PERSPECTIVE

Levelling foods for priority micronutrient value can provide more meaningful environmental footprint comparisons

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A growing literature in Life Cycle Assessment seeks to better inform consumers, food policymakers, food supply chain actors, and other relevant stakeholders about how individual foods contribute to sustainable diets. One major challenge involves accurately capturing potential trade-offs between nutritional provision and environmental impacts associated with food production. In response, food system sustainability literature has turned increasingly to nutritional Life Cycle Assessment, which assesses the environmental footprints of different foods while accounting for nutritional value. Here we provide examples that show how environmental footprints based on a priority micronutrient-focused functional unit can provide nutritionally meaningful insights about the complexities involved in sustainable food systems. We reinforce the idea that there are limitations in using single-value nutrition-environment scores to inform food guidance, as they do not adequately capture the complex multi-dimensionality and variation involved in healthy and sustainable food systems. In our discussion we highlight the need for future agri-food sustainability assessments to pay attention to regional nutritional and environmental variation within and between commodities, and to better interpret trade-offs involved in food substitutions.

The literature surrounding Life Cycle Assessment (LCA), a deterministic modelling method commonly used to calculate environmental footprints of agri-food systems, has grown substantially in recent decades[1–7]. Meta-analyses of LCAs[5], in addition to well-established national[8] and international[9] life cycle databases, have enabled consumers, food policymakers, and other key stakeholders (e.g., farmers and food manufacturers) to quickly compare various impact categories for different foods; for instance, greenhouse gas (GHG) emissions; land use; water scarcity; emissions of air pollutants (e.g., ammonia, NH_3, an acidifying gas with respiratory health implications); and the release of eutrophication inducing water pollutants such as nitrate (NO_3) and phosphate (PO_4^{3-}). Each of these environmental burdens (which also have implications for human health) differs to varying degrees with the production of globally diverse foods under different management systems and agroclimatic conditions[5]. While existing literature provides insights into the large variability in the environmental footprints of different food items, LCAs typically compare food items on a mass, volume, calorie, or single nutrient basis (usually protein[10]). While such approaches offer the benefit of simple comparisons, they do not appropriately reflect the function of food, which at a fundamental level is to provide nourishment[11]. The effect of different comparative denominators (with system-wide pollutant potentials being the numerator in each indicator of an

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LCA) cannot be underestimated, as results from the exact same food item and supply-chain coverage will be different if they are reported on a mass, calorie, or protein basis[12,13].

LCA has become more sophisticated since food-related functional unit debates started gaining attention in the literature[14], leading to the rapid expansion of the field of nutritional Life Cycle Assessment (nLCA). Yet, such sophistications, including the adoption of nutrient profiling systems as functional units (e.g., the Nutrient Rich Food index as utilised in Castañé & Antón[15] and adjusted for use in Finland[16] and the UK[17]) do not sufficiently capture important nutritional complexities of foods, particularly when comparing foods with different dietary functions (e.g., a source of protein vs. a source of fats, each of which provides a separate nutritional function), resulting in potentially misleading comparisons[18]. A growing interest in nLCA has thus identified the need for agri-food sustainability assessments to better account for nutrient quantity, nutrient quality, and/or nutrient diversity, usually by incorporating nutritional information within the functional unit[19]. For example, in cases where protein-rich foods are being compared, scholars have suggested that functional units ought to level for protein quality[20,21] or nutrient richness, rather than just using protein quantity[22]. While the growing nLCA literature has moved LCA methodology in the right direction in the context of food sustainability analyses, further work is required to provide more nutritionally relevant food impact comparisons catering to specific nutritional and agroecological contexts.

In this perspective, we briefly review the current state of the literature and use a recently developed nutrient scoring system[23] as an exemplar functional unit to illustrate how the environmental footprints of a given food vary when considering priority micronutrient value (PMV) compared to a fixed quantity of kilograms, calories, or protein. The PMV scoring system produces unique quantities for each food that provide, on average, one-third of recommended intakes across six micronutrients commonly lacking globally: iron, zinc, folate, calcium, vitamin A, and vitamin B_{12}. Levelling foods for PMV enables a more nuanced and dynamic interpretation of the food-environment trade-offs involved in food substitution (e.g., replacing animal-source foods, ASFs, with plant-source foods, PSFs). Moreover, the adoption of PMV as a functional unit supports more geographically representative impact assessments of the environmental footprints of foods in nutritional contexts where priority micronutrients are particularly lacking. This is a timely shift of attention towards the consideration of foods' multi-dimensionality regarding holistic sustainability through the inclusion of trade-off assessments inherent to food substitution, a complexity flagged as requiring urgent attention in nLCA according to the Food and Agriculture Organization of the United Nations[18]. Our concluding discussion highlights the need for future related studies to find ways to more comprehensively consider nutritional factors by (i) meaningfully contextualizing regional nutritional and environmental variation within *and* between food items; and (ii) better reflecting the complex food-environment trade-offs involved in food substitution [e.g., displaced production of ASFs to meet changing market demands and associated (in)direct burdens][24].

A nutrition equivalence gap in the environmental footprints of food literature. A widely utilised source of information in the LCA literature for quick overviews of food supply chains' environmental footprints is Poore and Nemecek's meta-data study, which evaluates the global environmental impacts of a wide range of common foods[5]. The study's two key findings reinforce common results within standard agri-food LCAs: First, there is considerable variability in environmental footprints across the range of producers of the same food item[25]; and second, ASFs tend to have higher environmental footprints than PSFs when using conventional functional units such as protein and energy, though there are some notable exceptions identified in the study: (1) dark chocolate production emits comparable GHGs and eutrophying emissions to ASFs; (2) nuts, rice, and olive oil are comparable to ASFs in terms of water use; and (3) dark chocolate, olive oil, pulses (such as beans and lentils), and nuts have similar land use profiles to pork and poultry[5]. These common results in the LCA literature have played an influential role in justifying sustainable food policy interventions centred on production intensification and dietary change. Specifically, sustainability-informed policy analysts have sought to reduce the total environmental impact of the food system by advocating for more efficient, high-yield production methods of foods on one hand, while pursuing societal-scale dietary transition towards plant-rich diets on the other[26–28]. Additionally, environmental footprint comparisons have been widely publicized and used to recommend abstention or restriction of ruminant sourced foods (such as beef and dairy) amongst environmentally-conscious consumers seeking to reduce their personal impact[29,30].

There is strong evidence supporting the claim that a macro-level shift from meat-heavy diets (in countries where consumption is high) to plant-rich diets would support climate change mitigation and biodiversity conservation by minimizing the total environmental footprint of the agri-food sector[31,32], and by freeing up land which could be ecologically restored[33]. At the micro-level, however, some have provided criticisms of using global meta-data values as a rationale for sustainable dietary advice for individual consumers without taking into account local nutritional and agro-ecological contexts[34,35]. For example, there is a risk that global-, regional-, and national-level point estimates of environmental impacts may not accurately capture the true sustainability of a food item at the local scale within a country[13], or at a farm, or even intra-farm-level, as impacts can vary from field-to-field[36] and, in the case of ASFs, on an animal-to-animal basis[37,38].

We thus caution that basing sustainable agri-food policy on global mean footprint values could lead to disincentivizing the sustainable production of foods which have a large *average* environmental footprint globally, but a rather small footprint if produced under specific conditions and production methods in certain geographical contexts (for instance, the production of beef using best practices in silvopasture[39,40] or Adaptive Multi-Paddock grazing techniques in contexts where it has proven to support carbon sequestration[41–44]). Some forms of ruminant production also hold potential to offset GHG emissions through optimized land use, for instance through the inclusion of white clover in a pasture which reduces the need for synthetic nitrogen, and associated emissions[38]. In addition, there is concern that the proposition of meat and dairy abstention or restriction may contradict geographically-contingent food cultures and may exacerbate already widespread nutritional deficiencies in some populations, especially in low- and middle-income countries (where consumption of ASFs is much lower than in high-income countries), or among vulnerable groups[45]. Finally, since many governments across the globe are striving to achieve net-zero economies, there is concern about a potential climate penalty paid by ASFs when short-lived biogenic GHGs associated with their production (methane, or CH_4, namely) are counted in carbon dioxide equivalents (CO_2-eq), as this could misrepresent the actual warming impact associated with CH_4 emissions in cases where the latter have stabilized or declined[46,47]. Indeed, although beyond the scope of the current study, the case of methane's short atmospheric lifetime (~15 years compared to ~114 years for nitrous oxide, or N_2O, an extremely potent GHG almost ten times more damaging than CH_4 in terms of

global warming potential over 100 years; GWP_{100}) is of critical importance to the climate change impact assessment of LCA studies, and many groups, not least the Intergovernmental Panel on Climate Change[48], are working proactively on better-quantifying and simplifying the physicochemical complexities of short- and long-lived climate pollutants[49,50], including in the context of future nLCA.

Our main concern here, however, pertains to the underlying nutritional inequivalences seen in traditional functional units used in many contemporary LCA studies. As briefly mentioned above, most existing agri-food LCAs use a mass or volume functional unit (for example, comparing the environmental footprint associated with the production of 1 kg or 1 L of food or beverage products). Similarly, functional units are sometimes based on energy (e.g., impacts per 1000 kcal) or fixed quantities of protein (e.g., impacts per 100 g of protein). However, functional units deployed as mass, energy, or protein do not necessarily provide nutritionally relevant food comparisons[10]. As shown in Fig. 1, there is considerable variation in functional units based on mass, energy, or protein content and those derived from a scoring system that rates foods according to their density in priority micronutrients; that is, their priority micronutrient value. As an example, to obtain the same PMV as found in about 440 grams of peas, much fewer grams of more micronutrient-dense foods

would be required—such as animal liver (7 grams), beef (113 grams), or eggs (177 grams) (see Fig. 1)[23]. This presents a challenge for sustainable agri-food policy at both the population and individual levels, as the promotion of food substitution for the sake of environmental sustainability may come at the expense of greater nutritional risk, particularly for more vulnerable populations[51]. This is important for micronutrient deficiencies such as iron, zinc, and folate deficiency, which are surprisingly common worldwide, but especially in low- and middle-income countries and among women of reproductive age and other groups with increased nutrient requirements (e.g., infants and young children, pregnant and lactating women)[51].

Developing a functional unit based on priority micronutrient value. To illustrate how environmental footprint comparisons are made more meaningful when functional units are adjusted for nutritional value, we compare various ASFs' and PSFs' land use occupation ($m^2 \times$ year), carbon footprints (kg CO_2-eq), water scarcity (litres), acidification footprints (grams of sulphur dioxide equivalents; SO_2-eq), and eutrophication footprints (grams of phosphate equivalents; PO_4^{3-}-eq), each obtained using three different functional units (i.e., mass, energy, and a functional unit developed using the PMV scoring system)[23]. PMV was chosen as an example to illustrate the importance of considering the contribution of nutrient-dense foods to global diet quality, and their essential role in reducing the global prevalence of micronutrient deficiencies, anemia, and child growth/underdevelopment. This enables environmental impacts (i.e., numerators) to be calculated not according to a fixed quantity of food, but rather a variable mass that generates more nutritionally-relevant comparisons across various foods with a central focus on reducing micronutrient deficiencies and undernutrition.

PMV was designed to accommodate limited food composition data that is representative of different regions globally. Thus, its primary limitation is that it does not account for other dietary factors related to the nutritional value of foods: other essential micronutrients (beyond the six selected ones), essential amino acids, essential fatty acids, nutrient ratios, fiber, food processing, etc. Nevertheless, developing a functional unit based on PMV is useful in enabling a more meaningful comparison of the relative environmental footprints of different foods in contexts where deficiencies in those nutrients represent a notable public health burden. Other nutritional indices could be feasibly developed to help inform nLCAs in other nutritional contexts (such as for nutrient requirements of individuals in high-income countries). There is also a need for more comprehensive nutritional functional units that better capture the overall nutritional value of foods when considering positive (health-promoting) and negative (potentially harmful) attributes that can be used for future global nLCAs.

Figures 2 and 3 show the land use and carbon footprints, respectively, of 35 commonly consumed foods per target PMV (an average of one-third of recommended intakes of vitamin A, folate, vitamin B_{12}, calcium, iron, and zinc for adults ≥25 years) when paired with LCA data from Poore and Nemecek for environmental footprints based on mass and energy. Figure 2 uses color coding to highlight a selection of eight foods as they shift rankings when moving from one functional unit to the next. Figure 3 uses error bars to denote the 5th and 95th percentile carbon footprints, which we use as a proxy for 'best'- and 'worst'-in-class for each food item, respectively. Figure 4 tracks the relative rankings of the 35 food items for five different life cycle impact categories: land use, GWP_{100}, water use, acidification potential, and eutrophication potential. As typical in the comparative LCA literature, Figs. 2, 3, and 4 reaffirm the point that
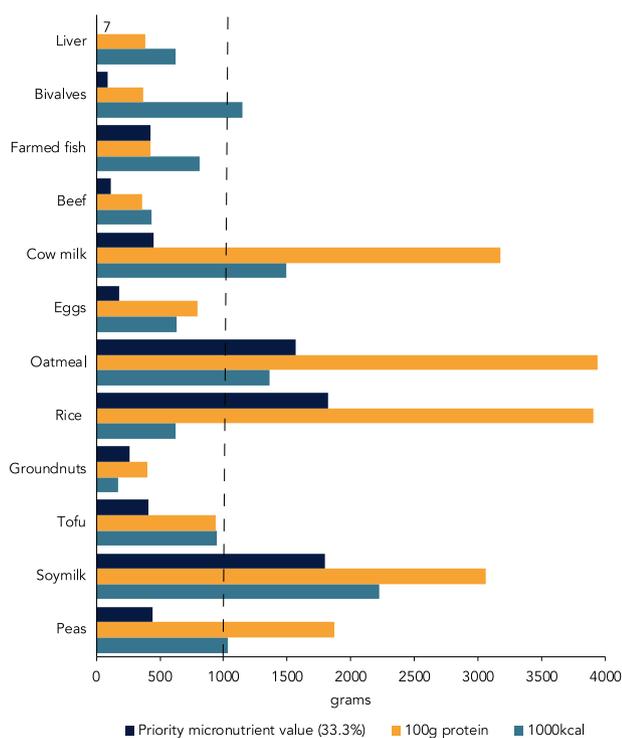

Fig. 1 Portion sizes of a sample of foods levelled for energy, protein, and priority micronutrient value. The portion sizes of a sample of foods levelled for energy (1000 kcal), protein (100 grams of protein), and a target priority micronutrient value (average of one-third of recommended intakes of vitamin A, folate, vitamin B_{12}, calcium, iron, and zinc for adults ≥25 years, with each micronutrient's contribution capped at 100% of recommended intakes). The dotted line represents portion sizes levelled for mass or volume (1000 g equivalent). The liver category represents an average of beef, goat, lamb, chicken, and pork liver. The bivalve category represents an average of a variety of species, including mussels, oysters, and clams. The farmed fish category represents an average of a variety of species, including trout, rainbow trout, salmon, carp, tilapia, sea bass, tambaqui, pangasius, kissing gourami, giant gourami, silver barb, common carp, silver carp, and striped catfish. See Supplementary Information for further details.
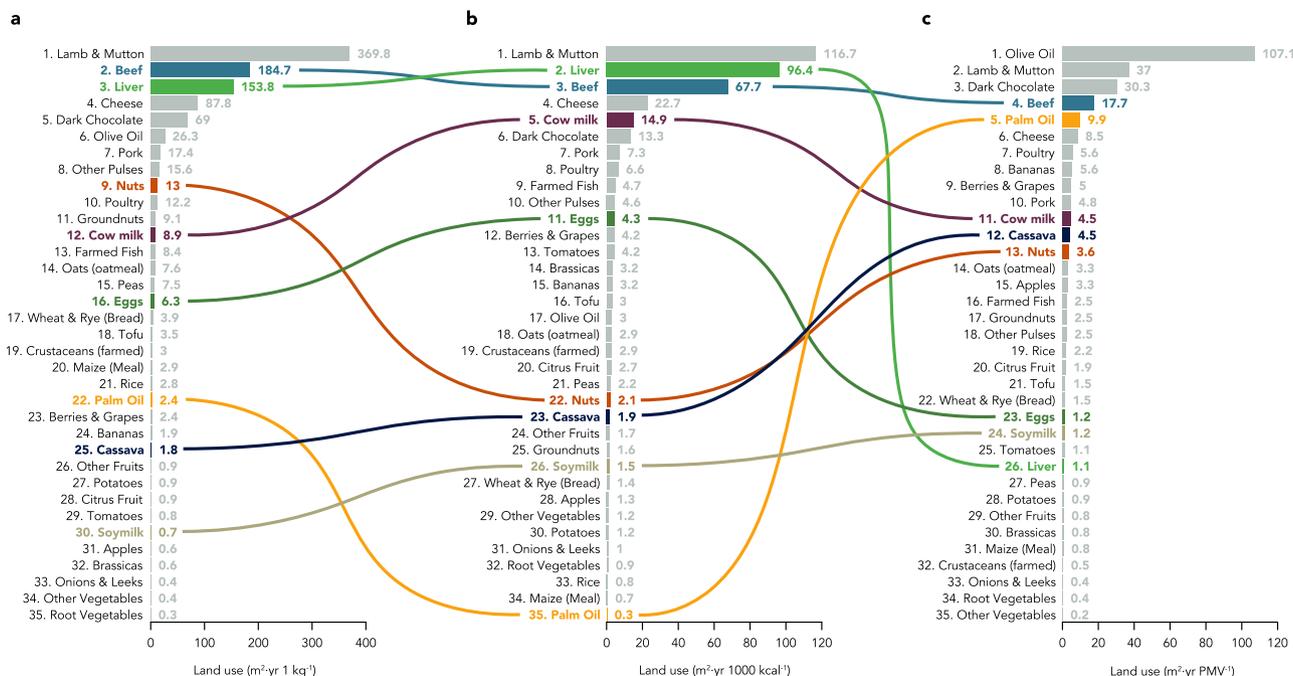
Fig. 2 Foods ranked by land use, levelled for weight, energy, and priority micronutrient value. Mean land use (reported as m^2*year) of food portions required (**a**) per kg or l, (**b**) per 1000 kcal, and (**c**) per target priority micronutrient value (an average of one-third of recommended intakes of vitamin A, folate, vitamin B$_{12}$, calcium, iron, and zinc for adults ≥25 years, with each micronutrient's contribution capped at 100% of recommended intakes), ranked from highest impact to lowest in each panel, showing how foods shift in ranking depending on the functional unit. In all panels beef represents an average of beef from dairy herds and beef from beef herds. Farmed crustaceans represents an average of a variety of prawn and shrimp species. Liver represents an average of lamb and mutton, poultry meat, pig meat, and the average of bovine meat (from dairy and beef herds). Farmed fish represents an average of a variety of species, including trout, rainbow trout, salmon, carp, tilapia, sea bass, tambaqui, pangasius, kissing gourami, giant gourami, silver barb, common carp, silver carp, and striped catfish. Color-coded arrows are used to allow easier tracking of shifting rankings for a sample of eight foods: Beef (blue); liver (light green); nuts (orange); cow milk (maroon); eggs (dark green); palm oil (yellow); cassava (dark blue); and soymilk (light beige). All source data for GHG emissions, land use, freshwater use, acidification potential and eutrophication potential are from Poore & Nemecek's Data Table 2[5]. See Supplementary Information and Supplementary Data 3 for further details.

environmental footprints vary significantly, with considerable ranges between the least and most impactful variants within each food type, and across different ecological indicators. Further, as in most LCA studies, PSFs tend to have lower footprints than ASFs[52]. Nevertheless, some noteworthy differences emerge when food quantities are established based on PMV. When examining land use, for example, liver (which is highly micronutrient dense), goes from being the third and second highest land user per unit mass and energy, respectively, to being among the top 10 lowest land users per target PMV. Cassava moves from being the 11th lowest land use food per unit mass to the 12th highest per target PMV, while palm oil goes from having the lowest land use per unit energy to the fifth highest land use per target PMV. We observe foods move 'up' or 'down' the rankings depending on the underlying functional unit, with more micronutrient dense foods trending down in their rankings as the functional unit becomes contextualized by the priority micronutrient value of the food in question.

When assessing environmental footprints based on PMV some ASFs become more comparable to their common plant-based protein alternatives. For example, eggs have a carbon footprint 48% higher than tofu per unit mass, and 19% higher per unit energy, but when assessed based on PMV, eggs have a carbon footprint 31% lower than tofu. Additionally, the divergence between common protein food substitutes is reduced when carbon footprints are assessed using the target PMV. For example, the global mean carbon footprint of cheese is about eight times larger than that of tofu per kg of retail weight, but only about 1.8 times larger once recalculated per target PMV.

Similarly, the global mean carbon footprint for beef (averaged across dairy herds and beef-specific herds) is 21 times larger than tofu when based on mass yields; whereas, when computed per target PMV, the carbon footprint for beef is just five times larger. Finally, when calculated per target PMV, the carbon footprint for liver is comparable to some of the foods with the lowest carbon footprints (tree nuts and peas). In contrast, when calculated per target PMV, some PSFs—namely, palm oil, olive oil, and dark chocolate—have some of the largest carbon footprints, performing worse than beef (the ASF with the highest carbon footprint). Of course, many healthy foods, like olive oil, are recommended not for their density in priority micronutrients but for other health benefits[53]. Overall, it can be concluded that, in terms of PMV, the carbon footprints of ASFs—while still typically higher than most PSFs—are closer to their plant-source counterparts than what is typically observed in protein-based footprint comparisons.

Other critical observations from our results pertain to the wide ranges seen between best- and worst-in-class performers for each food type (as seen in Fig. 3). Dark chocolate is remarkable in this regard, having both the smallest carbon footprint amongst the best-in-class performers when calculated according to PMV (at −1.74 kg CO$_2$-eq), and the highest carbon footprint amongst the worst-in-class performers (at 113 kg CO$_2$-eq). While similar ranges are seen when comparing foods on a retail weight or energy basis, again at the point of sale, the implications for food substitution are more pronounced when considering the target satisfying PMV. For example, while beef has the highest mean carbon footprint amongst ASFs in this selection per PMV
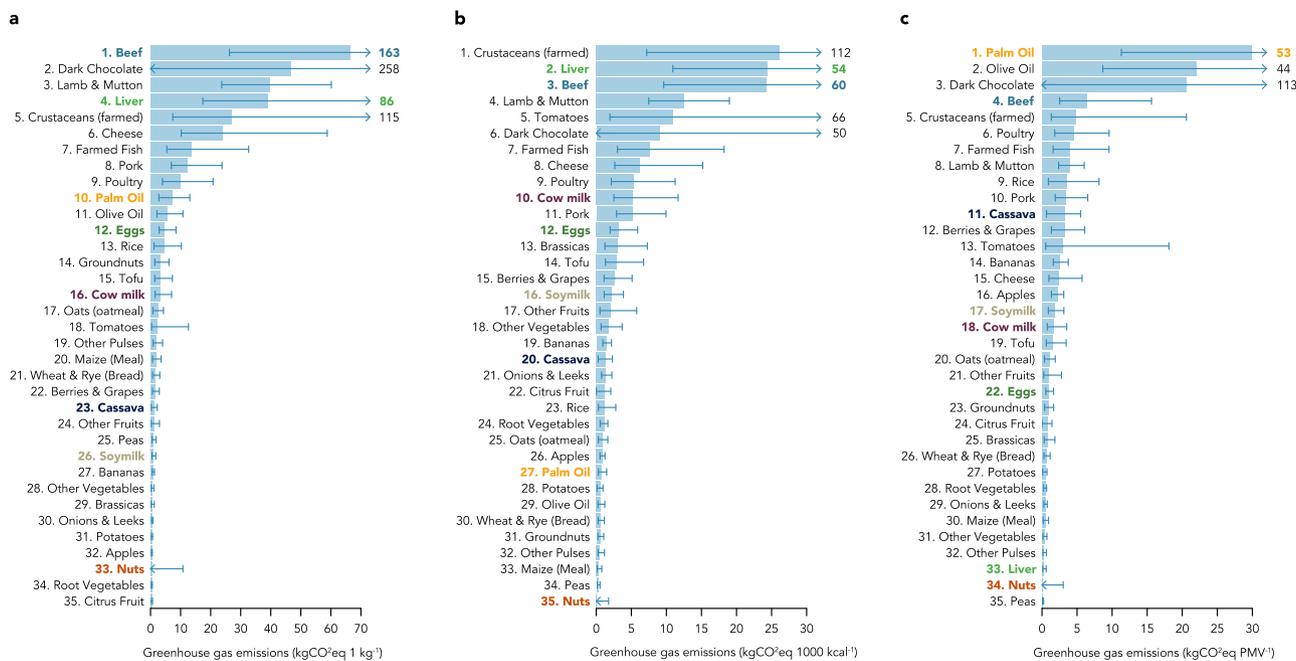
Fig. 3 Foods ranked by carbon footprint, levelled for weight, energy, and priority micronutrient value. The global mean carbon footprints (reported in kg CO_2-eq) of food portions required (**a**) per kg or l, (**b**) per 1,000 kcal, and (**c**) per target Priority Micronutrient Value (an average of one-third of recommended intakes of vitamin A, folate, vitamin B_{12}, calcium, iron, and zinc for adults ≥25 years, with each micronutrient's contribution capped at 100% of recommended intakes). Footprints are ranked from highest to lowest in each panel, showing how foods shift in ranking depending on the functional unit. Error bars indicate the 5th and 95th percentiles, which serve as a proxy for best-in-class and worst-in-class carbon footprints, respectively, for each food type. Arrows are used to indicate where values extend beyond the axis minimums or maximums in each panel. In cases where values extend beyond the axis, data labels are provided. An arrow denoting negative values implies a negative carbon footprint. Color-coding is used to allow easier tracking of shifting rankings for a sample of eight foods: Beef (blue); liver (light green); palm oil (yellow); eggs (dark green); cow milk (maroon); cassava (dark blue); soymilk (light beige); and nuts (orange).

(at 6.36 kg CO_2-eq), its best-in-class variant (at 2.51 kg CO_2-eq) would outperform the average selection of most other ASFs, including farmed crustaceans (4.81 kg CO_2-eq), poultry (4.54 kg CO_2-eq), farmed fish (3.99 kg CO_2-eq), lamb and mutton (3.98 kg CO_2-eq), pork (3.37 kg CO_2-eq), and a number of PSFs, including rice (3.52 kg CO_2-eq), cassava (3.25 kg CO_2-eq), and tomatoes (3 kg CO_2-eq). This highlights the need for caution when basing food sustainability decisions on a comparison of globally averaged LCA results.

Accounting for complexity in sustainable food guidance. The food-environment interface is replete with trade-offs and synergies (both within *and* across the three broad pillars of sustainability: economics, environment, and society), which makes it difficult to universalize food guidance for nutrition, health, and wider societal factors. Figure 4 shows how trade-offs can be found across different environmental indicators for the same food. For instance, nuts rank consistently as one of the least GHG-intensive foods regardless of which functional unit is used[54], but rank much less favorably when it comes to their water footprint (third highest per target PMV, at 1161.6 L)—about six times worse than beef (at 199.5 L). Moreover, trade-offs can be found across different environmental indicators for different production methods of the same food, as illustrated in Fig. 3 by the error bars. For instance, regenerative methods of primary production tend to reduce carbon footprints of ASFs relative to conventional production, but occupy considerably more land[41]. No-till crop production, on the other hand, tends to generate soil health benefits, but may not necessarily support pollution mitigation when compared to conventional tillage and, further, no-till systems often rely on intensive herbicide usage which has considerable implications for human (and environmental) toxicity[55,56]. These

complexities in agri-food value chains (e.g., the heterogeneity of global farming practices) hold important implications for sustainable agri-food policy and dietary guidance for consumers, particularly when it comes to the trade-offs involved in food substitution. Indeed, as demonstrated previously, one food commodity may have a high GWP_{100} and a low eutrophication potential, whilst another may have the reverse, meaning a researcher needs to determine which is more problematic for the geographical boundary under investigation to provide regionally meaningful recommendations on which pollution potential, and primary sources thereof, require more urgent mitigation (e.g., reducing enteric CH_4 may be the top priority in the case of ruminants, while NH_3 may require more attention in the context of pig systems).

The implications are especially acute for guidance around the consumption of ASFs: on the one hand, there is strong evidence that moderating meat intake and encouraging minimally processed plant-rich diets globally would support climate change mitigation[31,57], and could result in positive health outcomes at the population level[1,32]. On the other hand, nutrient-dense ASFs are an important source of high-quality protein, long-chain omega-3 fatty acids, unique beneficial bioactive compounds, and bioavailable micronutrients commonly lacking in diets globally, such as iron, zinc, vitamin B_{12}, and calcium[20,58]. Thus, ASFs make an important contribution to improving diet quality and achieving nutrient adequacy worldwide, particularly in low- and middle-income countries[58]. Despite providing an important opportunity to enhance equitable nutrition for all people, intake of ASFs is still too low in many low- and middle-income countries, particularly in sub-Saharan Africa and South Asia, as well as among groups with increased nutrient requirements globally, such as pregnant and lactating women, young children, adolescents, and women

Rank	Land Use footprint (m²*yr to obtain PMV)	GHG footprint (kg CO2eq to obtain PMV)	Freshwater footprint (L to obtain PMV)	Acidification footprint (g SO₂eq to obtain PMV)	Eutrophication footprint (g PO₄³⁻eq to obtain PMV)
Highest Footprint 1	Olive Oil	Palm Oil	Olive Oil	Olive Oil	Olive Oil
2	Lamb & Mutton	Olive Oil	Rice	Palm Oil	Farmed Fish
3	Dark Chocolate	Dark Chocolate	Nuts	Poultry	Palm Oil
4	Beef	Beef	Farmed Fish	Pork	Crustaceans (farmed)
5	Palm Oil	Crustaceans (farmed)	Apples	Beef	Dark Chocolate
6	Cheese	Poultry	Berries & Grapes	Berries & Grapes	Beef
7	Poultry	Farmed Fish	Crustaceans (farmed)	Tomatoes	Rice
8	Bananas	Lamb & Mutton	Cheese	Crustaceans (farmed)	Poultry
9	Berries & Grapes	Rice	Tomatoes	Rice	Pork
10	Pork	Pork	Groundnuts	Dark Chocolate	Berries & Grapes
11	Cow milk	Cassava	Pork	Farmed Fish	Tomatoes
12	Cassava	Berries & Grapes	Bananas	Bananas	Lamb & Mutton
13	Nuts	Tomatoes	Cow milk	Apples	Cheese
14	Oats (oatmeal)	Bananas	Poultry	Cheese	Bananas
15	Apples	Cheese	Wheat & Rye (Bread)	Lamb & Mutton	Apples
16	Farmed Fish	Apples	Dark Chocolate	Nuts	Brassicas
17	Groundnuts	Soymilk	Oats (oatmeal)	Brassicas	Nuts
18	Other Pulses	Cow milk	Beef	Eggs	Cow milk
19	Rice	Tofu	Lamb & Mutton	Cow milk	Oats (oatmeal)
20	Citrus Fruit	Oats (oatmeal)	Citrus Fruit	Citrus Fruit	Citrus Fruit
21	Tofu	Other Fruits	Brassicas	Cassava	Eggs
22	Wheat & Rye (Bread)	Eggs	Other Fruits	Groundnuts	Groundnuts
23	Eggs	Groundnuts	Eggs	Other Fruits	Potatoes
24	Soymilk	Citrus Fruit	Other Pulses	Wheat & Rye (Bread)	Onions & Leeks
25	Tomatoes	Brassicas	Other Vegetables	Oats (oatmeal)	Wheat & Rye (Bread)
26	Liver	Wheat & Rye (Bread)	Tofu	Soymilk	Other Pulses
27	Peas	Potatoes	Potatoes	Other Vegetables	Tofu
28	Potatoes	Root Vegetables	Maize (Meal)	Potatoes	Other Fruits
29	Other Fruits	Onions & Leeks	Soymilk	Other Pulses	Soymilk
30	Brassicas	Maize (Meal)	Peas	Onions & Leeks	Root Vegetables
31	Maize (Meal)	Other Vegetables	Root Vegetables	Root Vegetables	Cassava
32	Crustaceans (farmed)	Other Pulses	Palm Oil	Maize (Meal)	Other Vegetables
33	Onions & Leeks	Liver	Onions & Leeks	Tofu	Liver
34	Root Vegetables	Nuts	Liver	Liver	Maize (Meal)
Lowest Footprint 35	Other Vegetables	Peas	Cassava	Peas	Peas

Fig. 4 Foods ranked by land use, carbon footprint, freshwater withdrawals, acidification potential, and eutrophication potential, when levelled for priority micronutrient value. The relative rankings of the mean environmental footprints of a selection of 35 common foods across five impact categories (land use, GHG emissions, freshwater withdrawals, acidification potential, and eutrophication potential; measured in m²-yr, CO_2eq, l, SO_2eq, and PO_4^{3-}, respectively), when calculated according to a target Priority Micronutrient Value (an average of one-third of recommended intakes of vitamin A, folate, vitamin B_{12}, calcium, iron, and zinc for adults ≥25 years, with each micronutrient's contribution capped at 100% of recommended intakes). A sample of eight foods are color-coded to allow easier tracking of shifting rankings: Beef (blue); palm oil (yellow); cow milk (maroon); cassava (dark blue); nuts (orange); eggs (dark green); soymilk (light beige); and liver (light green). All source data for GHG emissions, land use, freshwater use, acidification potential and eutrophication potential are from Poore & Nemecek's Data Table 2[5]. See Supplementary Information and Supplementary Data 3 for further details.

of reproductive age, amongst which the public health burden of micronutrient deficiencies is highest[26,51,59]. Moreover, given that meat, fish, egg, and dairy consumption and animal husbandry are important culturally and economically[60,61], and that appropriate forms of animal agriculture can support food security[58,62], provide ecosystem benefits[63,64], and help to reduce food waste[65], there is much to gain from better interpreting how the nutritional value of ASFs affects their relative environmental footprints in different contexts.

The examples above help to illustrate how accounting for the PMV of foods offers a more nutritionally meaningful (though not comprehensive) way to compare the environmental impacts of food production, particularly in nutritional contexts where deficiencies of these nutrients represents a notable public health burden, with implications for sustainable and healthy dietary policy, programs, and consumer choices. As observed above, this is especially the case when comparing ASFs with common plant-based alternatives. It is important to acknowledge that comparisons based on mass can help describe the generalized climate costs associated with food production as they represent real-world yields from various systems; nevertheless, they are limited in their ability to capture important nutritional trade-offs which could result from exchanging higher polluting foods with lower ones. That said, any attempt to capture foods' nutritional and environmental impacts by using a single-value score will be limited by its inevitable simplification of the food system's multi-dimensionality. Recent efforts to estimate the combined health and environmental impacts of different foods[2,28,66] have led to findings which arguably require heavy contextualization before being used to inform policy and dietary guidance. An ideal case exemplar of this risk of miscommunication is that certain foods which typically have low environmental footprints per calorie—such as sugar-sweetened beverages or highly-processed snacks—should never be promoted as appropriate food substitutes for nutrient-rich foods merely because of their relatively smaller environmental impacts. Moreover, overconsumption, weight gain, and related noncommunicable diseases are increasing concerns worldwide, and foods rich in priority micronutrients are important for achieving nutrient adequacy without excess calories.

The future of agri-food environmental footprints. While an improvement from existing approaches, the example we use above for illustrative purposes—PMV—is still insufficient as a comprehensive nutritional metric for comparing food environmental footprints more broadly. As the field of nLCA evolves, there is a need for novel, sophisticated nutrient indices to enable more holistic, nutritionally relevant assessments of the environmental impacts of foods, towards improving our understanding of the nutrition-sustainability nexus in specific geographical, cultural, and dietary contexts. While considering each food's combined density in iron, zinc, calcium, folate, vitamin A, and vitamin B_{12} is important to address micronutrient malnutrition, it is important to note that PMV is just one aggregate indicator of nutritional value. Essential amino acids, essential fatty acids, other essential micronutrients, and non-essential but nevertheless beneficial compounds like fiber, phytonutrients, and bioactive compounds—as well as nutrient ratios and the type of processing of foods—also contribute to nutritional quality and play an important role in health and disease[67]. Therefore, future efforts in nLCA should continue to explore new means of accounting for the holistic nutritional value of foods within comparative assessments, and pursue the development of multi-dimensional food-nutrition portraits relevant to specific dietary and agroecological contexts.

The primary objective of future applied sustainability assessments of food commodities (whether at the product-level, meal-level, or diet-level) should be to help improve our understanding of the nutrition-environment nexus by basing LCAs upon more nutritionally relevant functional units. This may mean moving away from comprehensive single-score or two-dimensional rankings of foods' environmental footprints. Along these lines, it is important for nLCA researchers to better communicate the limitations and uncertainties of single-metric environmental impact scores in terms of capturing variation within food categories based on production characteristics, regional geographical variation, cultural and economic interests, and other observed trade-offs between various socio-ecological objectives inherent to food systems. Indeed, single-score or two-dimensional food rankings—including the example of PMV above, despite its clear advantages over single-nutrient functional units—potentially obscure complexity in global and local food systems as much as they illuminate the potential health and environmental benefits of food substitutions.

In addition, more robust environmental considerations also need to be included in nLCAs; for example, carbon stock changes through biomass sequestration and indirect land use change through displaced food production all need to be examined more thoroughly in relevantly extant literature to aid future directions of exploration and subsequent application. To this end, nLCA research groups need to not only have a solid understanding of nutritional sciences, but also be aware of the limitations of using 'off-the-shelf' environmental footprints (e.g., sourced from commercial or indeed open access databases and datasets). Using ready-made environmental footprints is often inevitable in nLCA due to existing data gaps, but is nonetheless a major roadblock in creating locally or regionally relevant guidance related to optimising land use. Put simply, environmental footprints require as much progression and transparency as does the development of novel, informative nutritional metrics.

In summary, if sustainable agri-food policy and consumer food choices are to be informed by global footprint comparisons of different foods, it is essential to base such comparisons on more nuanced, comprehensive, and nutritionally relevant functional units when using LCA to answer such research questions. Future work on nLCA could support better understanding of the environment-nutrition interface by building context-specific databases which enable consumers, agri-food policymakers, and other stakeholders to derive more accurate information about the specific foods available to them in their respective 'foodsheds', based on local production conditions and food portions containing similar nutritional value.

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R.K.R. conceptualized the paper and prepared the preliminary environmental footprint assessments. F.O. built the global food composition database. G.M. independently cross-checked all (n)LCA related processes according to internal review best practice (i.e., ISO/TS 14071). T.B. conducted the priority micronutrient value assessment. All authors supported the writing and editing process.

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