



# Extending the product-group-specific approach in nutritional life cycle assessment

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## Abstract

**Purpose** Recent methodological developments have integrated nutritional aspects into life cycle assessment (LCA) by using nutrient indices as functional units (nFUs). Previous developments have focused on protein-rich foods, but environmental impacts and nutritional composition vary across products in other product groups, highlighting the need to develop nFUs also for other product groups. Here, we present product-group-specific nFUs for vegetables, fruit and berries, and sources of carbohydrates as an extension to our previous study on protein sources.

**Methods** We first justified the basis of product grouping and the procedure to develop product-group-specific nutrient indices to be used as the nFU in the LCA for product groups of vegetables, fruit and berries, and sources of carbohydrates. The practical application of these indices was then tested through demonstrative LCAs for the selection of different foods. The performance and results obtained with product-group-specific nFUs, including previously developed nFU for protein sources, were evaluated through a comparison with an assessment done using a general index, which included all the nutrients with the recommended daily intake in Finnish nutrition recommendations.

**Results and discussion** The results showed that the product-group-specific nFUs resulted in index scores that were an average of 2.5 times higher, and therefore lower climate impacts per nFU for the assessed food products, than the general index. This demonstrated that product-group-specific nFUs accurately represented the relevant nutrients for the studied product group and provided specific information on the impact of substituting currently consumed foods. The relative results obtained with either product-group-specific indices or a general index were similar except in the protein source product group, showing that a product-group-specific nFU might favour a certain type of products, such as traditional protein source foods, when applied to a very heterogenous group of products.

**Conclusions** This study showed that the product-group-specific approach could provide valuable information when evaluating the sustainability of different meal components. The approach presented here can be adapted elsewhere and revised for different populations. However, future research is needed to extend the method to cover other product groups as well and validate the selection of nutrients in the nFUs.

**Keywords** nLCA · Nutrient index · Functional unit · Sustainable nutrition

## 1 Introduction

For food LCA, the recent methodological development includes the integration of nutritional aspects into the assessment of environmental impacts (nutritional LCA,

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nLCA), which enables a comparison of the environmental impacts of food products based on the nutritionally unified unit, such as 100 g of protein or nutrient indices including several nutrients (McLaren et al. 2021). Nutrient indices have been proposed to be used as the unit (functional unit, FU) for which the environmental impacts are assessed because they describe the nutritional composition of a product more comprehensively than FUs based on single nutrients (e.g. Saarinen et al. 2017; McLaren et al. 2021; Green et al. 2020). Initially, nutritional indices have been developed to classify and rank foods, for labelling and health claim purposes, for example NRF-indices (nutrient-rich foods) by Fulgoni et al. (2009). The field is still evolving, and methodological details have yet to be established (McLaren et al. 2021; McAuliffe et al. 2023). The methodology combining nutrient indices in LCA aims to help identify products whose consumption results in reduced environmental impacts without compromising a balanced nutrient intake.

One key methodological issue is whether the nutrient index-based FU should be based on a general across-the-board or product-group-specific measure of nutritional composition (Scarborough et al. 2010; McLaren et al. 2021). This choice may have implications for the selection of nutrients in the index. While general nutritional indices, e.g. NRF indices (Fulgoni et al. 2009), have been used more frequently in nLCAs (e.g. Hallström et al. 2019), there are also several product-group-specific indices for the nutritional functional unit (nFU) introduced: FNIprot7 by Saarinen et al. (2017), variations from the FNIprot7 for the UK by McAuliffe et al. (2018), NQI by Sonesson et al. (2019), NRFprotein-sub by Green et al. (2021), and an index for protein-rich foods by Kyttä et al. (2023). The product-group-specific indices for use as FUs have thus far only been developed for protein-rich foods. However, the environmental impacts and nutritional composition also vary between products in other product groups (e.g. Clark et al. 2022), highlighting the need to also consider product-group-specific nFUs for other foods.

Another critical issue particularly related to product-group-specific nFUs but not discussed widely in the literature is how to define product groups for a comparison between products and the identification of product functionality (McLaren et al. 2021). In the sustainability discussion, ‘protein sources’ is a widely used product group due to the high environmental impacts of animal-origin foods that are often rich in protein and micronutrients (e.g. iron), and the crucial role they and their substitutes play in the sustainable food transition. ‘Protein sources’ is also used as a product group in nutrition education to guide food choices—for example as part of the Finnish plate model (VRN 2014) and the Healthy Eating Plate (Harvard School of Public Health 2023). We based the

product grouping on the Finnish plate model in our previous study of protein sources (Saarinen et al. 2017; Kyttä et al. 2023), and the natural next step is therefore to evaluate the applicability of the product-group-specific method for the other meal components—vegetables, fruit and berries, and sources of carbohydrates—presented in the Finnish plate model.

The number of nutrients in the index may also be an issue when nutrient indices are used as the nFU. In practice, the indices generally include a limited number of nutrients, because the performance of indices has been found to decline when more than nine nutrients are included when using the indices in their initial purpose as a tool for nutritional education (Fulgoni et al. 2009). However, including quite a limited number of nutrients in the index may lead to an incomplete description of product functionality and differentiation between products. On the other hand, when the product-group-specific approach is used, a large number of nutrients may weaken the distinguishing power of the index in that product group in the same way as in a general index among all products.

In this study, we further develop the product-group-specific approach in nFUs as a method of nLCA. We introduce product-group-specific nutrient indices for vegetables, fruit and berries, and sources of carbohydrates to be used as the nFU. These form a family of product-group-specific nFUs with our previously developed index for protein-rich foods (Kyttä et al. 2023). The use of these nFUs is demonstrated through test nLCAs to help the evaluation of their performance. The performance of the product-group-specific nFUs is also analysed by comparing the results obtained with the family of product-group-specific indices with a reference index that includes all the main nutrients with a nutrition recommendation in Finland. Finally, we give a recommendation for proceeding in the further development and use of the product-group-specific approach.

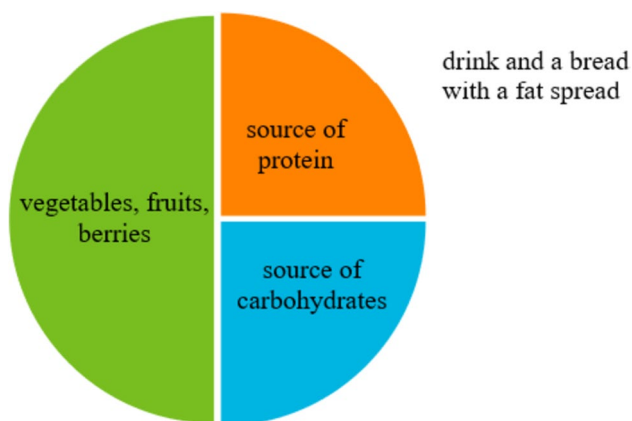
## 2 Materials and methods

### 2.1 Product grouping

In this study, we adapted the same grouping approach that was used in our previous studies (Saarinen et al. 2017; Kyttä et al. 2023) based on the Finnish plate model (Vnk 2014). This approach considers the functionality of the foods in meals and represents the consumer behaviour, because foods that are consumed similarly and are thus substitutable with each other are grouped together (Saarinen et al. 2017). The Finnish plate model (Vnk 2014) is designed based on Finnish and, as such, also on the Nordic nutrition recommendations to guide consumers to compile balanced and healthy meals. The Finnish plate model consists of half a plate of

vegetables, a quarter of a plate of a carbohydrate source, and a quarter of a plate of a protein source, complemented by a drink and a bread with a soft vegetable fat spread (Fig. 1). In this study, we focused on carbohydrate sources and vegetables to expand the consideration to the other main food groups on the plate besides protein sources, while the complementary drinks and spreads were not addressed. Fruit and berries were grouped with vegetables and bread with carbohydrate side dishes, due to their generally similar nutritional function. In this approach, it is important to consider food intake in the dietary context of the target population so that the information produced by the assessment is linked to the real situation (McLaren et al. 2021). It is also important to target the assessment at foods in their edible form, such as peeled and cooked, rather than raw materials (food ingredients), because nutrients are only obtained in that form (Saarinen et al. 2017; McLaren et al. 2021).

While the product grouping was based on the recommendations (i.e. the plate model), the selection of nutrients to the nFUs was based on the current food consumption. There are two critical steps in this approach: the classification of consumed foods into the product groups and the selection of nutrients to be included in the product-group-specific nutrient indices to be used as nFUs. Accordingly, we first classified the food raw material groups reported in the National FinDiet 2017 Survey (Valsta et al. 2018) to the product groups corresponding to the meal component grouping present in the Finnish plate model. In the Finnish dietary context (Valsta et al. 2018), carbohydrate sources include potatoes, pasta, rice, meal grains as a side dish, and various breads, especially wholegrain rye bread and mixed bread. The product group of vegetables, fruit, and berries include raw and cooked vegetables such as cabbages, root



**Fig. 1** The Finnish plate model of a balanced meal used in Finnish national nutrition recommendations (VRN 2014) including half a plate of vegetables, fruit and berries, a quarter of a plate of a carbohydrate source, and a quarter of a plate of a protein source, complemented by a drink and a bread with a soft vegetable fat spread

vegetables, leafy greens, vegetable fruits, raw fruit such as citrus fruit, apples and other fruits, and various wild and cultivated berries.

The nFU indices for each product group included were formatted following the principles presented below. The implementation of these indices as the FU was then tested by assessing the climate impacts of commonly consumed products in each product group. The foods assessed in this study are presented in more detail in Sect. 2.4 and in the supplementary material.

## 2.2 Creating the nutrient indices

The product-group-specific nutrient indices for sources of carbohydrates and vegetables were formatted following the baseline index approach introduced for protein-source foods in our earlier study (Kyttä et al. 2023). The inclusion criterion for nutrients in the index was that the food group under study was one of the most important sources of the selected nutrient in the current Finnish diet, which is a typical Western-type diet. This evaluation was made based on the National FinDiet Survey, which monitors the dietary habits and nutrient intake of the Finnish adult population (Karttinen et al. 2020; Valsta et al. 2018). Following this approach, the nutrient selection of each product group represents the nutrients which are currently obtained from the product group. Therefore, the nFU index enables to evaluate the impacts of changes in the current consumption.

According to this approach, the nutrients in the index for sources of carbohydrates were defined based on the nutrients obtained from cereals and potatoes. Following this principle, the nutrient index for sources of carbohydrates ( $NR-FI_{carb}$ ) included carbohydrates, fibre, iron (Fe), magnesium (Mg), folate, phosphorous (P), and potassium (K). The index for vegetables ( $NR-FI_{veg}$ ) was formatted based on the nutrients obtained from the consumption of vegetables, fruit, and berries, which resulted in fibre, potassium (K), thiamine, and vitamins C, K, and A being selected for the index.

We compared the product-group-specific indices with a reference index to evaluate the performance of product-group-specific indices and to test if the index performance decreased when the number of nutrients in the index was increased, as suggested by Fulgoni et al. (2009). The comparison was made by assessing all the same foods that were assessed using product-group-specific indices that also used the reference index as the nFU and then ranking the final climate impacts per the nFU results of assessed products, from lowest to highest. In addition to the product-group-specific indices for vegetables, fruit and berries, and sources of carbohydrates, we included the nutrient index for protein-source foods, which was developed in our previous study (Kyttä et al. 2023), in the comparison. The nutrient index for protein-source foods (later referred to as  $NR-FI_{prot}$ ) was

formatted based on the nutrients that were obtained from the currently consumed main sources of protein, meaning meat, eggs, and dairy products.

The reference index was formatted following a similar approach to that used by Hallström et al. (2019) by including all the beneficial nutrients that have a daily recommended intake value in Finnish nutrition recommendations (VRN 2014) in the index. This reference index (NR-FI<sub>all</sub>) included 23 nutrients: carbohydrates, proteins, fibre, poly- and monounsaturated fatty acids, calcium, iron, iodine, potassium, magnesium, phosphorus, selenium, zinc, folate, niacin, riboflavin, thiamine, and vitamins A, B6, B12, C, D, and E. Copper was excluded from the index because the National Food Composition Database in Finland (THL 2019) does not report the copper content of foods.

In addition to beneficial nutrients, nutrients to limit were evaluated using the LIM3 index, which includes saturated fatty acids, sodium, and added sugar (Drewnowski 2009), and LIM2 index for protein sources, which includes saturated fatty acids and sodium (Saarinen et al. 2017; Kyttä et al. 2023). The nutrients included in all the indices used as the nFU in this study are summarised in Table 1.

### 2.3 Calculation of nutrient indices

The nutrient indices used as the nFU were calculated using the same formula by Fulgoni et al. (2009) as in previous studies (Saarinen et al. 2017; Kyttä et al. 2023):

$$Index = \sum \frac{Nutrient_i}{DRI_i} \times 100 / \text{number of nutrients in the index},$$

where nutrient<sub>i</sub> is the amount of a selected nutrient in 100 g of a product, and DRI<sub>i</sub> is the recommendation for the daily intake given in nutrition recommendations (VRN 2014). The nutrient index scores were calculated separately for all sexes and age groups, which have their own intake recommendations in the Finnish nutrition recommendations (VRN 2014): men and women aged 10–13, 14–17, 18–30, 31–60, 61–74, and over 75; and children aged 12–23 months, 2–5, and 6–9. No capping at the DRI was used.

To calculate the LIM3 index, we used the same approach applied earlier by Saarinen et al. (2017), where the index was calculated for the amount needed to fulfil the nFU of the assessed food (i.e. reference flow). The LIM index is not used as an FU but as a separate metric to widen the evaluation of the nutritional composition of the foods, as suggested by Saarinen et al. (2017). In other respects, the LIM3 index was calculated similarly to the indices used as the nFU:

$$LIM3 = \sum i = 1 - 3 \frac{Nutrient_i}{DA_i} \times 100/3,$$

where nutrient<sub>i</sub> is the amount of saturated fatty acids, sodium, and added sugar in an amount equal to the reference flow per the nFU, and DA<sub>i</sub> is the daily allowance given in nutrition recommendations (VRN 2014). The scores were calculated for the same population groups as the indices used as the nFU. To evaluate how nutrients affected the interpretation of results in each product group, we recalculated the LIM2 index scores for protein sources per reference flow, as they were calculated per 100 g in the original study (Kyttä et al. 2023).

### 2.4 Demonstrative LCAs of food products

The assessed sources of carbohydrates were baked rye bread, wheat rolls, cooked white pasta, wholegrain pasta, white rice, wholegrain rice, potato, mashed potato made with milk and fat, and mashed potato made with water and fat. The assessed foods in the food group of vegetables, fruit, and berries included raw banana, apple, spinach, cabbage, carrot, salad (tomato-cucumber-lettuce, a third of each ingredient), and cooked broccoli and green beans, and baked beetroot (cooked in oil). The foods were assessed to the point where they were ready to eat, meaning the foods were peeled or cooked if necessary. The nutrient content of the assessed foods was derived from the National Food Composition Database in Finland (THL 2019). The nutrient content of each food is presented in the supplementary material. The sources of protein were previously assessed in Kyttä et al. (2023). The assessed sources of protein were patties and

**Table 1** The nutritional indices used in the study and the nutrients included in each index. The NR-FI<sub>prot</sub> index is adapted from a previous study by Kyttä et al. (2023)

Index	Nutrients included
NR-FI <sub>carb</sub>	Carbohydrates, fibre, Fe, Mg, P, K, and folate
NR-FI <sub>veg</sub>	Fibre, K, thiamine, vitamins C, K, and A
NR-FI <sub>prot</sub>	Proteins, Ca, Fe, Se, Zn, vitamins B6 and B12, niacin, riboflavin, and thiamine
NR-FI <sub>all</sub>	Carbohydrates, proteins, fibre, poly- and monounsaturated fatty acids, Ca, Fe, iodide, K, Mg, P, Se, Zn, folate, niacin, riboflavin, thiamine, and vitamins A, B6, B12, C, D, and E
LIM3	Saturated fatty acids, sodium, and added sugar
LIM2	Saturated fatty acids and sodium

balls made with beef, pork, broiler, trout, perch, chickpea, soya mince, or pulled oats (a Finnish protein-rich meat substitute containing oats, peas, and fava beans) as the main ingredients. These foods were also assessed to the point where they were ready to eat. In the case of protein sources, it typically means that other ingredients are added according to the recipe to complement the food item.

The LCA of vegetables, fruit and berries, and sources of carbohydrates was done similarly to the assessment of protein-rich foods in Kytta et al. (2023). The climate impacts were first assessed for 100 g of food, and it was then divided by the nutrient index scores for the same amount of a product to get the final climate impact per the nFU scores for the products. Thus, the nFU used was a unit of the nutrient index. The amount of product needed to fulfil the FU (i.e. reference flow) varies between products and population groups when using nFUs. The information about reference flows is useful when the results of the nLCA are interpreted (Saarinen et al. 2017), and we therefore also calculated the reference flows for each studied product and population group.

The system boundary of the assessment was from cradle to plate, i.e. to foods ready to eat. The assessment was made using SimaPro software and characterisation factors from the IPCC Fifth Assessment Report (IPCC 2013). Data from the Agrifootprint (economic allocation), World-FoodDatabase, and ecoinvent databases were used for the primary production of foods (Blonk 2022; Nemecek et al. 2019; Wernet et al. 2016). For vegetables produced in a

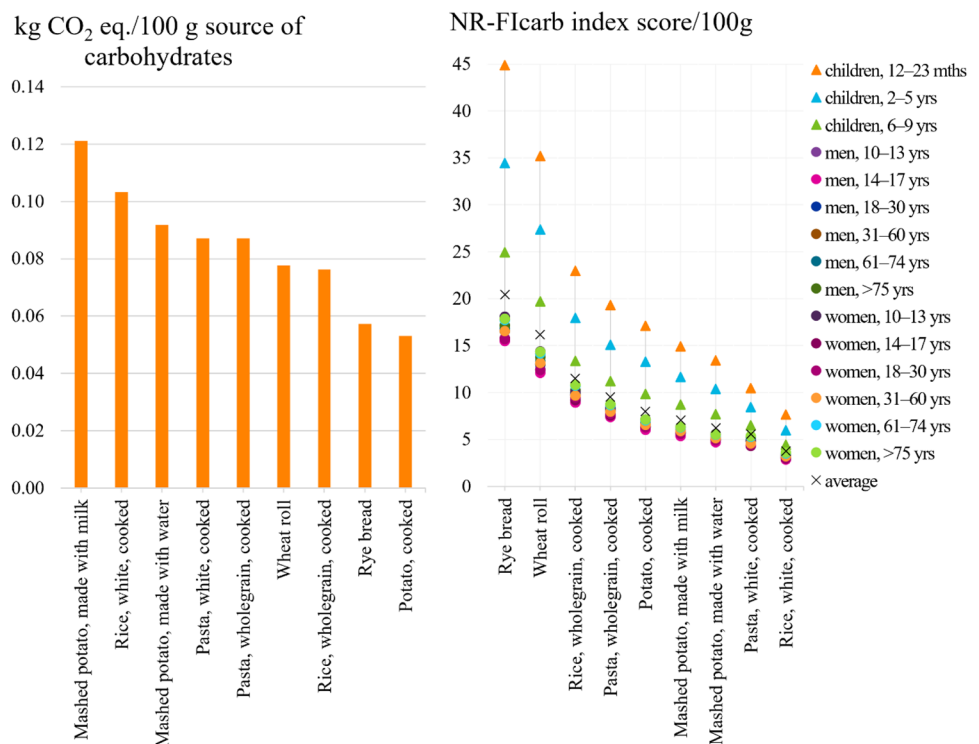
greenhouse, the Finnish data from Silvenius and Katajajuuri (2021) were used. As only some of the assessed foods are grown in Finland, the countries of origin varied depending on the product. A detailed description of all data and data sources used for each product is presented in the supplementary material. The emissions associated with packaging, transport to a distribution centre, and retail were derived from Clune et al. (2017). The energy consumption of cooking was derived from Frankowska et al. (2020). To unify the energy consumption between recipes, the energy consumption was adjusted to 1 kg of raw products. The share of inedible parts such as peel was assessed based on Finnish food measures (Sääksjärvi and Reinivuo 2004).

### 3 Results

#### 3.1 Climate impacts and index scores per 100 g of product

From the assessed sources of carbohydrates, the climate impacts of cooked potato and rye bread were lowest, and mashed potato made with milk and cooked white rice were highest, when assessed per 100 g of product (Fig. 2). The nutrient index scores per 100 g assessed with the NR-FIcarb index varied between the assessed population groups, being highest for children and lowest for men (Fig. 2). The nutrient index scores were lowest for white rice and white pasta and highest for rye bread and wheat rolls.

**Fig. 2** Climate impact per 100 g (kg CO<sub>2</sub> eq./100 g) and the nutrient index scores (per 100 g) of assessed sources of carbohydrates in descending order. The higher the result of the nutritional index, the more the product contains nutrients selected for the index in relation to the recommended intake



In the product group of vegetables, fruit, and berries, mixed salad had the highest climate impact per 100 g, more than twice that of other foods (Fig. 3) due to greenhouse-grown ingredients. The cooked foods baked beetroot and broccoli also had higher climate impacts than other foods, whereas the climate impacts of cooked green beans were at the same level as banana and strawberry. In contrast, the climate impact of spinach was the lowest. Spinach also had a notably higher NR-FIveg nutrient index score, which was more than twice that of the other assessed foods in the product group (Fig. 3). In contrast, the assessed fruit (banana and apple) had the lowest nutrient index scores.

### 3.2 Climate impacts per nFU

The climate impact per nFU of cooked white rice was the highest of all studied products, contributed to by the lowest nutrient content and second highest climate impact per 100 g of the assessed sources of carbohydrates (Fig. 4). Consequently, the high nutrient index scores and relatively low climate impacts per 100 g of breads resulted in the lowest climate impact per nFU, less than 20% of that for cooked white rice. Wholegrain rice, pasta, and potato also had a relatively low climate impact per nFU, less than 35% of the impact of cooked white rice.

In the product group of vegetables, fruit, and berries, mixed salad had the highest climate impact per 100 g

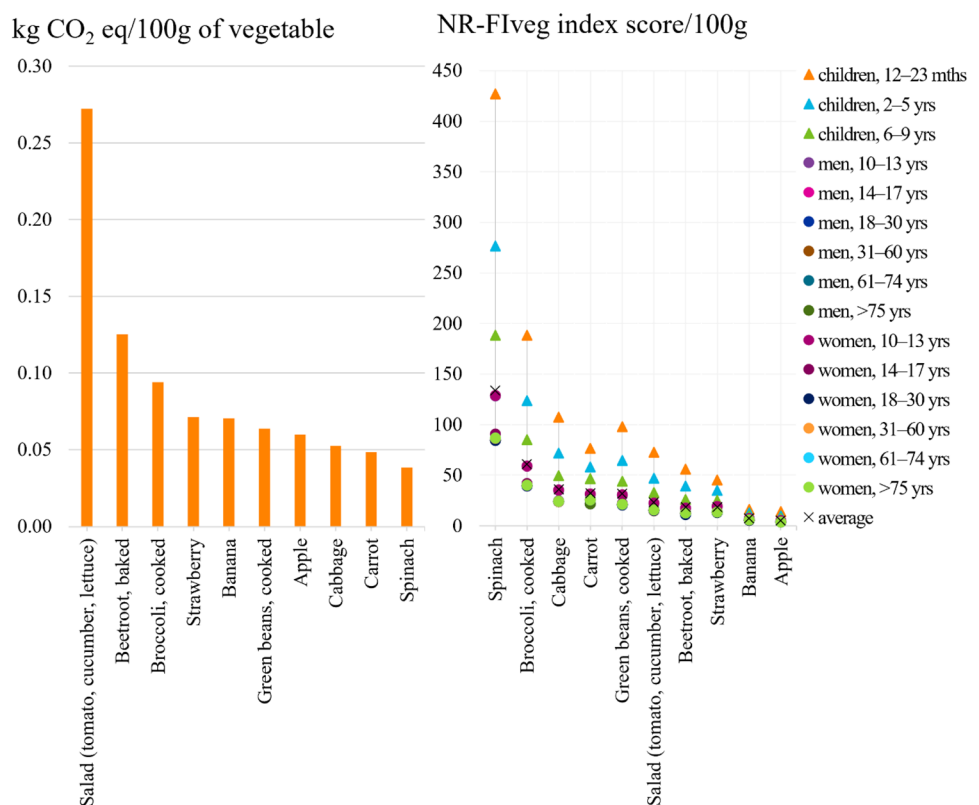
(Fig. 5), and the climate impact per nFU was therefore also the highest of all assessed foods in the product group. In contrast, the climate impact of spinach per nFU was only 2% of that for salad, which was contributed to especially by the highest nutrient index score. In contrast, banana and apple had the lowest nutrient index scores, leading also to a relatively high climate impact per nFU. The baked beetroot had the second highest climate impact per 100 g, leading to a relatively high climate impact per nFU, whereas other cooked foods had relatively low climate impacts per nFU.

### 3.3 Reference flows

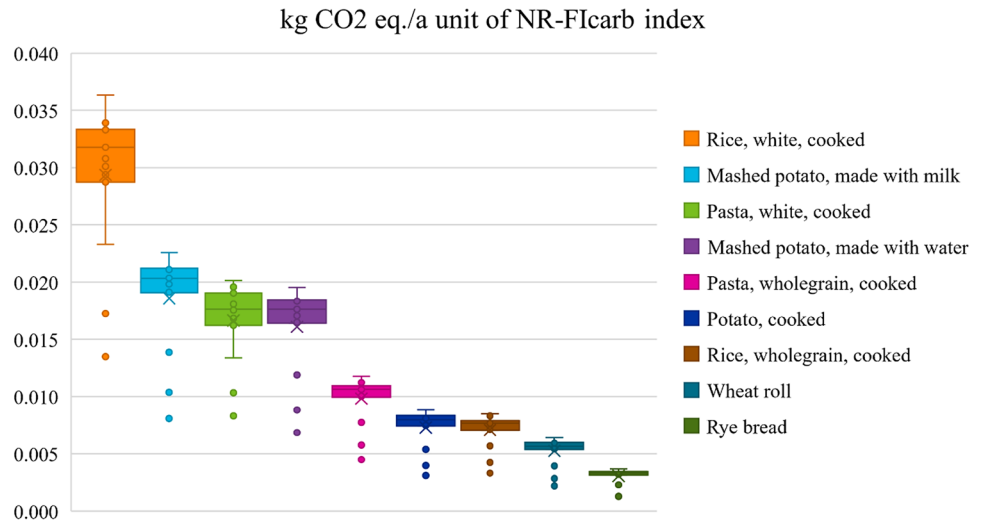
The amounts of products needed to provide the nutrition equal to a unit of NR-FIcarb index (reference flows) varied between population groups due to the different recommended daily intakes of nutrients for the population groups (Table 2). The reference flows for children and young people (under 14 years) especially differed from those for the rest of the population, but the elderly (> 75 years) also differed from the rest of the adult population. Because white rice and pasta had the lowest nutrient content measured with the NR-FIcarb index, the reference flow of a unit of NR-FIcarb index is also the highest. In contrast, the reference flows of breads equal to a unit of NR-FIcarb index were the lowest.

Similarly, for sources of carbohydrates, the reference flows equal to a unit of NR-FIveg index were lower for

**Fig. 3** Climate impact per 100 g (kg CO<sub>2</sub> eq./100 g) and the nutrient index scores (per 100 g) of assessed vegetables in descending order. The higher the result of the nutritional index, the more the product contains nutrients selected for the index in relation to the recommended intake



**Fig. 4** Climate impact per nFU (kg CO<sub>2</sub> eq./a unit of NR-FI<sub>carb</sub> index), the lowest results being those for children due to lower nutrient intake recommendations. The cross represents the mean, and the line the median, of the population groups



children, young people, and the elderly than for the rest of the adult population (Table 3). Due to the high nutrient content, the reference flow of spinach was the lowest per unit of the NR-FI<sub>veg</sub> index, and banana and apple therefore had the highest reference flows.

### 3.4 LIM index scores

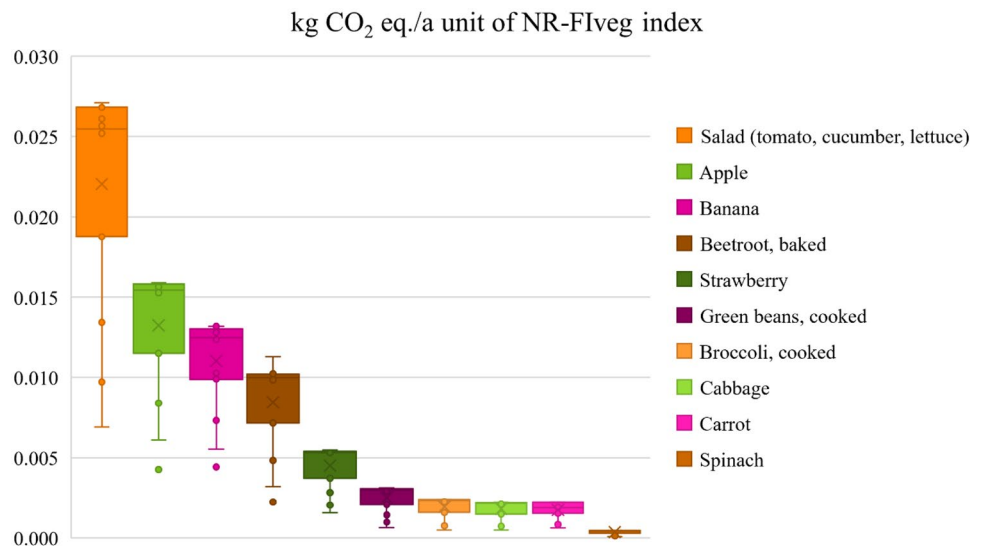
The LIM3 index scores per reference flow of assessed sources of carbohydrates were generally low due to the low content of saturated fatty acids, sodium, and added sugar in the foods (Table 4). Wheat rolls and rye bread had notably higher LIM3 index scores than the other foods because the bread recipes included added sugar in the form of syrup. Mashed potatoes also had higher LIM3 scores than cooked pasta, potato, and rice due to the salt in the recipe. The differences between the population groups were relatively

small, the scores for children being slightly lower for some foods such as bread and higher for some foods such as wholegrain rice and cooked potato.

The LIM3 index scores for vegetables, fruit, and berries were low, because the content of saturated fatty acids, sodium, and added sugar in the assessed foods is inherently low (Table 5). Baked beetroot had a notably higher index score than other foods, which was due to the salt included in the recipe used in this calculation. The index scores for children were slightly lower than those of the adult population for all the assessed foods.

In the case of protein sources, the LIM2 index scores per reference flow showed great variation, the scores for plant-based foods being notably higher than the scores for the other assessed foods (Table 6). The scores for children were higher than those of the adult population, especially for plant-based foods.

**Fig. 5** Climate impact per nFU (kg CO<sub>2</sub> eq./a unit of NR-FI<sub>veg</sub> index), the lowest results being the ones for children due to lower nutrient intake recommendations. The cross represents the mean, and the line the median, of the population groups



**Table 2** Reference flow (product in grams) equal to a unit of NR-FI<sub>carb</sub> index in descending order

Reference flow (grams)/unit of NR-FI <sub>carb</sub>	Rice, white, cooked	Pasta, white, cooked	Mashed potato, made with water	Mashed potato, made with milk	Potato, cooked	Pasta, wholegrain, cooked	Rice, wholegrain, cooked	Wheat roll	Rye bread
Children, 12–23 mths	13.1	9.6	7.5	6.7	5.8	5.2	4.4	2.8	2.2
Children, 2–5 yrs	16.7	11.9	9.6	8.6	7.5	6.6	5.6	3.7	2.9
Children, 6–9 yrs	22.6	15.4	13.0	11.5	10.1	8.9	7.5	5.1	4.0
Men, 10–13 yrs	30.8	20.8	18.6	16.4	14.5	12.2	10.1	7.1	5.6
Men, 14–17 yrs	35.2	22.9	21.3	18.7	16.7	13.5	11.2	8.3	6.5
Men, 18–30 yrs	32.9	20.8	20.1	17.5	15.7	12.5	10.3	7.7	6.1
Men, 31–60 yrs	32.3	20.6	20.0	17.4	15.6	12.4	10.2	7.7	6.0
Men, 61–74 yrs	31.2	20.2	19.7	17.2	15.4	12.3	10.1	7.5	6.0
Men, > 75 yrs	29.2	19.3	19.2	16.8	15.0	12.0	9.8	7.3	5.8
Women, 10–13 yrs	29.9	20.3	17.9	15.8	14.0	12.0	10.0	7.0	5.5
Women, 14–17 yrs	33.3	23.1	20.2	17.7	15.8	13.3	10.9	8.0	6.3
Women, 18–30 yrs	32.3	22.5	20.3	17.6	15.9	12.9	10.5	8.0	6.4
Women, 31–60 yrs	31.1	21.9	19.5	17.0	15.3	12.6	10.3	7.6	6.1
Women, 61–74 yrs	28.5	18.9	18.1	15.9	14.2	11.5	9.3	7.1	5.6
Women, > 75 yrs	27.9	18.7	18.0	15.8	14.1	11.5	9.2	7.0	5.6

### 3.5 Comparison of product-group-specific indices with the reference index

Using product-group-specific nutrient indices like the nFU led to a somewhat different order of products than using the reference NR-FI<sub>all</sub> index, when the foods are ranked based on climate impact per nFU (Tables 7, 8, 9). For vegetables, the ranking was the same, regardless of the nFU used, but in the product group of sources of carbohydrates, the ranking of mashed potato made with milk and cooked white pasta and the ranking of cooked potato and wholegrain rice were reversed when the reference index NR-FI<sub>all</sub> was used as the FU instead of a product-group-specific index.

Using the product-group-specific nutrient index instead of the reference index changed the ranking of products especially in the product group of sources of protein. Using the product-group-specific index (NR-FI<sub>prot</sub>) as the nFU led to the trout patty having the lowest climate impacts, whereas using the reference index with all nutrients (NR-FI<sub>all</sub>) gave it a ranking of five out of eight

(Table 9). In turn, the reference index NR-FI<sub>all</sub> resulted in a higher ranking of the plant-based foods chickpea ball and soya meal ball, as well as perch patty.

While the ranking of products remained somewhat similar in the product groups of vegetables, fruit and berries, and sources of carbohydrates, the relative differences between products differed from the results obtained with product-group-specific FU (Supplementary Material, Figs. S1 and S2), the reference index NR-FI<sub>all</sub> leading to relatively lower climate impacts for foods that contained more than one ingredient (mashed potatoes and baked beetroot).

In absolute terms, the product-group-specific index scores for different foods were notably higher than the reference index NR-FI<sub>all</sub> scores, being 2.5 times higher on average (Supplementary Material, Table S5). The climate impact per nFU was therefore higher when a reference index was used as the functional unit. The only exception was chickpea ball, which received a higher index score and therefore a lower climate impact per nFU when the reference index NR-FI<sub>all</sub> was used.



**Table 3** Reference flow (product in grams) equal to a unit of NR-FIveg index in descending order

Reference flow (grams)/ unit of NR-FIveg index	Apple	Banana	Beetroot, baked	Strawberry	Salad (tomato, cucumber, lettuce)	Green beans, cooked	Carrot	Cabbage	Broccoli, cooked	Spinach
Children, 12–23 mths	7.1	6.3	1.8	2.2	1.4	1.0	1.3	0.9	0.5	0.2
Children, 2–5 yrs	10.2	7.8	2.6	2.9	2.1	1.5	1.7	1.4	0.8	0.4
Children, 6–9 yrs	14.1	10.4	3.8	4.0	3.1	2.3	2.2	2.0	1.2	0.5
Men, 10–13 yrs	19.5	14.5	5.8	5.2	4.5	3.3	3.2	2.9	1.7	0.8
Men, 14–17 yrs	26.6	18.7	8.2	7.6	6.7	4.8	4.6	4.2	2.5	1.2
Men, 18–30 yrs	26.6	18.7	8.2	7.6	6.7	4.8	4.6	4.2	2.5	1.2
Men, 31–60 yrs	26.5	18.6	8.1	7.5	6.6	4.8	4.6	4.2	2.5	1.2
Men, 61–74 yrs	26.5	18.4	8.1	7.5	6.6	4.8	4.6	4.2	2.5	1.2
Men, > 75 yrs	26.5	18.4	8.1	7.5	6.6	4.8	4.6	4.2	2.5	1.2
Women, 10–13 yrs	19.3	14.0	5.7	5.2	4.5	3.3	3.2	2.8	1.7	0.8
Women, 14–17 yrs	25.5	17.8	7.9	7.4	6.2	4.6	3.9	4.0	2.4	1.1
Women, 18–30 yrs	26.2	18.1	9.0	7.7	6.6	4.9	3.9	4.2	2.5	1.2
Women, 31–60 yrs	26.0	17.6	8.0	7.5	6.4	4.7	3.9	4.2	2.5	1.2
Women, 61–74 yrs	25.8	17.5	8.0	7.4	6.4	4.7	3.9	4.2	2.5	1.2
Women, > 75 yrs	25.8	17.5	8.0	7.4	6.4	4.7	3.9	4.2	2.5	1.2

### 4 Discussion

In this study, we have extended the product-group-specific approach to nutritional functional units (nFU) by using the

same methodology for two new product groups, i.e. sources of carbohydrates and vegetables, fruit, and berries, than previously used for protein sources (Kyttä et al. 2023). In the following, we evaluate the key methodological issues that

**Table 4** LIM3 index scores (per reference flow of unit of NR-FIcarb index (Table 2) of assessed sources of carbohydrates, in descending order. The index assesses the intake of saturated fatty acids, sodium, and added sugar in relation to the daily allowance

LIM3 index score/unit of NR-FIcarb index	Wheat roll	Rye bread	Potato, cooked	Rice, wholegrain, cooked	Mashed potato, made with water	Rice, white, cooked	Pasta, white, cooked	Mashed potato, made with milk	Pasta, wholegrain, cooked
Children, 12–23 mths	2.29	0.52	0.53	0.43	0.053	0.049	0.039	0.027	0.020
Children, 2–5 yrs	2.21	0.51	0.45	0.36	0.051	0.047	0.035	0.025	0.018
Children, 6–9 yrs	2.24	0.52	0.57	0.45	0.051	0.047	0.035	0.026	0.019
Men, 10–13 yrs	2.31	0.54	0.50	0.38	0.053	0.047	0.034	0.026	0.019
Men, 14–17 yrs	2.13	0.48	0.55	0.40	0.049	0.043	0.030	0.024	0.017
Men, 18–30 yrs	2.00	0.46	0.52	0.37	0.047	0.041	0.028	0.023	0.015
Men, 31–60 yrs	2.11	0.49	0.52	0.37	0.049	0.042	0.029	0.024	0.016
Men, 61–74 yrs	2.35	0.54	0.53	0.37	0.054	0.046	0.031	0.026	0.018
Men, > 75 yrs	2.78	0.65	0.53	0.38	0.064	0.051	0.036	0.031	0.021
Women, 10–13 yrs	2.45	0.57	0.49	0.38	0.055	0.049	0.035	0.027	0.020
Women, 14–17 yrs	2.48	0.57	0.54	0.40	0.055	0.048	0.036	0.027	0.019
Women, 18–30 yrs	2.59	0.60	0.54	0.39	0.057	0.048	0.036	0.028	0.019
Women, 31–60 yrs	2.62	0.61	0.53	0.39	0.058	0.050	0.037	0.028	0.020
Women, 61–74 yrs	2.63	0.62	0.50	0.36	0.059	0.049	0.034	0.028	0.020
Women, > 75 yrs	2.78	0.65	0.50	0.36	0.062	0.051	0.036	0.030	0.021

**Table 5** LIM3 index scores per reference flow needed to fulfil the unit of the NR-Flveg index (presented in Table 3) of assessed vegetables, fruit, and berries, in descending order. The index assesses the intake of saturated fatty acids, sodium, and added sugar in relation to the daily allowance

LIM3 index score/unit of NR-Flveg index	Beetroot, baked	Banana	Apple	Carrot	Salad (tomato, cucumber, lettuce)	Strawberry	Cabbage	Broccoli, cooked	Green beans, cooked	Spinach
Children, 12–23 mths	0.386	0.035	0.026	0.019	0.010	0.009	0.005	0.005	0.004	0.003
Children, 2–5 yrs	0.353	0.031	0.028	0.016	0.011	0.009	0.006	0.005	0.005	0.003
Children, 6–9 yrs	0.516	0.034	0.029	0.019	0.014	0.009	0.007	0.006	0.006	0.004
Men, 10–13 yrs	0.469	0.032	0.029	0.018	0.013	0.009	0.006	0.006	0.006	0.004
Men, 14–17 yrs	0.645	0.035	0.032	0.024	0.017	0.011	0.008	0.008	0.007	0.005
Men, 18–30 yrs	0.645	0.036	0.032	0.024	0.017	0.011	0.008	0.008	0.007	0.005
Men, 31–60 yrs	0.648	0.037	0.034	0.024	0.018	0.011	0.008	0.008	0.007	0.005
Men, 61–74 yrs	0.654	0.039	0.038	0.025	0.019	0.012	0.009	0.009	0.008	0.006
Men, > 75 yrs	0.669	0.045	0.046	0.026	0.021	0.014	0.010	0.009	0.009	0.006
Women, 10–13 yrs	0.467	0.032	0.031	0.018	0.013	0.009	0.007	0.006	0.006	0.004
Women, 14–17 yrs	0.632	0.038	0.036	0.021	0.017	0.012	0.009	0.008	0.008	0.005
Women, 18–30 yrs	0.728	0.039	0.038	0.022	0.019	0.013	0.009	0.009	0.008	0.006
Women, 31–60 yrs	0.649	0.040	0.041	0.022	0.019	0.013	0.010	0.009	0.009	0.006
Women, 61–74 yrs	0.654	0.042	0.044	0.022	0.020	0.014	0.010	0.009	0.009	0.006
Women, > 75 yrs	0.659	0.043	0.046	0.023	0.020	0.015	0.010	0.009	0.010	0.006

**Table 6** LIM2 index scores per reference flow needed to fulfil the unit of the NR-FI<sub>prot</sub> index in descending order. The scores are recalculated from a previous study on protein sources (Kyttä et al. 2023).

The index assesses the intake of saturated fatty acids and sodium in relation to the daily allowance

LIM2 index score/unit of NR-FI <sub>prot</sub> index	Pulled oats ball	Chickpea ball	Soya mince ball	Beef patty	Pork patty	Broiler patty	Perch patty	Trout patty
Children, 12–23 mths	2.82	2.27	1.34	0.89	0.76	0.60	0.56	0.11
Children, 2–5 yrs	2.21	1.50	1.05	0.80	0.66	0.51	0.47	0.10
children, 6–9 yrs	2.84	1.90	1.32	0.92	0.78	0.67	0.64	0.12
Men, 10–13 yrs	2.12	1.43	1.02	0.83	0.66	0.54	0.54	0.12
Men, 14–17 yrs	2.45	1.66	1.20	0.89	0.77	0.66	0.60	0.12
Men, 18–30 yrs	2.19	1.46	1.08	0.82	0.73	0.64	0.58	0.11
Men, 31–60 yrs	2.14	1.44	1.05	0.81	0.71	0.62	0.58	0.11
Men, 61–74 yrs	2.11	1.42	1.02	0.88	0.72	0.60	0.60	0.13
Men, > 75 yrs	1.95	1.37	0.97	0.92	0.76	0.57	0.58	0.15
Women, 10–13 yrs	1.98	1.33	0.94	0.80	0.64	0.51	0.52	0.12
Women, 14–17 yrs	2.41	1.60	1.13	0.87	0.70	0.58	0.58	0.13
Women, 18–30 yrs	2.27	1.47	1.04	0.80	0.65	0.55	0.56	0.13
Women, 31–60 yrs	2.21	1.45	1.01	0.82	0.67	0.54	0.54	0.12
Women, 61–74 yrs	1.88	1.25	0.89	0.83	0.68	0.52	0.53	0.12
Women, > 75 yrs	1.82	1.25	0.90	0.87	0.69	0.57	0.54	0.14

are still open in this emerging field to advance the development of the approach. This is done by analysing the applied methodological details and the results of demonstrative nLCAs for a set of products belonging to the above product groups. We discuss the performance of product-group-specific nutrient indices for sources of carbohydrates and vegetables, fruit, and berries used as the nFU in terms of how they differentiate the products within the groups and in relation to the mass-based FU and nutrient index scores as follows: the effect of the number of nutrients in the nFUs, the nutrient selection for the nFUs, product grouping, and the strengths and limitations of our approach. However, it is worth keeping in mind that generalisations based on the results of individual products in this study should be made with caution, because both the climate impacts and nutrition content of the assessed foods are highly affected by the choices made, for example, in the choice of recipe.

#### 4.1 Performance of new nutritional functional units

The demonstrative LCAs and comparison of food products within the product groups of vegetables, fruit and berries,

and sources of carbohydrates showed a notable difference between using mass-based FUs and nFUs, as also highlighted in previous nLCA studies on protein sources (e.g. Saarinen et al. 2017; Hallström et al. 2019). The results demonstrated that the product-group-specific nFUs are effective in differentiating food products based on their environmental impacts in relation to nutritional content.

In the product group of the sources of carbohydrates, bread, potato, and wholegrain pasta and rice resulted in lower climate impacts per nFU than mashed potatoes, white rice, and white pasta due to higher nutrient index scores. Using the product-group-specific index NR-FI<sub>carb</sub> as the nFU especially differentiated white rice from the other foods because of low nutrient content and a relatively high climate impact. In the product group of vegetables, fruit, and berries, the climate impact per nFU was especially low for spinach due to the significantly high index score and especially high for mixed salad due to the high climate impact per 100 g. The climate impacts of fruit were at the same level as other foods within the product group per 100 g, but because of the low nutrient index scores, the climate impacts per nFU were relatively high

**Table 7** Climate impact per nFU of assessed carbohydrate-rich foods, using product group specific index (NR-FI<sub>carb</sub>) and reference index NR-FI<sub>all</sub>, including all nutrients, ranked from lowest (1) to highest (9)

	Rye bread	Wheat roll	Rice, wholegrain, cooked	Potato, cooked	Pasta, wholegrain, cooked	Mashed potato, made with water	Pasta, white, cooked	Mashed potato, made with milk	Rice, white, cooked
NR-FI <sub>carb</sub>	1	2	3	4	5	6	7	8	9
NR-FI <sub>all</sub>	1	2	4	3	5	6	8	7	9

**Table 8** Climate impact per nFU of assessed vegetables, fruit and berries, and fruit and vegetables, using a product-group-specific index (NR-FI<sub>veg</sub>) and reference index NR-FI<sub>all</sub>, including all nutrients, ranked lowest (1) to highest (10)

	Spinach	Carrot	Cabbage	Broccoli, cooked	Green beans, cooked	Strawberry	Beetroot, baked	Banana	Apple	Salad (tomato, cucumber, lettuce)
NR-FI <sub>veg</sub>	1	2	3	4	5	6	7	8	9	10
NR-FI <sub>all</sub>	1	2	3	4	5	6	7	8	9	10

compared to other foods. These results are very compatible with the previous understanding of these products' climate impacts and nutritional aspects. However, more research is needed on the validation of the nutrient indices used as nFUs.

It was also demonstrated that the system boundary remarkably affected the relative results between products. In this study, we used a cradle-to-plate system boundary, meaning that some vegetables which are typically not consumed raw were assumed to be cooked. The inclusion of the cooking phase affects the results of individual foods because it can increase the climate impact considerably, which happened with baked beetroot in this study, for example. In our previous study on protein sources (Kyttä et al. 2023), this was also demonstrated between raw materials and final edible products. This underlines the fact that system boundaries should be carefully considered and justified in nLCA applications (McLaren et al. 2021; Saarinen et al. 2017). When the study takes the consumer's perspective, reaching the boundary for edible products would provide the most comprehensive assessment.

According to the results, the nutrient index scores and consequently the climate impacts of products per nFU varied, depending on the population group under study in the same way as for protein sources in our previous study (Kyttä et al. 2023). The nutrient index scores for children especially differ consistently from those of the adult population due to the lower daily recommended intake of nutrients, but the elderly population also has special nutritional needs. In studies where nutritional aspects are combined with the environmental impacts of products or diets, the reference population is generally the adult population or an average population (e.g. Hallström et al. 2019; Springmann et al. 2020). General instructions are typically given for diets and dietary changes based on these studies (e.g. Bianchi et al.

2022). The results of this study strengthened the evidence that more attention should be paid to vulnerable population groups such as children when addressing the environmental impacts in dietary practices.

#### 4.2 Inclusion of index for nutrients to limit and a reference flow

In addition to the nutrient indices including nutrients to encourage, we assessed the intake of nutrients to limit from foods by using LIM3 index per unit nFU for sources of carbohydrates and the product group of vegetables, fruit, and berries, as well as LIM2 index per unit nFU for protein sources to widen the consideration of nutritional composition of foods. This method is suggested by Saarinen et al. (2017) because a low environmental impact per nFU alone does not indicate the nutrient-derived healthiness of the food. The LIM2 index, including salt and saturated fatty acids, was used for the protein sources because these products do not usually contain added sugar, which was therefore excluded in accordance with the principles of the product-group-specific approach. In some cases, however, the protein source foods can also include added sugars, and using LIM3 index to assess nutrients to limit may be more appropriate.

According to our result, among the assessed sources of carbohydrates, bread, including added sugar, and mashed potatoes made with milk or water and including added salt and fat, obtained the highest LIM3 index scores. Additionally, bread is among the biggest sources of salt in Finnish diet due to its relatively high consumption, although this did not affect the calculation. This weakens the status of bread as a sustainable product, interpreted in terms of the product's climate impacts per nFU. The same was seen to some extent in the case of baked beetroot, for which the LIM index score was highest in that product group of vegetables,

**Table 9** Climate impacts per nFU of assessed foods, using the product-group-specific index (NR-FI<sub>prot</sub>) and reference index NR-FI<sub>all</sub>, including all nutrients ranked from lowest (1) to highest (8)

	Trout patty	Perch patty	Pulled oats ball	Pork meatball	Soya mince ball	Chickpea ball	Broiler meatball	Beef meatball
NR-FI <sub>prot</sub>	1	2	3	4	5	6	7	8
NR-FI <sub>all</sub>	5	1	4	6	3	2	7	8

fruit, and berries. In this case, the climate impact per nFU was also quite high, and LIM therefore did not affect the relative ranking of the product as much. However, the LIM3 index scores per unit of the nFU for assessed foods in these product groups were generally low because they are inherently low in saturated fatty acids, and most of the foods did not include added salt or sugar.

For protein sources, the LIM2 index scores calculated per unit of nFU weaken the status of chickpea and pulled oats balls as a sustainable product, interpreted in terms of the product's climate impacts per nFU (Kyttä et al. 2023). The high LIM index scores are due to the recipes for these foods that were high in salt. Instead, LIM2 scores for other protein sources were low and at the same level between products from both animal and plant-based raw materials. This is partly contrary to LIM2 index scores calculated per 100 g (Kyttä et al. 2023). In that comparison, chickpea balls had by far the highest LIM score, but the score for pulled oats was moderate within the assessed foods, with beef and pork, and LIM2 scores for some fish-based products were lowest, followed by broiler (Kyttä et al. 2023). Thus, the calculation method, whether it is based on 100 g or the nFU unit, clearly affects the results. The method based on the nFU unit is recommended for assessments using nFUs because the LIM calculation is then based on the same unit as the nLCA itself (Saarinen et al. 2017).

In interpreting the results, it is important to take into account that the nutrients to limit are often added in the cooking phase of foods, and it is therefore quite easy to influence the LIM index scores in practice (Kyttä et al. 2023). Moreover, regarding this study's results, the fact is that the LIM index scores are affected by the choice of recipe in which the amount of salt varied, for example. However, in the protein sources, the effect of the unsaturated fatty acids in the product itself on the LIM index scores is much more difficult to influence.

Furthermore, the LIM index score calculated per nFU unit depends on the nFU index used, and the indices that result in high index scores therefore tend to result in lower LIM indices because the LIM index is calculated for a smaller amount of a product, with probably a smaller harmful nutrient content, and vice versa. Unlike the climate impact of foods per nFU, the LIM index scores for foods for children do not differ from those for adults. It is quite logical, because the amount of food from which the LIM is estimated changes at the same time as the recommended amount of limiting nutrients changes along the age groups.

In interpreting and communicating the results obtained with nFUs, the variation in the volume of reference flows (RF) for different foods should also be considered (Saarinen et al. 2017; McLaren et al. 2021). When a typical mass-based FU is used in the LCA, the reference flow is the same as the FU. When using nFUs, the RFs of compared products differ, and they also differ in relation to a typical portion size of a product. For

example, in the product group of vegetables, fruit, and berries, apples were needed 25-fold more in quantity than spinach to fulfil the nFU, indicating that spinach is a much more nutrient-dense food than apples.

A typical portion size varies between products, and in the case of apples and spinach, it is much larger for apples than for spinach. The question should therefore be which product should be eaten more, and which should be eaten less, to obtain more nutritional benefits and less environmental harm. Indeed, the consumption pattern for spinach differs markedly from other vegetables, fruit, and berries. The actual portion size of spinach is rather low, rarely reaching 100 g per meal. In our results, spinach was the best-performing food, and an increase of its consumption could therefore be recommended. However, it should be noted that the nLCA does not take into account the current consumption pattern, and one must therefore be careful when interpreting the results and separating them from the contribution of foods to the climate impacts of diets or the total intake of nutrients. This product-level approach provides information about the intrinsic composition of the products, not total nutrient intakes, or the role of a product in it. The nLCA also does not consider the potential risks related to foodstuffs and the recommendations of correct use. For example, consumption of vegetables high in nitrate (e.g. spinach and beetroot) is instructed to be avoided by infants (Finnish Food Authority 2022), even though the results of our assessment would suggest increasing the consumption.

### 4.3 Impact of the number of nutrients in the nutritional functional units

In our approach, the number of nutrients in the nFUs differed between the product-group-specific indices and the reference index, being seven (7) for carbohydrate sources; six (6) for vegetables, fruit, and berries; ten (10) for protein sources; and twenty-three (23) for the reference index.

In general, product-group-specific indices resulted in higher index scores for the assessed food products than the reference index. There were also larger relative and absolute differences in the nutrient index scores for products within the product groups based on the product-group-specific indices than the reference index (Supplementary Material, Table S5). This indicates that the product-group-specific indices have a higher distinguishing power than the reference index, which includes more nutrients. This is in line with Fulgoni et al. (2009), who found that the performance of indices tended to decline with an increased number of nutrients from nine nutrients when using the indices in their initial purpose as a tool for nutritional education. The relative difference was especially high in vegetables, fruit, and berries, as well as protein sources (Supplementary Material, Fig. S1), referring to more specialised nutrient content in these product groups than in carbohydrate sources. This

supports the use of product-group-specific nutrient indices like the nFU, particularly for those product groups to maintain the distinguishing power based on nutritional composition differences, and for consistency, perhaps also in other product groups.

Our results also indicate that product-group-specific indices consist of the nutrients that are relevant for the product group in question because other nutrients reduced the score. In other words, the assessed foods (which are considered to be included in these product groups) contained the nutrients identified as important to the corresponding product groups more extensively than other nutrients. On the other hand, including a quite limited number of nutrients in the index may also lead to an incomplete description of product functionality and differentiation between products in some situations. For example, the use of the general NRF9 index by Fulgoni et al. (2009) has been argued to favour plant-based products unjustifiably when compared to animal-source foods due to the exclusion of some essential micronutrients from the index that are abundant in animal products, but less so in plant products (McAuliffe et al. 2020). This supports the use of product-group-specific nFUs which can address the nutrients so that the chosen product group is an important source instead of more generic nutrient indices.

The higher index scores produced by product-group-specific indices therefore led to a lower climate impact per nFU compared to using the reference nutrient index as the nFU. This does not really have consequences for the interpretation because the assessment of the products and comparisons between products are supposed to take place within the functionality of the product group. In other words, in the product assessment and comparison between the products, the environmental impacts are assessed in relation to their nutritional performance in the nutritional functionality of the product group in question. Comparisons between a product-group-specific and a reference nutrient index, for example, or between different product-group-specific nutrient indices, should therefore not be made, and scale differences in absolute terms are therefore irrelevant.

Instead, differences in rankings based on different nutrient indices like the nFU are relevant for consideration of the performance of the indices. According to our results, product-group-specific nFUs led to a similar ranking of the environmental impacts of foods as the reference index for carbohydrate sources and vegetables, fruit, and berries. This does not particularly support the use of a product-group-specific approach. However, there were more differences in the ranking of protein sources based on the product-group-specific index and the reference index. This highlights the fact that the differences in the product-group-specific nutritional composition (i.e. nutritional composition in relation to the nutritional functionality of the product group) can differ from the generic nutritional composition so greatly

that it is visible in the rankings between the products. This supports the use of product-group-specific nutrient indices as the nFU if the product grouping in question is accepted to reflect consumers' eating and product selection habits. The role of product grouping is discussed further in Sect. 4.4.

#### 4.4 Product grouping

In this study, the plate model provided by the Finnish nutrition recommendations (VRN 2014) was used as a basis for product grouping. Although it is a national model and tool for food-based dietary guidance, it has an international equivalence with the Healthy Eating Plate (Harvard School of Public Health 2023), for example. Additionally, the Finnish nutrition recommendations are based on the Nordic nutrition recommendations (Nordic Council of Ministers 2012; 2023). The plate model used presents the basis of the nutritionally balanced meal and its components. The model is widely used in the nutrition education and nutritional policy action to demonstrate the balanced food composition of a meal to the general public. The product grouping used in the plate models can be different in different countries. For example, the Healthy Eating Plate (Harvard School of Public Health 2023) includes vegetables and fruit as separate groups. Using the Finnish plate model (VRN 2014) as a basis for product grouping assumes that the eating habits of the population follow the model, and consumers compile their meals by choosing between different options within the product groups.

The CODEX/FAO food category system (Lewis 2019) is an example of another type of food grouping that is proposed for the nLCA (McLaren et al. 2021). It is the hierarchical system that includes all foodstuffs. Product management in the food wholesale market is based on a similar hierarchical grouping, but the shelf structure of food shops is usually also affected by the purchasing behaviour of consumers. A hierarchical system evidently supports product management well, but less well than the comparative nLCAs that aim to provide information about product substitutions in the context of the sustainable dietary shift. In such considerations, the comparison should not be restricted by the raw material basis of products, for example, i.e. between meats or even its subcategories. Instead, the comparison should cover large product groups, for example 'the protein sources', as has been common in sustainability research in general. This grouping refers to the practical role of products in the context of eating. Taking the context of eating into account is tempting from the nLCA perspective because it groups foods with diverse raw materials or ingredients, and thus different environmental impacts, as substitutes for each other.

However, eating patterns are culturally dependent (Drewnowski and Fulgoni 2008). Food grouping should therefore be considered critically before using product-group-specific

nFUs in different dietary contexts. Dietary patterns are also changing. For example, plant-based protein sources are often also rich in carbohydrates, and in the dietary shift, this may challenge the entire plate model, as discussed in Kytta et al. (2023). In addition, food formulations may look very different in the near future, combining carbohydrates, proteins, fats, vegetables, and plant-based side streams (e.g. seeds, skins, leaves, stems) in ways that will potentially revolutionise the concept of a food or meal (e.g. Hassoun et al. 2022; Patel 2020).

Even in the current food supply, not all foods fit the plate model used in this study. Mixed foods such as soups and casseroles are already commonly consumed; this again calls for further discussion of the relevant grouping of foods. It is suggested that a general across-the-broad nutrient index could be used for them, as well as for entire meals (Saarinen et al. 2017; McLaren et al. 2021). However, the development and evaluations of the own index for mixed foods, for example, are still lacking. Nor have drinks, snacks, and sweets been addressed in the nLCA research and in the methodological development of the nFUs.

#### 4.5 Strengths and limitations of the study

The study aimed to advance the development of the product-group-specific approach to integrating nutritional aspects in the FU of the food LCA. The strength of the study is that it applied and discussed the application of this approach to product groups other than protein sources. To our knowledge, this has not been done previously.

By providing the demonstrative LCAs, the study showed in practice how the approach could be implemented and the results interpreted. The study deepened the understanding of this approach compared to previous developments in the literature (e.g. Saarinen et al. 2017; McAuliffe et al. 2018; Hallström et al. 2019; Green et al. 2021; Kytta et al. 2023; McLaren et al. 2021). The development was done in the context of Finnish eating habits, but it can also be applied to other cultural contexts.

However, some limitations of the study must be acknowledged. First, our LCAs give only demonstrative results for the climate impact of food in relation to nutritional composition. Their purpose was to demonstrate the method, not to evaluate the effects of real foods, inform consumer choices, or policymaking. The product boundaries, evaluation methods, and data were chosen to be as appropriate, consistent, and comparable as possible, but they do not meet the strictest guidelines for product-specific LCAs, although they try to comply with the ISO standard (ISO 2006). For example, demonstrative LCAs do not follow the guidelines of the EC's PEF initiative. The practical applications of the developed nFUs must therefore be done in future LCA studies, considering also issues related to representativeness of

data and uncertainties of nLCA (Katz-Rosene et al. 2023; Ortenzi et al. 2023). Also, the food waste generated during post-farm processing, at retail, and consumer stage should be considered in future nLCA studies, as discussed by McAuliffe et al. (2023).

Furthermore, regardless of the efforts made, the nFU still does not consider all the beneficial nutritional aspects. For example, the possible role of bioactive compounds such as phenolic compounds was not analysed as part of the product-group-specific method for vegetables, fruit, and berries. In future development, whether they are more suitable to be added to the nFU, or whether they should perhaps be treated as part of health effects, should be addressed. Accordingly, disqualifying nutrients, presented in this study by the LIM index, could perhaps be addressed as a cause of health effects. More research is needed in this field, as discussed by McLaren et al. (2021).

We also did not address the amino acid composition of proteins in our development. This has been dealt with elsewhere. McAuliffe et al. (2022) have introduced a method for this using Digestible Indispensable Amino Acid Scores (DIAAS) scoring as a correction factor for protein quality, but the method is still developing and contains high uncertainty.

## 5 Conclusions

The product-group-specific approach to nutritional functional units (nFUs) that has previously been developed for protein sources performed well for two other product groups, namely sources of carbohydrates and vegetables, fruit, and berries. The approach, including the principles of the selection of nutrients for the nFUs as a core element of the approach, proved to contribute to the LCA results in a way that is compatible with the previous nutritional scientific knowledge. However, the difference between product-group-specific and reference indices was narrower than for protein sources. It is therefore concluded that it is recommendable to develop and evaluate the approach further.

In future applications and developments, it is recommendable to.

- Use product-group-specific nFUs when assessing different meal components and the impact of substituting currently consumed foods in a specific product group
- Consider the impacts of consumption phase (e.g. added salt/sugar and food waste)
- Extend the evaluation of the approach to product groups not represented in the plate model used in this study
- Adjust the evaluation of the approach, particularly the set of nutrients in the nFU, for other food cultural contexts
- Validate the selection of the nutrients for product-group-specific nFUs

- Link the approach to practical means to utilise LCA-based knowledge

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**Data availability** All data generated during this study are included in this published article, and other data are available in the sources given.

## Declarations

**Competing interests** The authors declare no competing interests.

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