nutritional metrics. However, we see more of a difference at the country level (Table B2); to illustrate differences between countries we divided them into quintile rankings. Generally, countries that made jumps in rankings had a substantially high nutrient content for their food supply to offset their starting environmental values. For example, on average, African countries are less efficient in terms of production so their overall supply will generally have higher associated emissions. Therefore, when these countries move percentile rankings, it implies their nutritional adequacy or diversity is much higher relative to other countries.

3.3. *Methodological choice in n-LCA*

3.3.1. *Capped and uncapped nutrition metrics in n-LCA*

For nutrient adequacy metrics applied at the supply level, if qualifying nutrient amounts exceed 100% of daily needs the metric is capped at 1 to ensure that countries do not receive higher scores for an excess of nutrients that do not provide additional health benefits (Drewnowski et al., 2018). At the food product level, we do not cap nutrient amounts because excess nutrients in one food item can compensate for a lack of nutrients in another (Green et al., 2020). Studies, however, should consider certain aspects when using uncapped NRF21.2_{food} scores. Uncapped metrics can obscure nutrient density differences between food groups (i.e., an uncapped value over 100 does not indicate that a food group meets all nutrient requirements) and the dominance of one or two nutrients in a food item can affect the relative sustainability rankings. As shown in Fig. 4, uncapped and capped nutrient metric scores can differ. For example, we see that seafood has much higher NRF scores on an uncapped basis than other food groups (excluding vegetables) but on a capped basis it has similar values to LNS, fruits, and RT. As previously discussed, this is likely due to seafood's excessively high vitamin B12 content (Fig A1). Vegetables also have a relatively high vitamin A content; however, on a capped basis they remain the highest-ranking group indicating that their higher nutrient density scores are independent of the vitamin A content. On the other hand, for meat products, poultry does the best on a capped basis because, on average, it has higher values for many nutrients. However, on an uncapped basis, bovine meat ranks highest but this results from its high vitamin B12 content (Fig A2) because for most other nutrients, poultry has similar or higher values than bovine meat. This shows that food items with one or two nutrients present in large quantities can receive higher NRF scores despite being less nutrient dense than other foods. Here, the role of local context is very important. For example, if the nutrient in question is one for which severe nutrient deficiencies exist (e.g., calcium or vitamin A— as shown in Fig A4), then the higher score would be warranted. However, if the nutrient has an adequacy ratio of one or greater (e.g., carbohydrates, vitamin B6— as shown in Fig A4) then the higher NRF score would be misleading. Future studies should explore these options more in-depth.

3.3.2. *Contingent versus non-contingent measures and scaling in n-LCA*

A second issue relates to non-contingent and contingent nutrition metrics. We define capped nutrient indices to be non-contingent measures because they have an independent and absolute maximum (i.e., 100). Uncapped nutrient metrics are a hybrid between non-contingent and contingent measures. They have an independent maximum, because this value does not change in relation to other food items; however, they do not have an absolute maximum because they are not capped at 100. Diversity measures are contingent because their values are dependent meaning that values change in relation to other food items in the food supply. Moreover, these metrics do not have a known maximum value. Thus, there is no natural value of diversity that we can benchmark against unlike with the capped NRF21.2_{supply} metrics for which a value of 100 indicates that all nutrient requirements are met and that upper intake values for disqualifying nutrients (i.e., nutrients whose intake we should limit for health reasons) is not exceeded. However, as explained in the methods, to increase the interpretability and comparability of Q we normalized it against an artificial, maximum Q value that we calculated. Nevertheless, interpretability remains a challenge; due to the multidimensional nature of Q, unit increases are not meaningful, and the Q values themselves are only useful when compared against one another.

As mentioned, for interpretability reasons, we scaled the NRF21.2_{supply} metric to have a maximum value of 100. Another benefit of scaling is the minimized risk of fractional scores (i.e., scores less than 1). Fractional indices create an increase in calculated environmental impacts, and this increase is not proportional to the rate at which impacts would decrease with index values above 1.

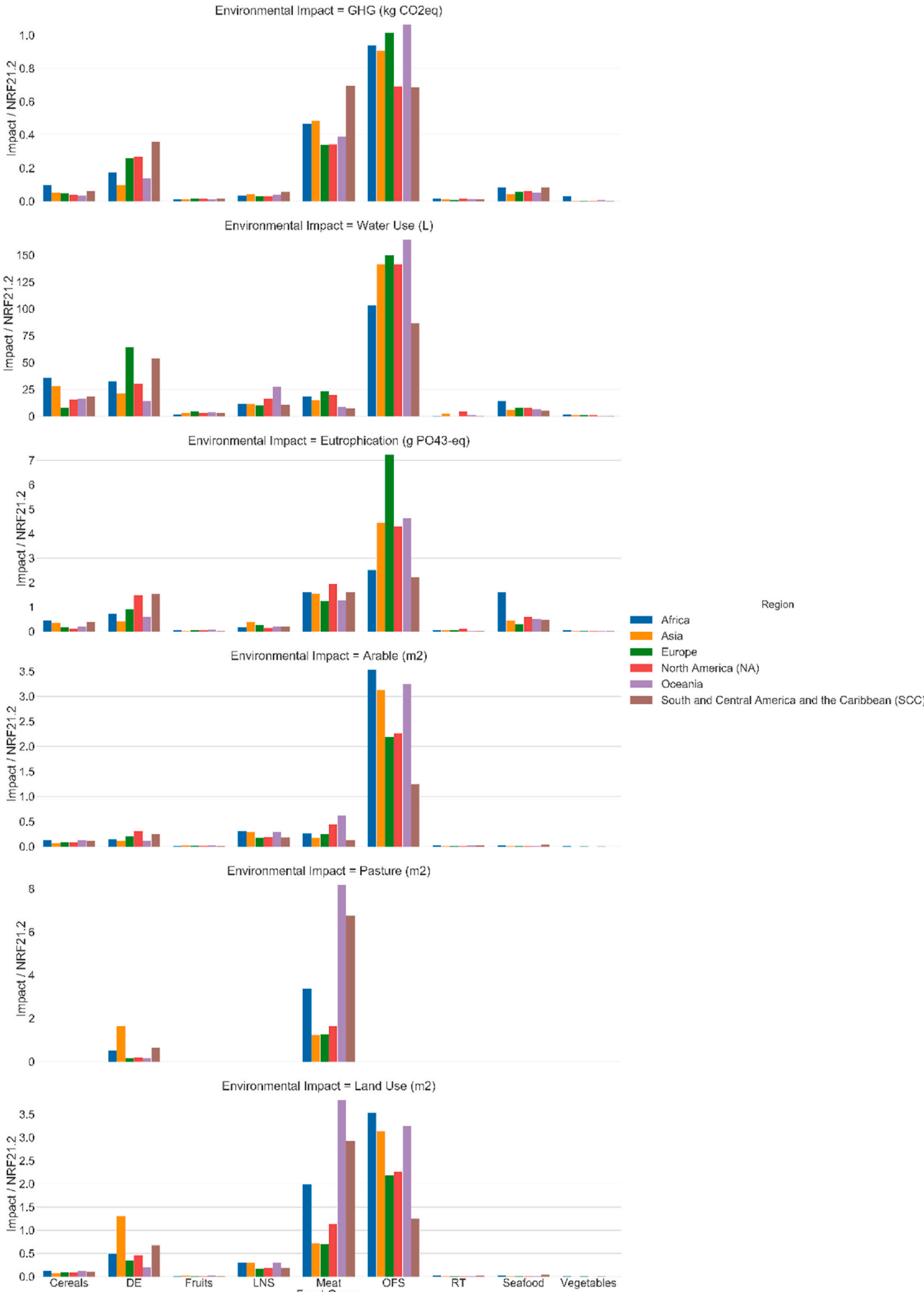

Fig. 5. Nutritionally-invested environmental impacts differentiated by region. Nutrient Rich Food (NRF); Dairy and eggs (DE); Legumes, nuts, and seeds (LNS); Oils, fats, and sugars (OFS); Roots and tubers (RT).

3.3.3. Energy standardization in n-LCA

In the past, NRF metrics have been calculated without consideration for a food item's energy content. Recent indices include this aspect because it makes the food independent of portion size (Fern et al., 2015) and the metric better aligns with the updated Healthy Eating Index guidelines (Drewnowski et al., 2018). For energy standardization, we use 2000 calories because this is the standard value used in many analyses; in reality, however, this number varies by factors such as physical activity and gender (Nelson et al., 2018). From an LCA perspective, energy standardization is needed at the food product level because it increases the comparability of foods. Meats and fruits confer different outcomes on the human body because they have dissimilar nutritional compositions and consuming 100g of spinach is not the same as consuming 100g of pig. Therefore, energy standardization is needed to compare food products. However, at the food supply level, this standardization factor distorts the actual nutrients that are present in the supply because one has to multiply nutrients by different scaling values depending on the caloric content, which changes the actual amount of nutrients present. Moreover, a national food supply should be a complete set of nutrients; consequently, we argue that there is no need to consider the differences in 100g of spinach versus 100g of pig at the supply level in LCA.

To better understand the importance of energy standardization, we calculated Spearman rank correlations between different applications. Between the $NRF21.2_{supply}$ and energy standardizing results at the supply level before dividing by the DRI, which is the method of the $NRF21.2_{food}$, we found a Spearman rank correlation of 0.43. Between the $NRF21.2_{supply}$ and standardizing to energy content after dividing by the DRI, which is the Nutrient Balance Score method (Fern et al., 2015) we found a correlation of 0.839. Additionally, we also found that, on average, the values calculated in this manner were lower when compared with the $NRF21.2_{supply}$.

3.3.4. Nutrient inclusion in n-LCA

As explained in the methods, we include disqualifying nutrients and set the NR-LIM value to 1 if it is less than 1. This is to avoid both negative and fractional scores. NRF scores of 1 implies that environmental impacts remain unchanged, which means the nutritional benefits play no role in benefiting society. This of course slightly undercuts the contributions of foods that are not nutrient dense like sunflower oil, which has an NRF value close to 1. However, the alternative is to exclude disqualifying nutrients, which would bias results in favor of food items high in these nutrients.

When including disqualifying nutrients in nutrient indices, there is a risk the FU will be negative (Saarinen et al., 2017), and there is a much higher risk this will occur for energy dense foods such as oils, animal fats, and butters. In such instances, the environmental impacts will be negative, which implies an environmental benefit (Saarinen et al., 2017); this can be confused with environmental impacts that are actually negative (e.g., carbon sequestering foods). LCA practitioners may argue including disqualifying nutrients violates the premise of the FU, which is to represent the benefits of a product; however, as we are adjusting the environmental impacts, we argue that this approach is more of a hybrid between the FU and LCA impact weighting phases. Accordingly, disqualifying nutrients can be included in the manner proposed in the methods. Q could include disqualifying nutrients because there is no risk of a negative FU. However, it would be misleading for a country to receive a higher diversity rating because of its disqualifying nutrient content. Consequently, we suggest to remove all disqualifying nutrients; in theory, however, sodium could be included because small portions are needed for physiological function (WHO, 2016).

Finally, this study did not include all essential nutrients, because we only considered regionally-differentiated data from the GENuS database. However, nutrients can be correlated, and from an LCA perspective, the inclusion of every nutrient is not necessary because the food-benefit to society will still be represented if we include those nutrients most correlated with others. For example, we found that protein, magnesium, zinc, and phosphorus have positive correlations of 0.7 or higher with many nutrients (Table B3). Another study found that eight nutrients explained over 60 percent of health outcomes as determined by the correlation with the Healthy Eating Index (Arsenault et al., 2012). In such cases, the extra time that would be spent for data collection is unwarranted.

4. Discussion

4.1. Nutritional-LCA alters the relative environmental footprint rankings of food products and countries

When accounting for nutritionally-invested environmental impacts with n-LCA, we see changes in relative environmental footprint rankings. For example, on a kg basis, OFS has a lower environmental footprint than other food groups like meat; however, when nutrition is accounted for, OFS does the worst environmentally (Table 3). Going forward, studies should be conducted within food groups to better understand substitution potentials. We also found that the relative environmental impacts of vegan and vegetarian products changed when accounting for nutrients of concern for non-omnivores (Fig. 3, Table A3). However, the $NRF_{protein\text{-}sub}$ metric does not include protein quality [e.g., Digestible Indispensable Amino Acid Score (DIAAS)], and its incorporation would provide even greater insights, by showing a greater stratification between foods, because, quite often, animal-based proteins have a better digestibility and are a more complete source of amino acids (Loveday, 2019). At the national scale (Table B2), two countries may have high footprints but if the supply of one country is more micronutrient dense compared to the other then the nutritionally-invested environmental impacts will reflect this. Changes in country sustainability rankings could have implications for the allocation of international funds and research.

4.2. Food groups can alleviate national nutritional deficiencies in an environmentally-sustainable manner

Dual analyses that combine food product (Figs. 1, Fig. 2, Fig. 3) and food supply (Fig A3, Table 2) findings are important because certain commodities can be prioritized for production to fill nutrient gaps at the country level in an environmentally-friendly manner. For example, a potassium deficient region such as Southern Asia (Fig A4) can begin to import or produce foods high in potassium whose production is also acceptable to that area in terms of environmental impacts. In this case, Fig A1 shows that food groups high in potassium include RT, fruits, and vegetables. However, this region also has a higher water footprint and should avoid foods that require large amounts of water. Table 3 shows that RT, on average, use the least amounts of water on a nutritional basis; thus, this group is a reasonable option. Additionally, parts of sub-Saharan Africa are deficient in vitamin B12 (Fig A3) and food groups high in this nutrient include seafood, DE, and meat (Fig A1). As this region has high eutrophication potentials (Fig A4), it should prioritize a food group like DE, which has a relatively lower footprint with the nutritional FU. These analyses allow actors to account for micronutrient deficiencies and overall nutrient adequacy, when environmental impacts are measured on a nutritional basis; both are important facets of nutrition security.

Future research should target studies in this area; however, we need better data on trade (e.g., re-imports, country of origin), nutritional contents of food items (e.g., antioxidants, protein and carbohydrate quality), and DRIs reflective of bioavailability and interaction factors. Furthermore, the role of food products in supporting a sustainable food supply is highly dependent on the local conditions (e.g., what nutrient deficiencies are present, what environmental boundaries are at risk of being exceeded). More detailed modelling studies should be initiated to truly understand these tradeoffs. Finally, it should be noted that certain areas may also seek to biofortify or fortify (e.g., vitamin D in orange juice) their foods instead of adjusting their supply to include alternative foods. While this is a valid strategy, biofortification is not feasible for all nutrients and much is still unknown regarding the environmental impacts of fortification as there has been limited research in this space. Additionally, in some cases, the health and nutritional benefits of supplements are unclear. In general, some actors will aim to fill nutrient gaps with food items while others will turn to fortification. This decision will depend on the nutrient deficiency in question as well as on purchasing power and consumer willingness.

4.3. Regional differences in production greatly influence sustainability outcomes

This study demonstrates that regional variation is important; while hotspot analyses at the global level are warranted, efforts should focus on more localized interactions of nutrition and the environment. One reason for this is that regional variations stratify results (Figs. 4 and 5); for example, at the global scale, cereals have higher nutritionally-invested water use impacts than LNS. At the regional scale, however, impacts for LNS are higher than cereals in Oceania and NA. Additionally, nutritional contents (Fig. 4) and environmental impact intensities of production vary by region. This is due to a variety of factors including, technology differences, soil profiles, or management practices (Green et al., 2020; Poore and Nemecek, 2018a). Furthermore, from previous studies, we know that local distribution plays a major role in nutrient and food access and that access is highly variable across incomes and locality (i.e., rural versus urban, food desert versus non-food desert). More accessible data on trade and local nutritional profiles will allow for more regionalized analyses. Such research will support the adoption of more targeted interventions (e.g., fortification) that address specific needs of an area.

4.4. Methodological and data choice affect sustainability messages to the public

We illustrated the role of methodological choice (i.e., capped versus uncapped metrics, contingent versus non-contingent metrics, energy standardization, scaling, and nutrient inclusion) and how this can affect results. Regarding the first method choice, the relative sustainability of food groups differs if metrics are calculated on a capped or uncapped basis (Fig. 4). In general, food groups excessively high in specific nutrients (Fig. A1) will receive higher NRF scores on an uncapped basis. As discussed, within the meat group, bovine meat receives the highest uncapped $NRF21.2_{food}$ score because of its vitamin B12 content (Fig A2), but poultry does better on a capped basis because on average (i.e., excluding B12) it is more micronutrient dense. Arguably, this higher score is highly relevant in countries where there are vitamin B12 deficiencies but perhaps less so in areas in which there is adequate vitamin B12 (Fig A4). Moreover, the choice of energy standardization can influence results, and future studies should conduct a more stringent examination of these metrics when applied at the supply level. For n-LCA, we discussed how to include disqualifying nutrients while avoiding misleading environmental impact results. When only considering the dimensions of nutrition and environment, including disqualifying nutrients is needed to avoid attributing more favorable environmental impacts to less nutrient-dense foods (e.g., OFS); however, when including the health dimension, disqualifying nutrients should be excluded from the FU and used in the impact assessment phase (Green et al., 2020). Finally, we saw how the interpretability of metrics including diversity metrics, which are contingent (i.e., they do not have a known or absolute maximum) can be difficult. Chiefly, the 'most sustainable' product can change based on data and methodological choice. This has implications for the communication of research results to policy makers and the public— and this will then determine how these actors choose to optimize agri-food systems.

4.5. Nutrient diversity and nutrient adequacy metrics offer different insights for nutrition security in LCA

We demonstrated that nutrient diversity and nutrient adequacy metrics are uncorrelated and complementary metrics; thus, they can offer different insights for nutrition security. Nutrient indices directly account for nutritional needs (i.e., DRI values) and can be applied at all food levels (i.e., food items, diets, supply, etc.). On the other hand, the applicability of diversity metrics is constrained because they are contingent and only relevant to aggregate food levels like diets and production systems. Joint nutritional and food quantity diversity metrics, like Q, can proxy for potential nutrient deficiencies by accounting for nutrients or antioxidants that are not directly measured. Quantity diversity indices like H are useful in contexts wherein nutritional data is limited (e.g., novel production systems, new crop varieties). However, nutrient diversity metrics are more comprehensive as they reflect differences in nutrient densities of individual food items; therefore, if products A and B have similar nutritional profiles the overall food supply will not receive a higher diversity score.

4.6. Study limitations

The limitations of this study are discussed throughout the manuscript; however, we summarize them as follows. With respect to nutritional data, bioaccesibility, bioavailability, and bioactivity could not be accounted for; moreover, we did not consider nutrients excluded from the regionally-differentiated databases. Additionally, we only had regionally-specific nutritional composition values for certain areas. We also did not account for post-retail processing losses (e.g., cooking), which, while not a strict limitation because our focus is production and not consumption oriented, is a matter to be considered when interpreting results. When comparing the presented results to other studies, the nutrients considered and the nutrient metrics used must be taken into account. For environmental impacts, we only have regional and not country specific values and the environmental impacts embedded in trade could only be considered within the confines of the Food Balance Sheets and the available environmental data. Furthermore, certain impact categories such as biodiversity and ecotoxicity could not be considered due to lack of data.

5. Conclusion

5.1. Relevance of n-LCA for sustainable production systems, foods, diets, and supply

In this paper, we explored outcomes of and methodological theories behind n-LCA for agri-food systems. While our focus was production-oriented, many of our findings are relevant for n-LCA studies of sustainable diets. Summarily, we found that weighting environmental impacts of food products and national food supply by their nutritional value can offer new and perhaps better insights into how actors can optimize food systems. For example, foods or countries may have a relatively low environmental footprint on a mass basis but a much higher one when nutritionally-invested impacts are considered. This question, however, is complicated by methodological issues of contingent versus non-contingent measures, nutrient inclusion, and energy standardization. We further found that within such a context, the role of nutritional deficiencies must be integrated into n-LCA in a more robust manner to fully understand the regionally-dependent nutritional and environmental needs of an area. Relatedly, we found that food products can cover nutritional deficiencies in an environmentally-friendly manner, but that methodological questions of capped versus uncapped nutrients and scaling play integral roles in interpreting results. While there is still much to learn in the space of n-LCA, going forward, to drive change, we need practitioners (e.g., farmers, industry professionals, and policymakers) to adopt n-LCA findings.

5.2. Outlook: enhanced food processing combined with nutrition-sensitive agriculture to operationalize n-LCA

One way to operationalize n-LCA with practical applications is to combine the environmental dimension of food systems with nutrition-sensitive agriculture and enhanced food processing techniques. Nutrition sensitive-agriculture is the consideration of nutrition, and not just yields, in agricultural systems. Examples include optimizing crop rotations for maximal nutrition, concertedly choosing mineral fertilizers that boost nutrient contents, or integrating nutrient-dense traditional crops into the market. Enhanced food processing cases include low thermal intensities that avoid damaging nutrient contents or pre-treating food to maximize the preservation of nutrients before extrusion or other high temperature processes. Neither of these are new concepts but using n-LCA to measure environmental and nutritional impacts across these optimized supply chains could elucidate new insights.

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CRediT authorship contribution statement

Ashley Green: Conceptualization, Methodology, Calculations, Writing – original draft, Visualization. **Thomas Nemecek:** Conceptualization, Supervision, Writing – review & editing. **Sergiy Smetana:** Writing – review & editing. **Alexander Mathys:** Conceptualization, Supervision, Writing – review & editing.

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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