The International Journal of Life Cycle Assessment
https://doi.org/10.1007/s11367-025-02465-4

LCIA OF IMPACTS ON HUMAN HEALTH AND ECOSYSTEMS

Combining nutritional value with environmental impact: a novel approach to nutritional life cycle assessment

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Received: 31 October 2024 / Accepted: 31 March 2025

Abstract

Purpose In nutritional life cycle assessment (nLCA), nutrient provision is the key function of foods. This warrants replacing the traditional mass-based functional unit (FU) in LCA by a nutrient-based FU. However, such replacement causes several methodological issues and there is at present no uniform approach for integrating nutritional value into the FU of LCA. We therefore propose a novel approach where the mass-based FU is adjusted for nutritional value using a dimensionless Qualifying Index (QI).

Methods To demonstrate our approach, we calculated the nLCA for 164 food items from the environmental impact database of foods made by The Dutch National Institute for Public Health and the Environment. We used global warming potential (GWP, in kg CO_2 eq/kg) as indicator of environmental impact. As a measure of nutritional value, we used the QI, a dimensionless, numerical value expressing the relation between nutrient density and energy density of a food. To calculate the QI, we selected 21 qualifying nutrients, based on their contribution to the overall Dutch dietary intake. All QIs were calculated with and without capping to assess the influence of (excessively) high nutrient levels, and weighting was applied to calculate food-group-specific QIs.

Results and discussion For the majority of the 164 food items considered, the calculated QI was above 1, with higher values of QI representing higher nutrient density. The highest QI values were observed for vegetables and fish, whereas the lowest QI values were observed for fats, oils, and grain products. GWP values were highest for protein foods and lowest for fruits, vegetables, and grain products. For most foods, GWP decreased after nutritional adjustment, as their QI values were > 1. Food-group-specific weighting led to more distinctive GWP values. Additional analysis showed that the QI-nLCA methodology can be applied not only to compare individual food items, but also meals and diets.

Conclusions This study introduces a novel approach to nLCA, in which the original mass-based FU is corrected for by the QI, a numerical value expressing the relation between nutrient density and energy density of a food. This QI-nLCA enables a more comprehensive evaluation of foods, meals, and diets. It can be applied to different environmental indicators and, as such, could add to evidence-based decision-making by policy makers in the field of healthy and sustainable nutrition.

Keywords Sustainable nutrition · Nutritional life cycle assessment · Functional unit · Qualifying index · Method development

Communicated by Matthias Finkbeiner

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1 Introduction

Life cycle assessment (LCA) is a methodology for assessing the environmental impact of a product, process, or service (ISO 2006a, 2006b). LCA methods have been developed for various products, including food products. Traditionally, LCAs for food products have used mass-based functional units to assess the impact of a food product on, e.g., global warming potential (GWP), land use, or water use (Saarinen et al. 2017). As such, it provides insight in the process of making food production environmentally more efficient, but the goal of food production is ultimately food consumption, and thus the provision of essential nutrients for human health. While an LCA approach with a mass-based functional unit can also be used for establishing the impact of food consumption, such an approach comes with a notable trade-off. The EAT Lancet study, for example, modeled the optimal dietary intake in terms of planetary boundaries for food production (Willett et al. 2019). However, it was later shown that the modeled diet lacks adequate amounts of vitamin B12, calcium, iron, and zinc, and thus does not provide all essential nutrients required for human health (Beal et al. 2023).

In 2021, the Food and Agricultural Organization (FAO) issued a report recognizing the need for combining nutritional value with environmental impact in LCAs for food items, in the form of so-called nutritional LCAs (nLCAs) (McLaren et al. 2021). In nLCAs, the provision of nutrients is considered the main function of a food item and the nutritional value, not mass or volume of the food, is considered a functional unit. Indeed, over the past decade, an increasing number of studies have examined the environmental impact of foods in relation to their nutritional value, often expressed as a nutrient density score or index (McAuliffe et al. 2020; Green et al. 2021; McLaren et al. 2021). The choice of method used to calculate this nutrient density score, however, significantly affects the results of such assessments, and there is thus far no agreed, uniform approach for integrating the nutritional value of food products as a functional unit in the LCA methodology. Approaches that have emerged include both across-the-board and food-group-specific nutrition-based functional units using a diversity of nutrient metrics, resulting in different outcomes depending on the context (McLaren et al. 2021; Green et al. 2023). In addition, the use of a nutrient-based FU per se appears to result in nLCA outcomes that are difficult to comprehend. Nutritional quality metrics, unlike mass-based measurements, are generally not intuitively understandable and do not allow for easy comparison between food products, as the quantity required to fulfill one unit of the functional unit can vary greatly between products (Saarinen et al. 2017; McLaren et al. 2021).

When the identification of trade-offs between environmental impact and the nutritional value is dependent on methodological issues, and as a result may differ between foods, meals, or complete dietary patterns, this complicates evidence-based decision-making. To help policy makers, but also consumers to make decisions on sustainable food consumption, a methodology is required that is both consistent and comprehensible across different contexts. We therefore propose a method that is not only applicable to foods, meals, and diets, but also has a comprehensible link to the original mass-based FU of LCA, by using a (dimensionless) nutritional correction factor rather than a nutrient-based FU. More precisely, the original mass-based functional unit of the LCA is maintained, but the LCA outcome (e.g., global warming potential [GWP] per kg) is adjusted for nutritional value, i.e., nLCA = LCA (kg CO_2 eq/kg)/nutritional value. As a measure of nutritional value, we use the Qualifying Index (QI) (Fern et al. 2015), an easy-to-interpret, dimensionless numerical value expressing the relation between nutrient density and energy density. Food items with QI > 1 are considered nutrient dense, whereas food items with QI < 1 are considered energy dense (Fern et al. 2015). Thus, dividing the LCA by the QI reduces environmental impact per kg for nutrient-dense food items, while it increases the environmental impact per kg for energy-dense food items.

2 Materials and methods

2.1 Calculation of the qualifying index

To measure the nutritional value of foods, we used the Qualifying Index (QI), which is a numerical value expressing the relation between nutrient density and energy density in the food (Fern et al. 2015). The QI is calculated with the following equation:

$$QI = \frac{E_d}{E_p} * \frac{\sum_{j=1}^{N_q} \frac{a_{q,j}}{r_{q,j}}}{N_q}$$

where:

E_d = average daily energy needs of the population group (kcal).

E_p = energy in the amount of food analyzed (kcal).

$a_{q,j}$ = amount of qualifying nutrients in the amount of food analyzed (g, mg or µg).

$r_{q,j}$ = RDI of qualifying nutrients (g, mg or µg/day).

N_q = number of qualifying nutrients considered.

To select the qualifying nutrients for the QI, we first determined which were the most relevant nutrients in the four main food groups of the Dutch food-based dietary

Table 1 Overview of nutrients included in the Qualitative Index (QI)

Food group	Nutrients included in this study	Nutrients included in Kyttä et al. (2023b)	Rationale for differences
Protein foods	Protein, Ca, Fe, I, Zn, vit B1, vit B2, vit B3, vit B6, vit B12	Protein, Ca, Fe, Se, Zn, vit B1, vit B2, vit B3, vit B6, vit B12	Se excluded, limited substantiation for RDI (Gezondheidsraad 2018) and adequate intake (RIVM 2023a) Iodine included, as dairy is the major natural source of iodine intake in the Netherlands
Grain and starch foods	Carbohydrates, fiber, K, Fe, Mg, folate	Carbohydrates, fiber, K, P, Fe, Mg, folate	P excluded, limited substantiation for RDI (Gezondheidsraad 2018) and adequate intake (RIVM 2023a)
Fruits and vegetables	Fiber, K, folate, vit C, vit K1, vit A (RAE*)	Fiber, K, vit B1, vit C, vit K, vit A	Vit B1 excluded, fruits and/or vegetables are not first or second source of this nutrient; folate included, as vegetables are the second source of this nutrient (RIVM 2023a)
Fats and oils	Vit A (RAE*), vit D, linoleic acid, alpha-linolenic acid	An index for fats and oils was not included in this study	Fats and oils are the first source of linoleic acid and alpha-linolenic acid, second source of vitamin D, and second and third source of retinol and RAE*, respectively (RIVM 2023a)

*Retinol equivalent activity

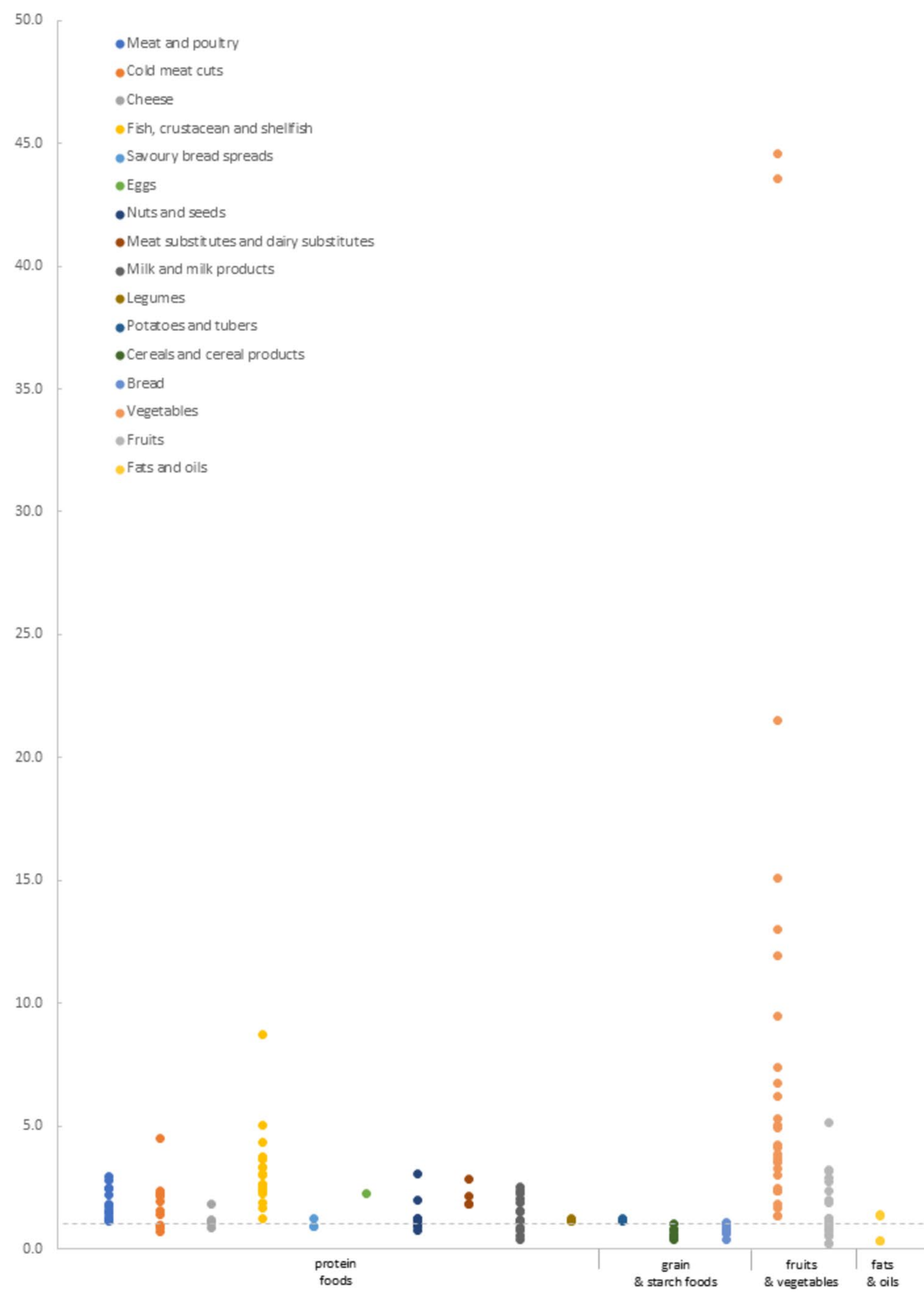
Table 2 Contribution of food groups to nutrient intake and resulting weighting factors

	Protein foods		Grain and starch foods		Fruits and vegetables		Fats and oils	
	Contribution (%)	Weight	Contribution (%)	Weight	Contribution (%)	Weight	Contribution (%)	Weight
Nutrient								
Protein	61.87	0.08	23.51	0.06	4.68	0.01	0.05	0.00
Carbohydrates	12.95	0.02	43.91	0.11	12.07	0.04	0.05	0.00
Fiber	11.60	0.02	47.07	0.12	27.36	0.08	0.04	0.00
Potassium	33.49	0.04	18.84	0.05	21.83	0.07	0.16	0.00
Calcium	61.43	0.08	7.63	0.02	7.84	0.02	1.12	0.01
Magnesium	30.30	0.04	27.21	0.07	11.30	0.03	0.08	0.00
Iron	26.51	0.04	27.72	0.07	12.51	0.04	0.14	0.00
Zinc	52.87	0.07	21.28	0.05	7.05	0.02	0.02	0.00
Iodine	35.12	0.05	34.12	0.09	4.18	0.01	0.13	0.00
RAE	41.26	0.05	1.49	0.00	21.33	0.06	15.35	0.14
Vitamin D	40.60	0.05	0.42	0.00	0.00	0.00	21.38	0.20
Vitamin K1	11.03	0.01	2.09	0.01	74.45	0.22	5.59	0.05
Vitamin B1	35.15	0.05	23.40	0.06	11.01	0.03	3.25	0.03
Vitamin B2	53.92	0.07	9.00	0.02	8.05	0.02	2.80	0.03
Vitamin B3	33.62	0.04	17.89	0.05	16.37	0.05	3.36	0.03
Vitamin B6	77.25	0.10	0.34	0.00	0.00	0.00	2.14	0.02
Vitamin B12	41.24	0.05	19.83	0.05	8.59	0.03	0.00	0.00
Folate equivalents	22.85	0.03	22.16	0.06	23.50	0.07	4.37	0.04
Vitamin C	11.55	0.02	9.78	0.02	46.31	0.14	0.00	0.00
Linoleic acid	28.49	0.04	20.41	0.05	2.99	0.01	23.40	0.22
Alpha linolenic acid	27.48	0.04	18.58	0.05	9.93	0.03	22.57	0.21
SUM	*750.56*	*1.00*	*396.70*	*1.00*	*331.36*	*1.00*	*106.01*	*1.00*

guidelines. These food groups are as follows: (I) protein foods: dairy and dairy substitutes, meat and meat substitutes, fish, eggs, legumes and nuts, and seeds; (II) grain foods: bread, pasta, rice, other cereals and cereal products, potatoes, and tubers; (III) fruits and vegetables; and (IV) fats and oils.

To select the relevant nutrients, we built upon the work by Kyttä et al. (2023a, b), who identified the nutrients provided by the typical sources of each food group and included nutrients based on the criteria that the food group under study was one of the most important sources (i.e., first or second source) of the selected nutrient in the current Finnish diet. Data from the Dutch National Food Consumption Survey (DNFCS) 2019–2021 (RIVM 2023a; Van Rossum et al. 2023) were used to examine the contribution of the food group under study to the selected nutrient intake in the current Dutch diet. Table 1 shows the selected nutrients per food group in our study compared to the study of Kyttä et al. (2023b). This procedure yielded a total number of 21 qualifying nutrients (N_q) across the different food groups. These 21 qualifying nutrients were used to calculate an overall QI, as outlined above.

Fig. 1 Scatterplot of nutritional value of foods as measured by the Qualifying Index (QI)



The QI calculations were based on 100 g of food and a daily energy needs (E_d) of 2250 kcal (the average of the standard 2500 kcal for adult men and 2000 kcal for adult women (Gezondheidsraad 2001)). It should be noted that the QI itself is dimensionless, as it is the arithmetic mean of the amount of each qualifying nutrient in 2250 kcal of a given food relative to RDI for that nutrient. The nutrient values ($a_{q,j}$), as well as energy values (E_p) per 100 g of food item, were derived from the Dutch Food Composition database (DFCD) (NEVO-online, version 2023/8.0) (RIVM 2023b). As RDIs ($r_{q,j}$), we used the average values of men and women aged 18–30 years (Gezondheidsraad 2001, 2006, 2018, 2021).

2.2 Capping

Capping refers to truncating nutrient metrics at 100% of RDI values. While there is as yet no consensus on the application of capping in indices used for nutritional LCA, it is considered relevant for energy standardized metrics and assessments within specific food groups (Bianchi et al. 2020; Green et al. 2023). As both are the case here, we calculated QI values both with and without capping. To calculate capped values, we used 100 kcal of a food item as a reference, thus assuming that a nutrient content higher than the RDI in 100 kcal of a food item would have no additional benefit. In the calculation of the overall QI, which is standardized to 2250 kcal, this corresponds to capping nutrients at a value of 22.5 if their nutrient-RDI ratio exceeds 22.5.

2.3 Food-group-specific QIs

An important methodological issue in nLCA is whether the same index should be applied to all food products or not (McLaren et al. 2021; Kyttä et al. 2023a). To address this issue, we first examined the adequacy of the application of the overall QI for the different food groups, which we defined as the percentage of QI delivered by the food-group-specific nutrients. For each food group, we calculated the overall QI of foods using only food-group-specific nutrients (see Table 1) in the nominator (i.e., $a_{q,j}$ = amount of food-group-specific nutrients and $r_{q,j}$ = RDI of food-group-specific nutrients), but with N_q remaining 21. This QI was then expressed as a percentage of the original overall QI for each food, and an average adequacy was calculated per food group.

Subsequently, we calculated food-group-specific QIs, using differential weighting. Although the QI is developed as an overall measure of nutritional value, it can be adjusted for specific purposes. Differential weighting has been described as a method to attach greater significance to specific nutrients in the QI, without changing the mathematical and statistical conditions of the concept (Fern et al. 2015). Weights were based on the relative contribution of the food group to the intake of included nutrients in the general population, using data of the DNFCS (RIVM 2023a; Van Rossum et al. 2023) (see Table 2). All weights were scaled in order to sum up to 1 (Ridoutt 2021). To calculate the food-group-specific QI of foods,

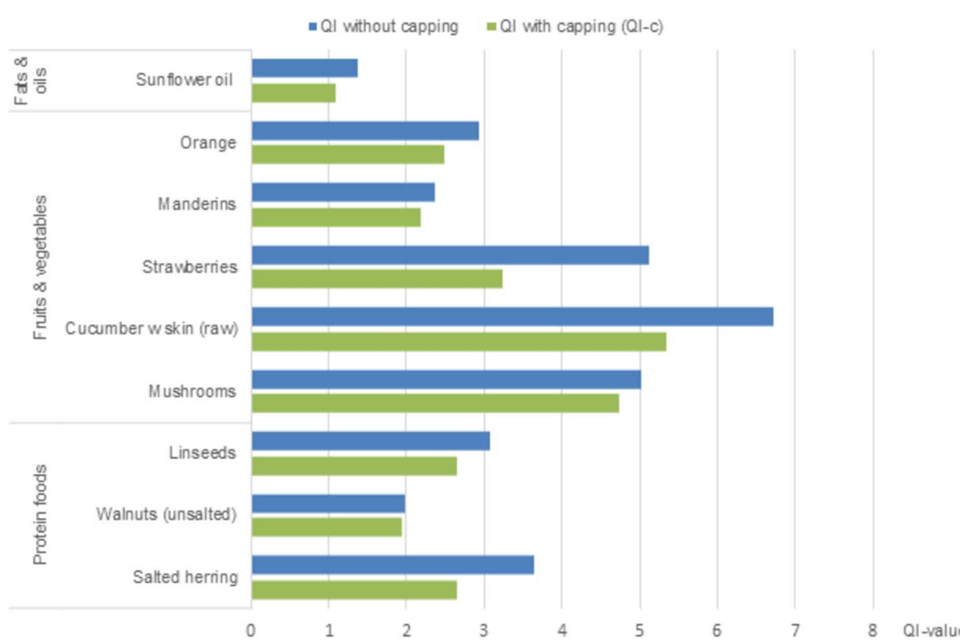


Fig. 2 Nutritional value of specific foods as measured by the Qualifying Index (QI), with change in nutritional value after capping (QI-c)

each nutrient-QI ($\frac{E_d}{E_p} * \frac{a_{q,j}}{r_{q,j}}$) was multiplied by the weighting factor and then summed to get the food-QI.

2.4 Life cycle assessment data for food products

Environmental impact data, more specifically GWP (in kg CO_2 eq/kg) of food products, were obtained from the environmental impact database of foods made by The Dutch National Institute for Public Health and the Environment, which currently includes 239 food items that were reported to be included in this database because they are frequently consumed in the Netherlands according to the Dutch National Food Consumption Survey and/or have a relatively high environmental burden per kilogram of food (RIVM 2021).

From this database, we selected 180 food items belonging to one of the four main food groups as described above: 96 protein products (categories: milk and milk products; cheese; meat and poultry; cold meat cuts; fish, crustacean and shellfish; eggs; meat substitutes and dairy substitutes; legumes; nuts and seeds; and savory bread spreads), 21 grain and starch products (categories: potatoes and tubers; bread; cereals and cereal products), 31 vegetable products, 25 fruit products, and 7 fat-based products. The food items

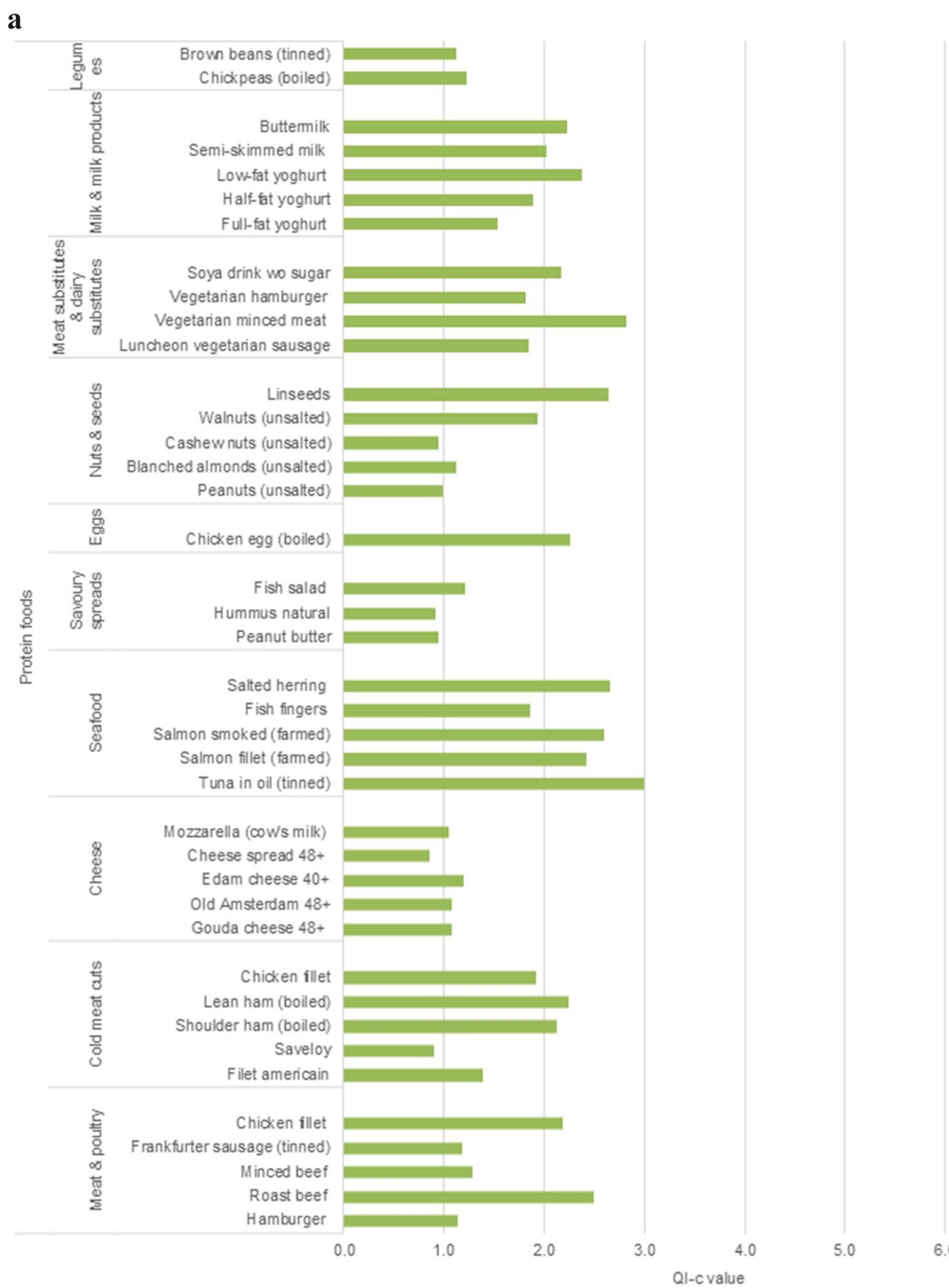
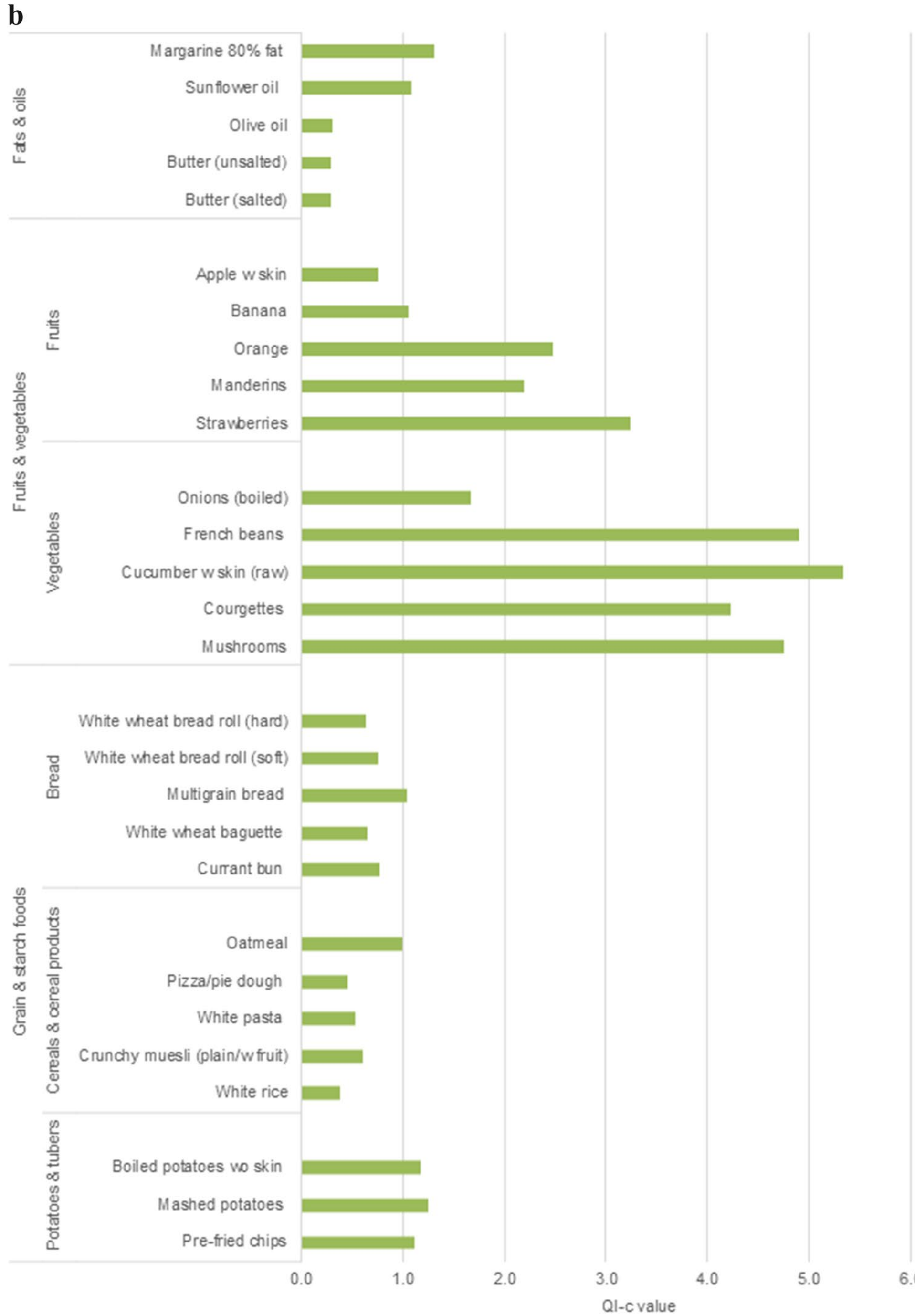


Fig. 3 **a** Nutritional value of selected protein foods, with capping (QI-c). For information on selection, see *Methods* Section 2.4. **b**Nutritional value of selected grain & starch foods, fruits & vegetables, and fats & oils, with capping (QI-c). For information on selection, see *Methods* section 2.4

Fig. 3 (continued)



were coupled with nutrient data based on the "NEVO-code," a unique number given to all foods included in the DFCD, which was also included in the environmental impact database.

For five selected products, nutrient data was unavailable but could be obtained from a previous version of the DFCB. For three products, nutrient data was unavailable in both the current and previous DFCB, and these were therefore excluded, resulting in a database of 177 products. For 10 food items, nutrient data was incomplete with two or more missing nutrients; these foods were therefore excluded. For 78 food items, data for one nutrient was missing; in the majority of cases ($n = 75$), the missing nutrient concerned nutrient contents that are generally low in the specific products (e.g., vitamin K1 in foods other than fruits and vegetables and iodine in oils). In those 75 cases, nutrient content was considered 0.00 (mg or µg), and in the three remaining cases, the foods were excluded from the database.

To calculate the GWP of a food item in relation to their nutritional value (i.e., the nLCA), we divided the GWP value

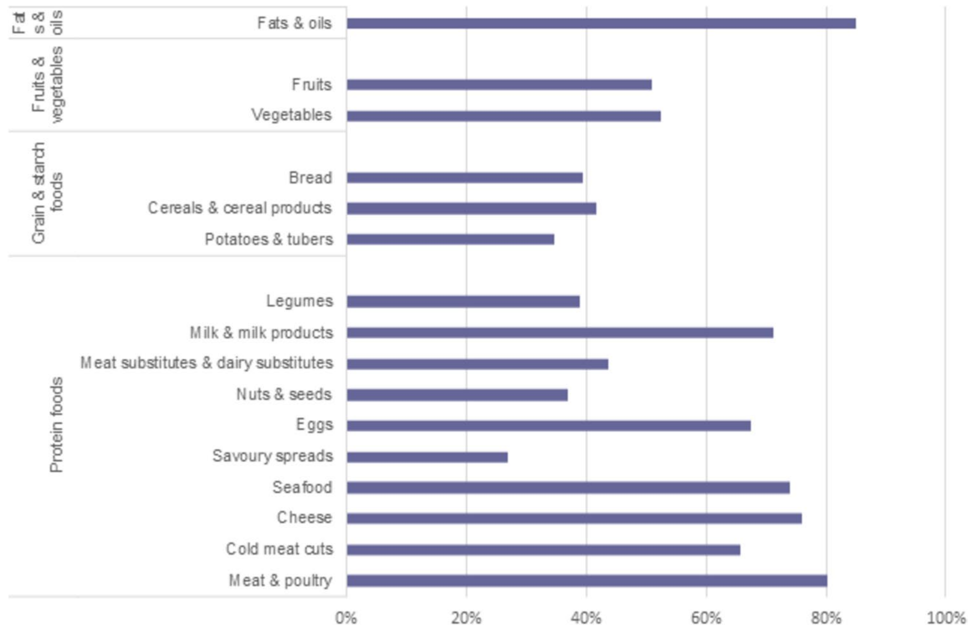


Fig. 4 Percentage of nutritional value (QI-c) delivered by the food-group-specific nutrients

in kg CO_2 eq/kg by the overall QI and the food-group-specific QI for that food item. QI as well as nLCA calculations were performed for all remaining 164 food items in the database and are presented as supplementary material (Table S1). For the purpose of clarity, we only presented a selection of food items per food group in the results section. This selection was based on DNFCS intake data: we selected the five foods with the highest frequency of intake (reflected by number of consumption days) in the food categories belonging to the specific food group. If the category contained less than five food items, all food items in that category were selected (Table S2).

3 Results

3.1 Qualifying Index

Highest values for the overall QI were observed for vegetable and fish products (Fig. 1 and Table S1; average values 8.7 and 3.2, respectively), whereas lowest values were observed for fats and oils (average 0.7) and cereal products (average 0.6). Capping did not affect QI values calculated for most food products, but for some foods, capping lowered their QI. These were primarily food products with low energy content but (very) high levels of one or more specific nutrients, e.g., vegetables with high vitamin K1 content and seafood with high vitamin B12 content (Fig. 2, Table S1). A QI with capping was therefore used in all further analyses and is hereafter referred to as QI-c. Figure 3a and b presents the QI-c of selected foods and Fig. 4 presents the adequacy of the QI-c for the different food categories, whereby adequacy was calculated as the percentage of the QI-c delivered by the food-group-specific nutrients (see *Methods*). Adequacy of the QI-c was more than 65% for animal-based protein foods and fats and oils, around 50% for fruits and vegetables, and 30 to 40% for plant-based proteins and grain foods.

3.2 nLCA

GWP values, expressed as kg CO_2 eq/kg, were highest for protein foods, in particular meat and poultry, cold meat cuts, and cheese (Table S1; average GWP 21.4, 13.4, and 10.8 kg CO_2 eq/kg, respectively). GWP values were lowest for fruits and vegetables, in particular fruits, and for grain foods (average 1.6 kg CO_2 eq/kg) and bread (average 1.4 kg CO_2 eq/kg). For the majority of foods, GWP values decreased when adjusted for nutritional value, but for foods with QI-c values < 1, adjustment increased GWP values, as demonstrated in Fig. 5a and b. Examples of these foods are butter and olive oil, but also refined grains such as white bread products, white pasta, and white rice, and some proteins such as saveloy, cheese spread, peanuts, and peanut butter.

3.3 Food-group-specific analyses: protein foods

To assess the impact of an across-the-board approach versus a food-group-specific approach, we calculated food-group-specific indices, using differential weighting (see *Methods*). Weighting for protein-specific nutrients increased the QI-c values in most animal-based protein foods, but decreased QI-c values in most plant-based protein foods, with vegetarian minced meat as a notable exception (Table S1, Fig. 6a).

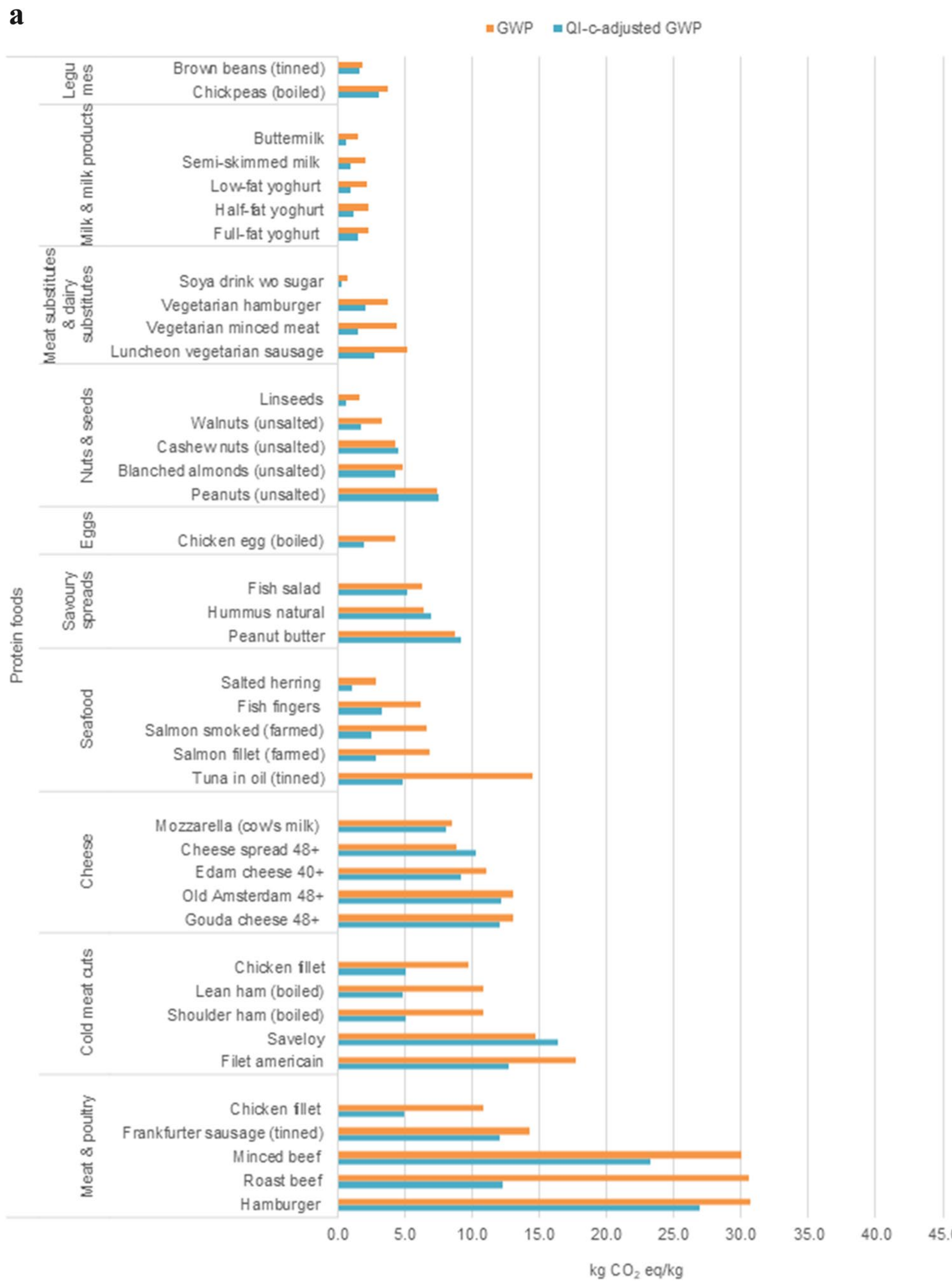


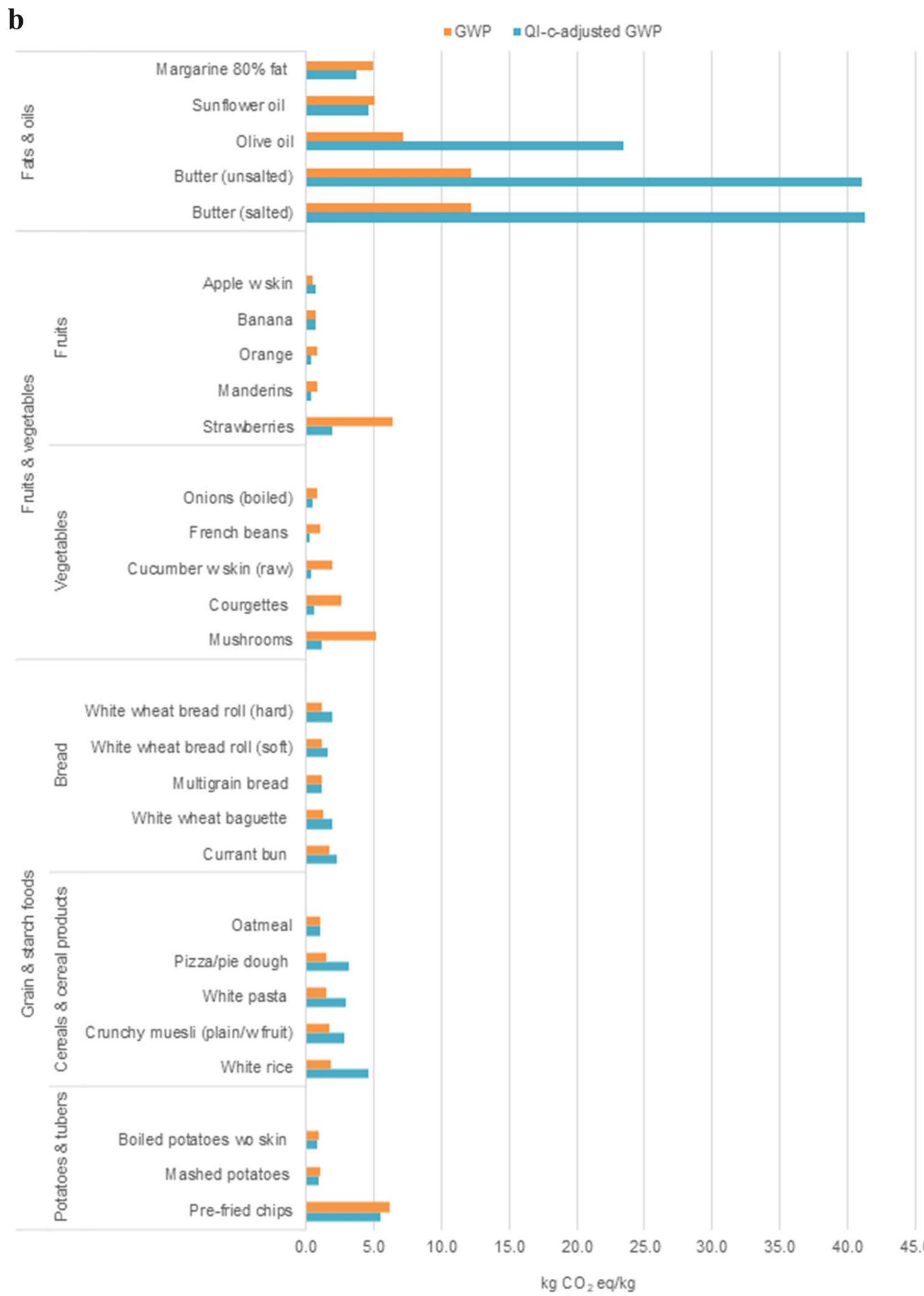
Fig. 5 **a** Global warming potential (GWP) in kg CO_2 eq per kg product for selected protein foods, unadjusted and adjusted for nutritional value (QI-c) of food items. For information on selection, see *Methods* Section 2.4 **b** Global warming potential (GWP) in kg CO_2 eq per kg product for selected grain & starch foods, fruits & vegetables and fats & oils, unadjusted and adjusted for nutritional value (QI-c) of food items. For information on selection, see *Methods* section 2.4

Adjusted GWP values changed accordingly (Table S1, Fig. 6b); i.e., weighted nutritional adjustment resulted in lower GWP values for animal-based protein foods, and in similar or higher GWP values for plant-based protein foods, compared to no adjustment and unweighted adjustment.

3.4 Food-group-specific analyses: grain and starch foods

Weighting for grain-specific nutrients increased the QI-c values for all products included in this category, and, correspondingly, decreased the adjusted GWP values as compared to unweighted nutritional adjustment (Table S1, Fig. 7a). For some food items, especially in the bread category, weighting changed QI-c values < 1 to QI-c values > 1. Adjusted GWP values changed correspondingly (Table S1, Fig. 7b); i.e., weighted nutritional adjustment resulted in lower GWP values for food items with weighted QI-c values > 1, compared to no adjustment and unweighted adjustment. For grain and starch foods with weighted QI-c values < 1, weighted nutritional adjustment still resulted in higher GWP values, but less so than after unweighted adjustment.

Fig. 5 (continued)



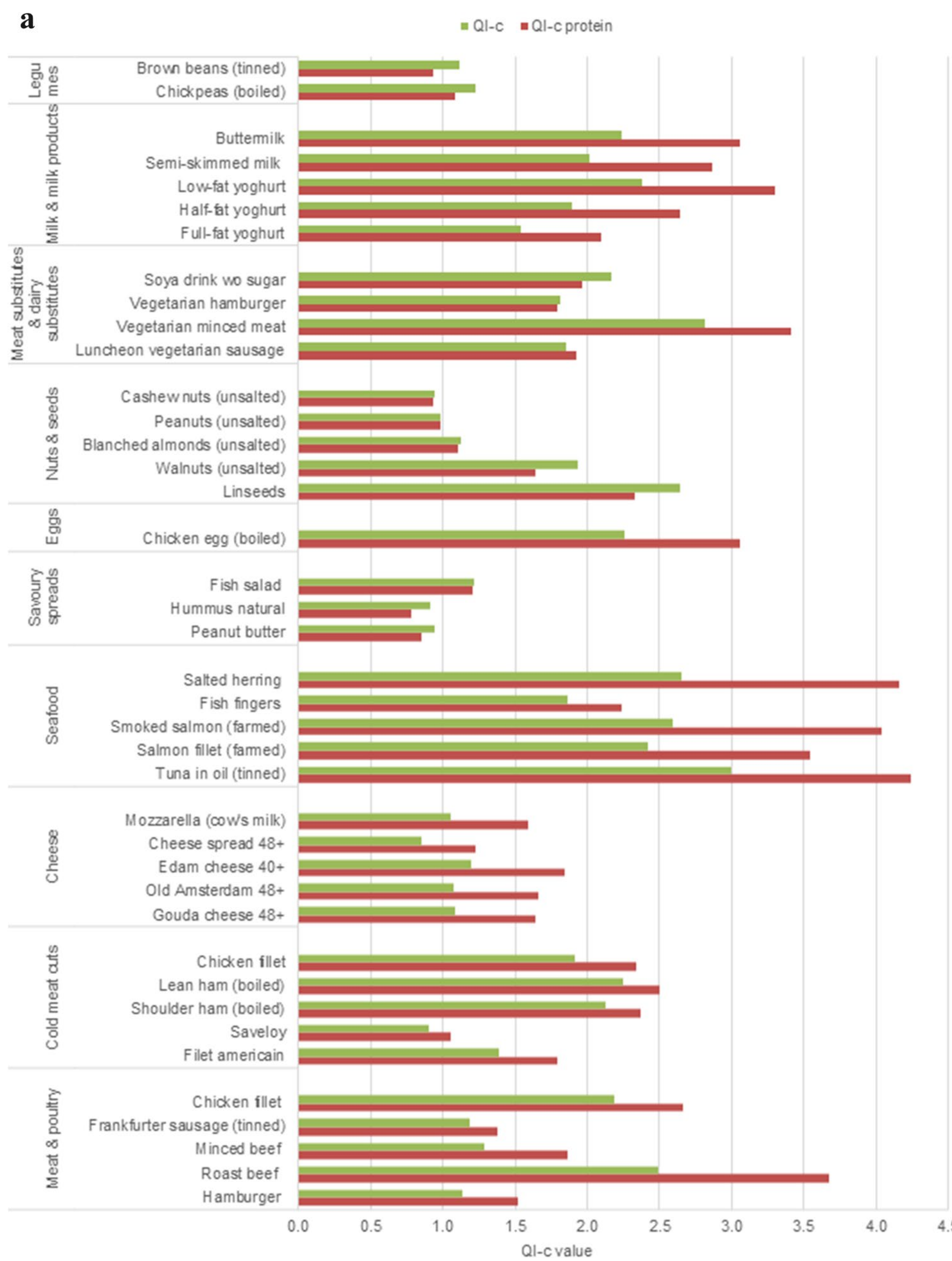
3.5 Food-group-specific analyses: fruits and vegetables

Increases in QI-c after weighting were observed for most fruits and vegetables (Table S1, Fig. 8a), resulting in additional decreases in nutritionally adjusted GWP values (Table S1, Fig. 8b). Mushrooms (Fig. 8a), olives, coconut milk, and sweetcorn (Table S1) were an exception, with lower QI-c values after weighted adjustment, resulting in higher adjusted GWP values as compared to unweighted nutritional adjustment (Table S1, Fig. 8b).

3.6 Food-group-specific analyses: fats and oils

Weighting increased the QI-c values for all fats and oils (Table S1, Fig. 9a). As the weighted QI-c values of butter remained < 1, the increase in GWP value after weighted nutritional adjustment was smaller than after unweighted adjustment (Fig. 9b). The higher weighted QI-c for olive oil, sunflower oil, and margarine (values > 1) corresponded with decreases in adjusted GWP values, when compared to unweighted nutritional adjustment (Fig. 9b).

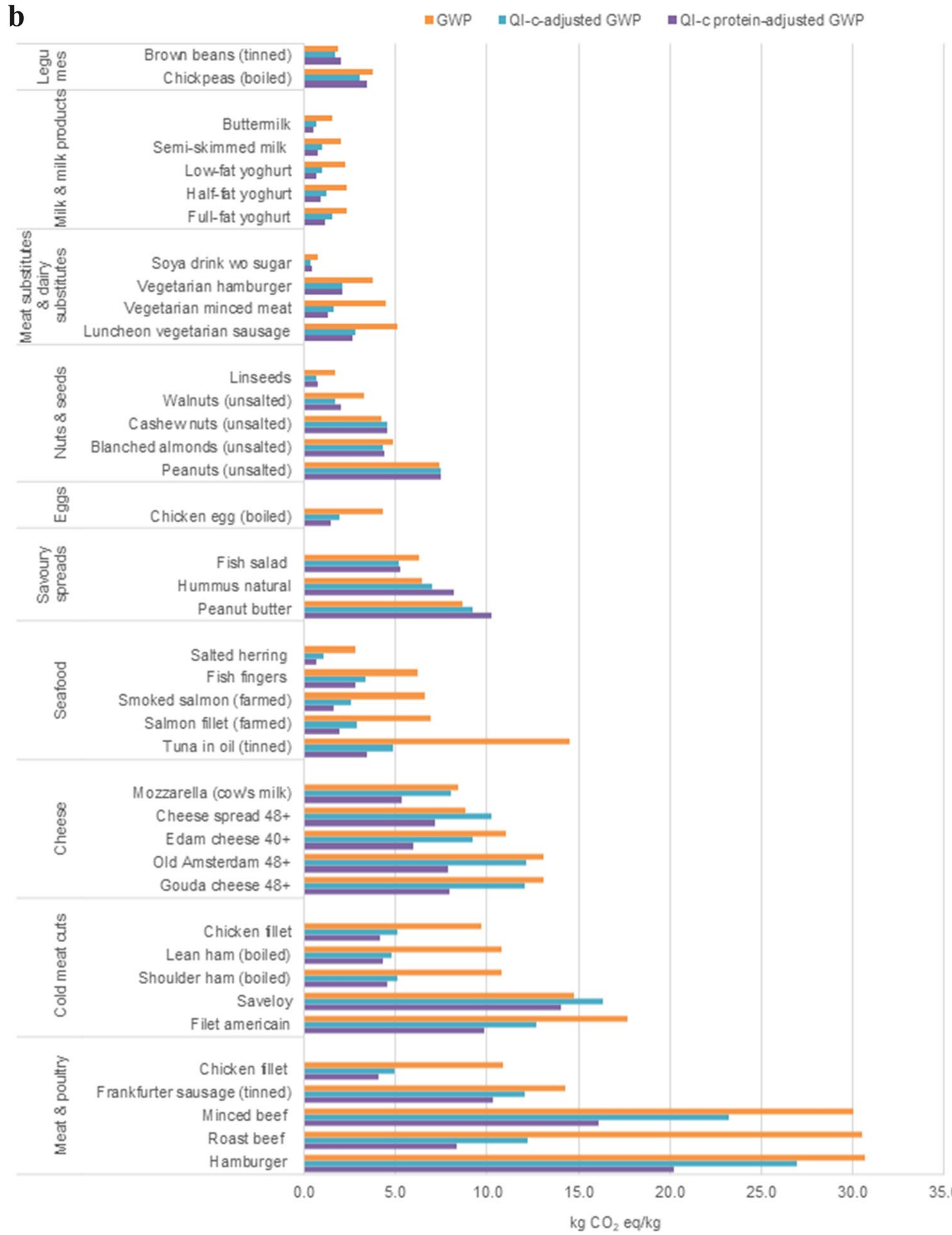
Fig. 6 **a** Unweighted nutritional value (QI-c) and weighted nutritional value (QI-c protein) of selected protein products. For information on selection, see *Methods* Sect. 2.4 **b** Global warming potential (GWP) in kg CO_2 eq per kg product of selected protein foods: unadjusted, adjusted for unweighted nutritional value (QI-c) of product, and adjusted for weighted nutritional value (QI-c protein) of product. For information on selection, see *Methods* section 2.4



4 Discussion

In this study, we introduced a novel approach to nLCAs. Traditionally, LCAs for food products are calculated based on mass (e.g., impact per kg product) or sometimes volume (Green et al. 2023). The use of a mass-based FU, however, has limitations when considered in the context of human nutrition, and therefore the concept of a nutrient-based FU has been advocated (McLaren et al. 2021). While the use of nutritional value as a FU does consider that the primary function of a food item is the provision of nutrients, several methodological issues arise when replacing the mass-based FU with a nutrient-based FU (McLaren et al. 2021; Green et al. 2023). As a result, nLCA outcomes are difficult to comprehend, not easily comparable across foods, meals, or complete diets and therefore complicate evidence-based decision-making on sustainable food consumption. To overcome these methodological issues, we have developed an approach that uses the Qualifying Index (QI) as a nutritional correction factor, rather than a separate FU, for traditional mass-based LCAs, resulting in a more intuitive solution. In short, the concept of our QI-nLCA is based on dividing the mass-based LCA by the QI, a dimensionless numerical value which expresses the relation between nutrient density and energy density (nutrient-energy balance) in foods (Fern et al. 2015). Thus, QI-nLCA = LCA/QI.

Fig. 6 (continued)



A QI value between 0 and 1 indicates a lower nutrient-energy balance (i.e., denoting energy-rich foods), whereas a value > 1 indicates a higher nutrient-energy balance (i.e., denoting nutrient-rich foods). Correcting a GWP values for food products for QI values between 0 and 1 therefore increases nutrient-adjusted GWP values, whereas correction for QI values > 1 reduces nutrient-adjusted GWP values. Saveloy, white rice, and butter, for example, are food items with QI values < 1, whereas chicken egg, boiled potatoes, and sunflower oil are all food items with QI values > 1 (Fig. 1). With nutritional adjustment, GWP values for saveloy, white rice, and butter increased from 14.7 to 16.4, from 1.8 to 4.6, and from 12.2 to 41.1 kg CO_2 eq/kg, respectively, whereas GWP values for chicken egg, boiled potatoes, and sunflower oil decreased from 4.3 to 1.9, from 0.9 to 0.8, and from 5.0 to 4.6 kg CO_2 eq/kg, respectively (Fig. 2a and b).

In this study, we included those food groups that contribute to the intake of essential nutrients (Van den Assum et al. 2020). As a result, we observed QI values > 1 for most foods considered, and relatively little discrimination between, for example, animal-based protein foods and plant-based protein foods. However, GWP values for plant-based protein foods were generally lower than for animal-based protein foods, suggesting that, from a sustainability perspective, plant-based foods can be a better choice when nutritional value (in terms of nutrient provision) is similar. From a human health perspective, is it important to note that high nutrient density does not necessarily imply low disease burden—and

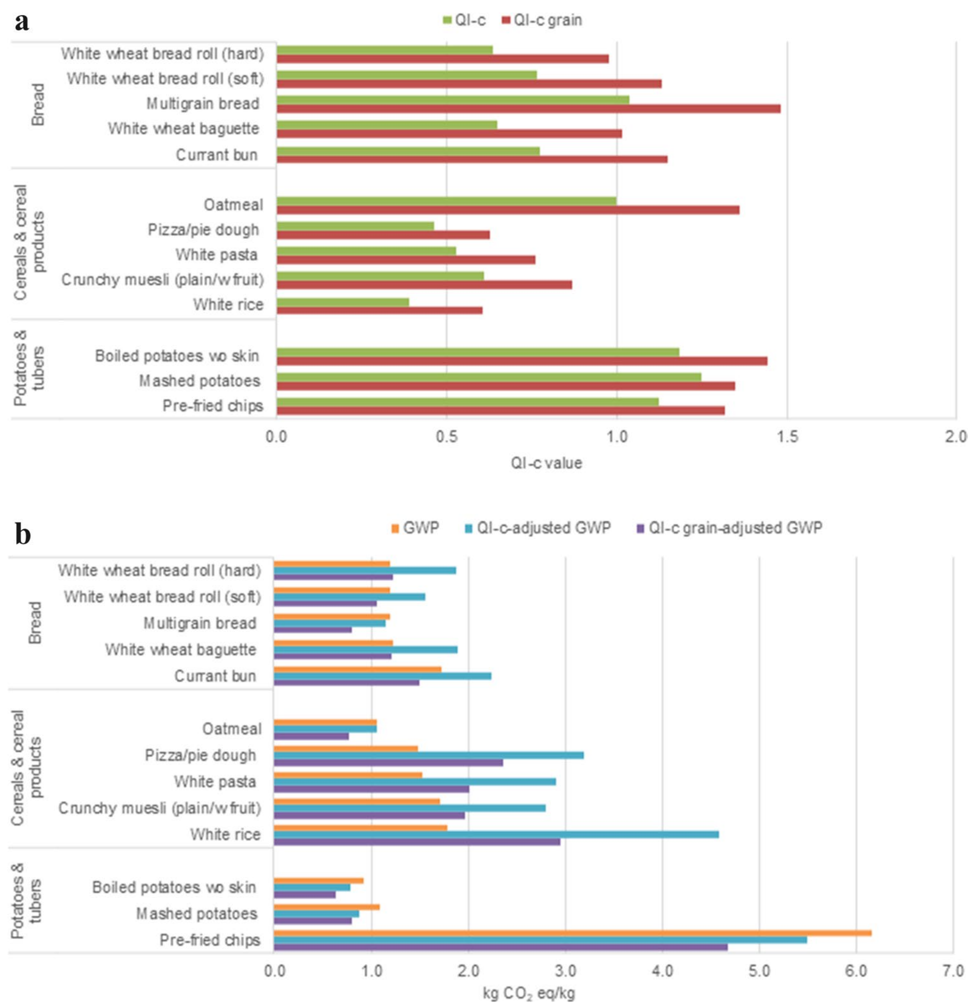


Fig. 7 **a** Unweighted nutritional value (QI-c) and weighted (QI-c grain) of selected grain and starch products. For information on selection, see *Methods* Sect. 2.4 **b** Global warming potential (GWP) in kg CO_2 eq per kg product of selected grains and starches: unadjusted, adjusted for unweighted nutritional value (QI-c) of product, and adjusted for weighted nutritional value (QI-c grain) of product. For information on selection, see *Methods* section 2.4

vice versa. Nutrient density refers to nutritional adequacy to support normal functioning of the body, while disease burden relates to the risk of non-communicable diseases. Recent work clearly highlighted that while some foods, e.g. vegetables, have a high nutrient density and a low disease burden, other foods that have a high nutrient density actually also have a high disease burden, e.g., processed meat (Cardinaals et al. 2024). Previous nLCA studies have tried to incorporate both positive and negative health effects by including so-called nutrients to limit in their indices, like salt, added sugar, and saturated fat. We decided not to, as the relevance of nutrients to limit is under discussion—the Global Burden of Disease, for example, no longer includes added sugar and saturated fat as risk factors (GBD 2019 Risk Factors Collaborators 2020)—and because the concept of the QI already includes a "punishment" based on energy density. As it was previously shown that nutrient profile models that include (saturated) fat, sugar, and sodium correlate highly with energy density (Drewnoski et al. 2009), the energy density factor included in the calculation of the QI could be seen as proxy for nutrients to limit. Indeed, QI values < 1 were typically observed in food items high in sugar, saturated fat, and/or sodium, such as saveloy and butter mentioned previously, as well as croissants, full-fat cheese spread, and ice cream.

Our intention was to demonstrate a concept, which can of course be refined in future studies. But as it is now, the use of a nutrition correction factor, rather than a nutrient-based functional unit, means that current food LCA databases, based on mass, can easily be used to calculate nLCAs for foods. In addition, the QI-nLCA can be applied to complete meals as well as diets. For example, a meal consisting of 250 g of French beans, 280 g of boiled potatoes, and 100 g of chicken fillet, with a dessert of 150 g full-fat yoghurt and 100 g of strawberries, corresponds to a GWP value of 2.6 kg CO_2 eq, unadjusted for nutritional value, but a GWP value of 1.2 kg CO_2 eq when nutritional value is taken into account (Table 3). Arguably, to also be applicable to whole diets, the QI would need to adequately represent nutritional value of basic foods as well as non-basic foods. To explore the applicability of the QI to non-basic foods, we performed additional analyses on three discretionary food groups, i.e., soft drinks and fruit

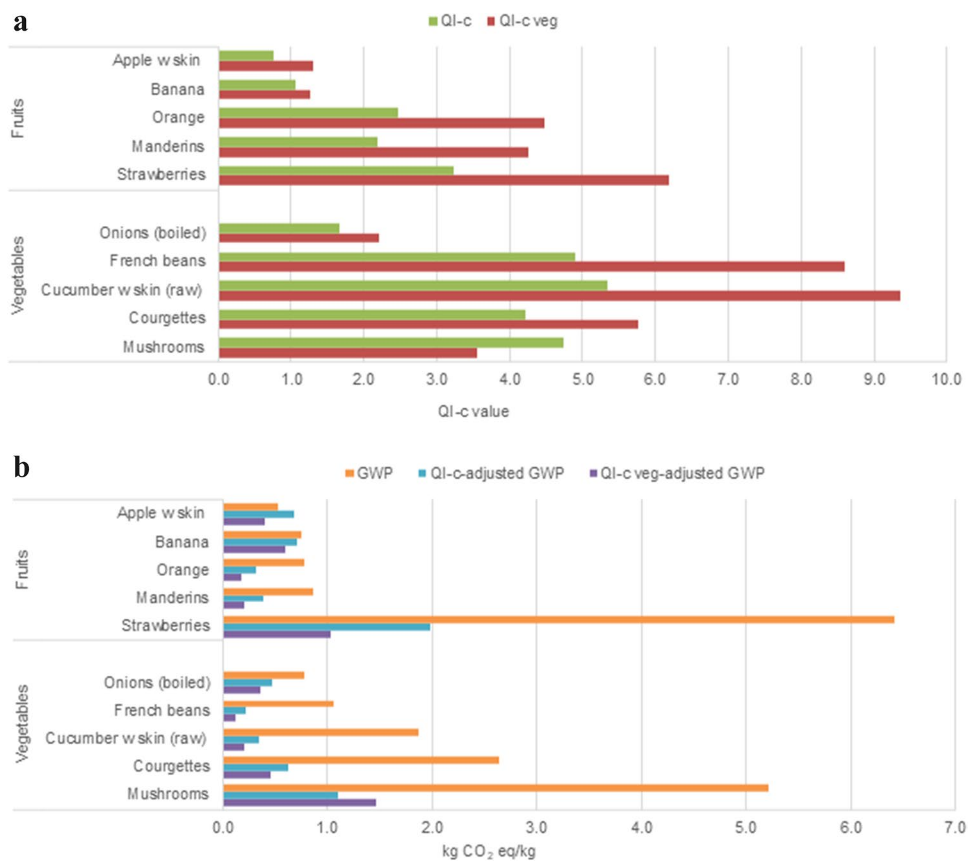


Fig. 8 **a** Unweighted nutritional value (QI-c) and weighted (QI-c veg) of selected fruits and vegetables. For information on selection, see *Methods* Sect. 2.4 **b** Global warming potential (GWP) in kg CO_2 eq per kg product of selected fruits and vegetables: unadjusted, adjusted for unweighted nutritional value (QI-c) of product, and adjusted for weighted nutritional value (QI-c veg) of product. For information on selection, see *Methods* section 2.4

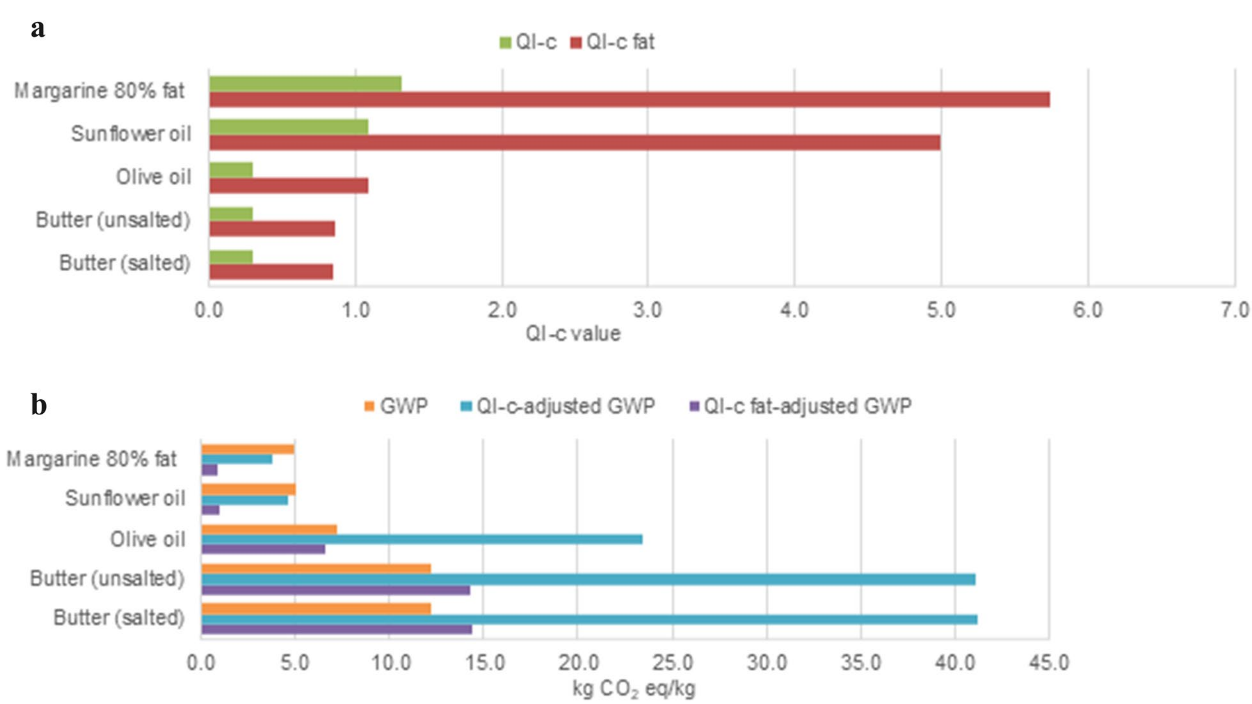


Fig. 9 **a** Unweighted nutritional value (QI-c) and weighted (QI-c fat) of selected fats and oils. For information on selection, see *Methods* Sect. 2.4 **b** Global warming potential (GWP) in kg CO_2 eq per kg product of selected fats and oils: unadjusted, adjusted for unweighted nutritional value (QI-c) of product, and adjusted for weighted nutritional value (QI-c fat) of product. For information on selection, see *Methods* section 2.4

Table 3 Global warming potential (GWP) in kg CO_2 eq of a composite meal, unadjusted and adjusted for nutritional value (QI-c)

Meal component	Portion size (kg)	GWP per portion (kg CO_2 eq)	GWP per portion, adjusted for QI-c (kg CO_2 eq)	GWP per portion, adjusted for food-group-specific QI-c (kg CO_2 eq)
French beans	0.25	0.27	0.06	0.03
Boiled potatoes	0.28	0.26	0.22	0.18
Chicken fillet	0.10	1.09	0.50	0.41
Yoghurt	0.15	0.35	0.23	0.17
Strawberries	0.10	0.64	0.20	0.10
TOTAL	*0.88*	*2.61*	*1.21*	*0.89*

juices, pastry and biscuits, and savory snacks, in the LCA database (Table S3 in SI appendix). With the exception of orange juice and Dutch sausage, the food items in these categories all have QI values below 1 and, consequently, higher nutrient-adjusted GWP values. These results do not only support our reflection above, on energy density as proxy for limiting nutrients, they also suggest that the QI-nLCA is indeed applicable to a variety of foods in the diet.

Notably, QI values could not be calculated for above-mentioned non-basic food products with zero calories, such as diet/light soft drinks. For such products, the original GWP values would need to be used. We also observed that in some basic food products, low energy content in combination with high levels of one or more specific nutrients led to extreme values for the QI. This was, for example, the case for various vegetables (as a result of high levels of vitamin K or A), but also for some fruits (vitamin C), some nuts and oils (fatty acids), and some fish (vitamin B12). Capping was therefore used to avoid overcrediting the role of these nutrients in the calculation of the QI (Bianchi et al. 2020; Green et al. 2023). Overall, changes in QI values with capping were small, except for a minority of foods with extremely high levels of previously mentioned nutrients. For spinach, for example, the overall QI was reduced from 44.6 to 8.1 with capping, which can still be considered a high value.

When applying the QI, with capping, to the food LCAs, we observed that the nutrient composition of an overall (across-the-board) QI did not adequately emphasize the relevant nutrients for all foods. More specifically, it did not result in sufficient distinction for especially carbohydrate-rich foods, such as bread, pasta, and rice, and to a lesser extent, fruits and vegetables. We therefore also applied weighting factors to nutrients relevant to the specific food groups to also calculate food-group-specific QIs. This resulted, for example, in fiber and carbohydrates obtaining greater weights in the food group with grains, than in the protein foods group and fatty acids obtaining greater weights in the fats and oils group than in the fruits and vegetables group. Especially for the carbohydrate-rich foods, but also for fruits and vegetables, this led to QI values more in line with the actual nutritional value. For example, the food-group-specific QIs for white rice, crunchy muesli, and apple sauce remained <1, whereas the food-group-specific QIs for brown rice, oatmeal, and apples increased to value above 1, resulting in more distinctive nLCA values (see Table S1 in SI Appendix). When applied to the example meal presented in Table 3, the nutrition-adjusted GWP value calculated with food-group-specific QIs as correction factor summed up to 0.9 kg CO_2 eq.

5 Conclusions

In this study, we developed a new concept for nutritional life cycle assessments, in which the original mass-based functional unit (kg) is maintained but corrected for by a multi-nutrient, dimensionless Qualifying Index (QI). The methodology of this study can easily be applied to nLCA calculations to compare individual foods, composite meals, and whole diets. The QI-nLCA methodology can effortlessly be applied to any other environmental indicator and, as such, could add to better evidence-based decision-making by policy makers in the field of healthy and sustainable nutrition.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s11367-025-02465-4.

Author contribution S.P. and O.L. conceived the idea for this research, S.P., M.v.E., and T.H. designed the research. M.v.E. performed the research and analyzed the data. S.P, O.L, J.G., and T.H. provided feedback on the analysis and interpretation of the data. M.v.E., S.P, O.L, J.G., and T.H. wrote the paper.

Funding Financial support for this study came from the Dutch Dairy Association.

Data availability The data presented in this paper were derived from publicly available data sources which are referenced in the paper, and calculation made therewith using equations outlined in the paper. Data will be made available upon request.

Declarations

Competing interests S.P. is employed at the Dutch Dairy Association and O.L, J.G., and T.H. are employed at companies that are members of the Dutch Dairy Association. M.v.E. is an independent consultant at Buro Vlinder. The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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