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Multi-criteria evaluation of plant-based foods –use of environmental footprint and LCA data for consumer guidance

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ABSTRACT

Many consumers are willing to move to a more plant-based diet, as is apparent from the increasing demand for plant-based protein sources on many markets. There is scientific evidence that such diets are associated with lower environmental impacts, especially climate impact, land use, and energy use. However, all food production affects the environment, and there is scope for more sustainable food choices even among plant-based foods. We present a method for environmental multi-criteria evaluation of plant-based products to enable communication through a consumer guide, which was developed in cooperation with World Wide Fund for Nature (WWF) Sweden and involves a real-life case of implementation. The guide included 90 products, divided into five product groups. Four environmental impact categories were evaluated (climate impact, biodiversity impact, water use, pesticide use), to give a fuller, more complex picture of potential environmental impacts of plant-based products than when evaluating only one impact category, such as climate impact. Available environmental footprint data and LCA data adapted for the specific consumer market (Sweden) were used. A method for calculating absolute sustainability thresholds for single products was developed, based on newly published global sustainability boundaries for the food system (Willett et al., 2019). To account for the different dietary functions of food, different thresholds for evaluating different food groups were applied, thus accounting for the role, and to some extent the nutrient content, of different food products. This enabled evaluation of foods based on the same grounds, *i.e.*, using the global sustainability boundaries and the same functional unit for all food products (1 kg of food at a store in Sweden), while visualizing differences in environmental impacts of products within a certain food group. This revealed the best choice of protein sources, vegetables, *etc*. The method provides a way to use large amounts of data of varying quality, and reduces the complexity in evaluating the environmental impacts of food. It therefore hopefully facilitates sustainable plant-based food choices, for more environmentally sustainable food consumption.

1. Introduction

There is consensus that transitioning from Western diets high in meat and dairy to more plant-based diets is important in reducing environmental pressure from the food system (Springmann et al., 2018), as it can lower climate impact (Hallström et al., 2015), land use (Röös et al., 2017), and energy use (Pimentel and Pimentel, 2003). However, production of all foods, including plant-based foods, is associated with environmental impacts such as climate impact, eutrophication, ecotoxicity, and use of resources such as water, energy, and land. Much focus has been on the environmental impact of livestock consumption, while sustainable choices of plant-based foods have received less attention.

As environment-conscious consumers turn to vegetarian or vegan diets or reduce their intake of meat (Dagevos, 2016), sustainable choices of plant-based foods are becoming increasingly important for consumers. In many high-income countries, there are currently strong signs of increased interest in plant-based protein sources and rapid product development in ready-made meat alternatives (Foodmanufature, 2020; SVT, 2019). This suggests that a growing number of environmentally concerned consumers are willing to change their food habits. Vainio (2019) found that such consumers are more likely to respond to scientific evidence but lack information, despite considerable research on the sustainability of foods and diets. There is thus a need for *easily accessible* and *comparable* consumer information on the environmental impact of food products (Hellweg and i Canals, 2014).

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Consumer information alone is not enough to enable major shifts in diets (Willett et al., 2019; Röös and Tjärnemo, 2011). However, to enable conscious decisions by those consumers who are prepared to take such decisions, information on the sustainability of plant-based foods is needed. Today consumers can choose certified products, *e.g.*, organic products, which have been shown to have certain sustainability advantages (Seufert and Ramankutty, 2017). However, such labels only indicate the 'better' products within a category (*e.g.*, best milk, tomatoes, *etc.*), do not provide consumer guidance on products within groups (*e.g.*, apples or bananas), and are based on practices rather than outcomes. A few interesting labeling options that can provide guidance across products based on outcomes have been reported in the literature, *e.g.*, environmental footprint-based labels using carbon, water, and nitrogen footprint (Leach et al., 2016) and a environmental footprint-based label for meals that also includes health effects (Lukas et al., 2016). The Environmental Product Declarations (EPD) (Fet et al., 2009) is another example aimed at enabling labeling and consumer information on foods and products in general, as is the European Union-led Product Environmental Footprint initiative, which aims at providing a multi-criteria assessment method for the environmental performance of a good or service from a life cycle perspective (EU, 2013). However, none of these initiatives has yet been widely implemented. Labeling all food products (which is necessary to support food group choices) is challenging and costly for many reasons, for example Röös et al. (2011) describe challenges with climate labeling. An alternative to labeling all individual food products is an off-package consumer guide (*e.g.*, phone app, website, brochure) that provides information about different foods on a more general level. Consumer guides that include multiple environmental criteria include the World Wide Fund for Nature (WWF) meat guide (Röös et al., 2014) and the fish guide, which allow comparisons between different types of (meat and fish) products. However, there is no guide for plant-based foods like cereals, legumes, new plant-based protein sources, plant-based dairy alternatives, fruit, nuts, and vegetables. Development of food consumer guides is challenging, since food production has multiple impacts on the environment and any tool aiming at holistically communicating environmental impacts of different foods needs to include multiple environmental impact categories. At the same time, the complexity has to be substantially reduced to enable consumers to make informed choices and move towards less harmful consumption patterns, including providing ways to benchmark products against *e.g.,* each other or against environmental targets (Galindro et al., 2019). Data availability is also a challenge. Many life cycle assessments (LCA) have been performed to evaluate the environmental effects of different foods, and the results have been compiled in review papers (*e.g.*, Clune et al., 2017; Poore and Nemecek, 2018). However, such studies commonly only include a few impact category and/or include site-specific production systems or global averages not relevant for foods on a specific market. Thus, relevant data for the specific markets on which the guide is to be used need to be compiled and processed. Criteria for levels of sustainability, based on either relative scale (*i.e.*, among similar foods) or absolute scale (*i.e.*, relative to some sustainability threshold), also need to be developed.

The aim in this study was to develop a method for multi-criteria evaluation of plant-based foods that can be used in consumer communication, building on experiences from developing the WWF consumer guide for meat products (Röös et al., 2014). Method development was performed as part of development and design of a consumer guide by WWF-Sweden, *i.e.*, it was based on a real case example. This required the method to be transparent, to be built on well-established scientific data, and to produce easily understandable information for consumers. Challenges with using environmental footprint and LCA data for real-life consumer communication were also assessed.

2. Material and methods

2.1. Development process

Development of a consumer guide for plant-based food (the 'Vego-guide') was initiated by WWF-Sweden to complement existing consumer guides for fish and meat (Röös et al., 2014). WWF-Sweden acted as project owner throughout, *i.e.*, made the

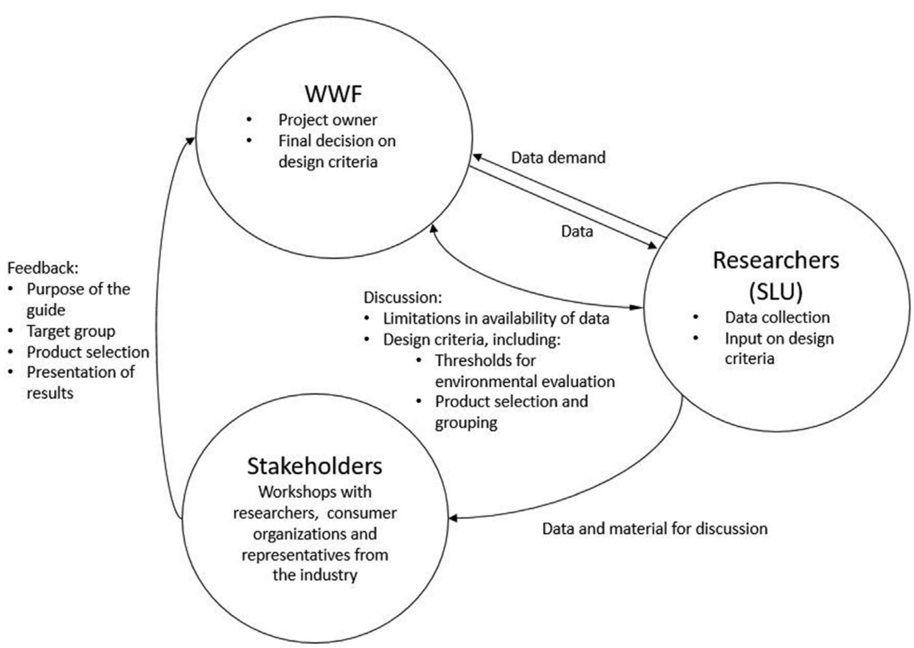

Fig. 1. Illustration of Vego-guide development. WWF-Sweden acted as project owner and took the final decisions on the guide and design criteria.

Table 1
Design criteria for development of the Vego-guide.

Design criteria	Description
1) Target group	Interested consumers and food professionals already choosing some vegetarian food, but wishing to make more sustainable choices.
2) Aim (of the guide)	A) To increase consumption of plant-based foods, B) to communicate environmental impacts of plant-based foods and increase knowledge on their sustainable production and consumption, and C) to address sustainability challenges associated with consumption of plant-based foods.
3) Data	Scientifically accepted and available data, *e.g.*, LCA data from published peer-reviewed papers, well-established LCA databases, and reports/ conference proceedings where methods and data are clearly presented, which enabled critical review.
4) Products	Common plant-based products and low-volume products of special interest to consumers.
5) Functional unit	Life cycle impact of 1 kg product in a store in Sweden.
6) System boundary	From cradle to retailer in Sweden.
7) Environmental indicators	Relevant environmental impact and resource use indicators for production and distribution of plant-based products.
8) Tools	Use of existing certification and control schemes when possible.

final decisions regarding design criteria (section 2.2), including selection of products, target group, evaluation criteria, and thresholds. Researchers collected background data, devised evaluation criteria, and provided continuous feedback at workshops during the development of the guide. *Three* workshops were held with external stakeholders, including consumer organizations and other food sector actors (see Table S1 Supplementary Material (SM)), to gather feedback on the purpose of the guide, the target group, product selection, and presentation of results (Fig. 1).

2.2. Design of the guide

Design criteria for the Vego-guide were established by WWF-Sweden and were based on those used for the meat guide (Röös et al., 2014) (Table 1).

The target groups of interested consumers and food professionals were selected as they were assumed to be influenced by, and interested in, information about environmental impacts of foods.

A total of 90 products were included, divided into five food groups (Table 2), to enable specific environmental evaluation of product groups (section 2.3). The groups were based on the main function of the product in the diet, with the foods in a group being interchangeable in a meal. However, some foods can be used in different ways, *e.g.*, nuts and seeds are often used as snacks, but can replace meat in a transition to a plant-based diet (Willett et al., 2019), so they were grouped with protein sources (Table 2).

The functional unit (FU), 1 kg *food in a store in Sweden*, was chosen after considerable discussion (see section 4.2). For the protein sources and carbohydrate sources groups, the FU 1 kg *edible product in a store in Sweden* was used, to enable fair comparison between canned beans, dry beans, and ready-made protein sources (such as soy-based meat replacers in the protein group), and between cereals (low water content before preparation) and root vegetables (high water content before preparation) in the carbohydrate group. Alternatives to a mass-based FU include *e.g.*, considering the nutritional value of the food in various ways (Sonesson et al., 2019; Weidema and Stylianou, 2019). Selection of

Table 2
Products[a] included in data collection, divided into product groups.

Protein sources	Carbohydrate sources	Plant-based drinks/cream	Fruit and berries	Vegetables and mushrooms
	Cereals		Fruit	Vegetables
Green peas	Barley	Almond drink	Apples	Artichoke
Yellow peas	Maize	Coconut drink	Bananas	Asparagus
Dry beans	Millet	Soy drink	Cherries	Avocado
Faba beans	Oats	Oat drink	Dates	Broccoli
Canned beans (including lentils)	Pasta	Oat cream	Grapefruit and pomelo	Cabbage
Chick peas	Quinoa	Coconut milk	Grapes	Capsicums/ peppers
Dry lentils	Rice		Guava and mango	Cauliflower
Soybeans	Rye		Kiwi	Celery
Ready-made products	Sorghum		Lemons and limes	Cucumber
Mixed without animal products[b]	Wheat		Melons	Eggplant
Pea-protein products	Root vegetables		Oranges	Garlic
Quorn	Beetroot		Papayas	Ginger
Soy-based	Carrots		Peaches	Lettuce
Tofu and tempeh	Potatoes		Pears	Green beans
Nuts and seeds	Swedes		Pineapples	Mushrooms
Almonds	Sweet potato		Plums and sloes	Olives
Cashew nuts	Jerusalem artichoke		Tangerines, mandarins *etc.*	Onion
Chestnuts	Parsnips		Watermelon	Pumpkins and squash
Coconut (grated)			Berries	Spinach
Hazelnuts			Cranberries	Tomatoes
Walnuts			Blueberries	
Pistachios			Raspberries and other berries	
Peanuts			Strawberries	
Sesame seeds				
Sunflower seeds				

[a] All products for which data were collected, WWF-Sweden will decide which products to include in the Vego-guide.
[b] Including *e.g.*, falafel.

Table 3
Environmental indicators and their applicability rating for inclusion in the Vego-guide. ++ = High, + = fairly high, 0 = not relevant/very low availability of data, ? = not known. *From Steffen et al., 2015. **From Huijbregts et al. (2016).

	Environmental indicators									Resources			
	Climate change */Global warming**	Biosphere integrity*	Novel entities*/ Eco/human toxicity**	Stratospheric ozone depletion*,**	Trop. ozone formation	Atmospheric aerosol loading*/ Part. Matter**	Ocean acidification*/ Terr. acidification**	Biogeochemical flows*/ Eutrophication**	Ionizing radiation	Land system change*/Land use**	Fresh water use*/Water use**	Fossil resources**	Mineral resources**
1. Relevance for production of plant-based foods	+	++	++	?	+	?	0	+	0	++	++	+	?
2. Importance to users	++	+	++	0	0	0	0	+	0	+	++	+	0
3. Availability of scientifically accepted methods	++	+	+	?	0	++	++	+	?	+	+	++	+
4. Availability of data	++	+	0	?	0	?	+	+	+	++	++	+	0
Total score	**7+**	**5+**	5+	0+	1+	2+	3+	4+	1+	**6+**	**7+**	**5+**	1+

FU was discussed throughout the project, and the novel approach of considering the functions of foods when setting the thresholds (see section 2.5), rather than the FU, was chosen as the way forward. This design choice is discussed at length in section 4.2.

Environmental impact categories considered relevant for the food sector in general and plant-based foods in particular were selected using the well-known planetary boundaries framework (Steffen et al., 2015) and the mid-point categories of ReCiPe (Huijbregts et al., 2016), a frequently used environmental impact assessment method within LCA. The indicators contained in the framework were evaluated by expert judgment by the authors, using the following criteria: 1) relevance for plant-based products; 2) importance for guide users; 3) availability of scientifically accepted evaluation methods; and 4) data availability. The six indicators that scored highest in the evaluations were climate impact/global warming, fossil resources, land system change/land use, biosphere integrity, water use, and novel entities/ecotoxicity (Table 3).

Further processing of these six environmental categories resulted in choice of the following four indicators: climate impact, biodiversity impact (land use and biodiversity loss evaluated together), water use, and pesticide use (see section 2.4 on how these were measured). Use of fossil resources was not included, as it is reflected in the climate impact. Biogeochemical flows were included initially (as use of nitrogen and phosphorus) and evaluated using different indicators. However, to reduce the complexity of the guide biogeochemical flows were ultimately excluded, as the impact is similar for all plant-based foods when their nitrogen content is considered (Abrahamsson, 2019).

2.3. Framework for environmental assessment

As in other WWF guides, environmental impact was communicated using a ‘traffic-light’ system, *i.e.,* using three levels: green (best), yellow, and orange (worst) to illustrate the environmental impact of the foods evaluated. For consistency, the same thresholds for the green, yellow, and orange (red in the meat guide) ratings as in the meat guide were chosen for land use (included in the biodiversity assessment) and climate impact for the protein sources group. A better-than-green choice, called ‘green star’, was introduced in the Vego-guide for the climate and biodiversity impact categories, as plant-based products generally have much lower climate impact and land use than animal-based products. For example, in the meat guide, the threshold for green for climate impact is set to <4 kg CO2e/kg meat to differentiate between meat from different animal species, but since most plant-based foods have a much lower climate impact, the green star level enabled differentiation between foods with climate impact between 0 and 4 kg CO2e. Otherwise, most plant-based products would have a *green* rating, hence not providing useful consumer information. Different underlying indicators and evaluation criteria were used to evaluate the four environmental impact categories (Fig. 2).

When weighting the environmental indicators into one score, we avoided established weighting methods available for use in LCA (Pizzol et al., 2017), for two main reasons: First, data availability was not similar for all selected food products, *i.e.*, we could not find comparable inventory data that could be evaluated using one weighting method for all food products. We therefore constructed an evaluation system that could be applied to products and environmental indicators with varying degrees of data availability and quality. Second, established LCA methods do not capture the full environmental impact of agricultural production (van der Werf et al., 2020; Notarnicola et al., 2017). Environmental footprint can be complemented with other evaluation criteria, such as established certification schemes or legislation, to overcome these

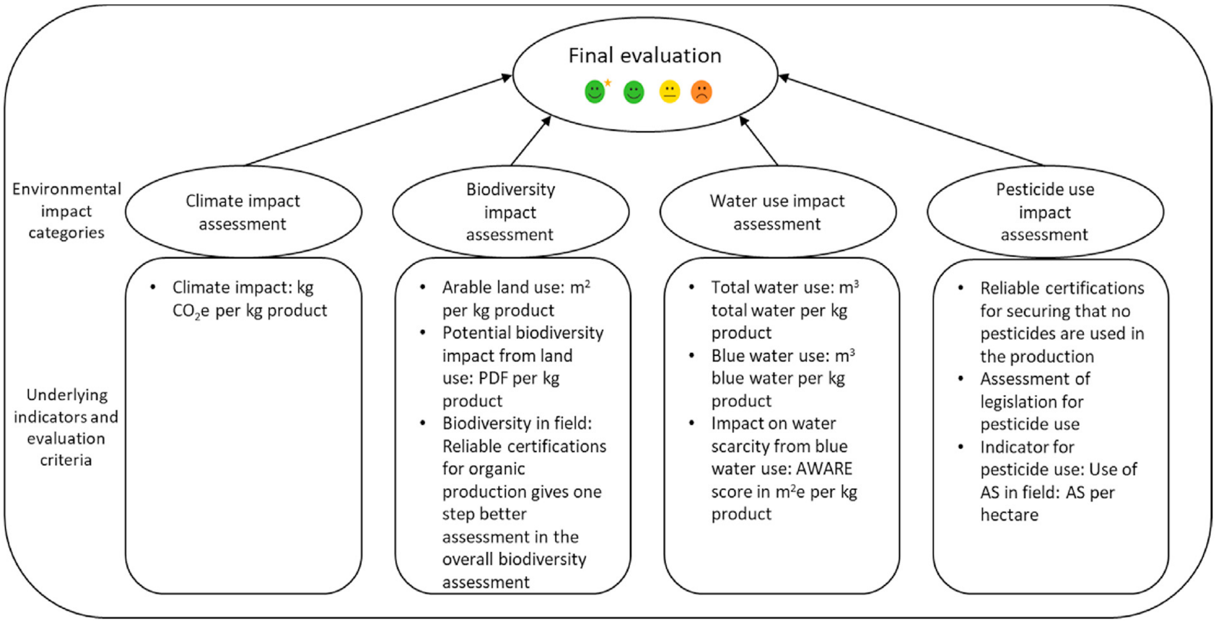

Fig. 2. Methods used for evaluating the four selected environmental impact categories. For biodiversity impact, water use, and pesticide impact, several underlying indicators and evaluation criteria were used. The results for the four categories were given equal weighting in the final assessment. The functional unit was 'per kg food in a store in Sweden'.

challenges. Established certification schemes verify production methods that lead to certain environmental outcomes, so certification can be a valuable complement in environmental assessment of food products when data on actual outcomes are lacking.

2.4. Environmental impact categories

2.4.1. Climate impact

The climate impact was based on global warming potential in kg CO2e per kg product, using data from previous LCA studies (123 scientific studies, 31 conference papers, 42 reports and other grey literature, and two databases). See Karlsson Potter et al. (2020) for details of data collection. Estimated averages for food transport to and within Sweden and for packaging (Moberg et al., 2019) were added to the climate impact if not included in the original study. The data most relevant for foods on the Swedish market were determined based on import statistics for all products and on their representativeness for current production systems, including technological development (see Karlsson Potter et al., 2020). For most individual products, relatively few studies were identified and it was therefore not considered feasible to use an average value for climate impact. Instead, the precautionary principle was applied to identify a threshold for different individual products, expressed as "climate impact is likely to be lower than X kg CO2e per kg product" based on the study with the highest climate impact.

2.4.2. Biodiversity impact

The biodiversity impact was based on a combination of land use per kg product and potential biodiversity loss from land use, which was assessed using the indicator *potentially disappeared fraction* (PDF) (Chaudhary et al., 2018) using country-average characterization factors.

Land use was used as an indicator of biodiversity impact because global land use is the main driver for biodiversity loss (IPBES, 2019). Arable land is also a limited resource, and use of arable land use per kg product is an important indicator of resource use efficiency in producing different products. However, effects on biodiversity from land use differ depending on where the land is located. The PDF indicator was used to capture some of these effects, as recommended by the United Nations Environment Programme-Society of Environmental Toxicology and Chemistry (UNEP-SETAC) for assessing biodiversity impacts from agriculture (UNEP, 2019). The method provides characterization factors for all world regions, which were required in this project since food products on the Swedish market come from all over the world, and the method allows for distinction between different land use types, although these are still rather broad. Based on historical data, the characterization factors describe the fraction of total global species that risk becoming extinct due to land use in a certain region.

Organic production is associated with higher biodiversity in the field (Tuck et al., 2014; Bengtsson et al., 2005). Therefore, reliable certification schemes for organic production were used to give a 'one-step-better' evaluation of biodiversity loss, *i.e.*, a product rated *yellow* based on land use (m2 per kg product) and biodiversity impact from land use (estimated in PDF) received a final evaluation of *green* if certified organic.

2.4.3. Water use

The water use impact was also based on a combination of different indicators. These were total water use, defined as total *green, blue, and grey* water use based on Mekonnen et al. (2011), the water scarcity indicator AWARE (Boulay et al., 2018), and blue water use based on Mekonnen et al. (2011). How to assess water use and its impact is currently under debate. Use of water scarcity indicators (*e.g.*, AWARE) has been criticized for *e.g.*, shifting the focus from water use and competing use of water globally (Hoekstra, 2016). In LCA, there are two different ways to view water use, as resource use and the *potential* environmental impacts from water use (Pfister et al., 2017). Therefore, we used a combination of indicators. Total water use describes use of water as a resource, following the conclusion by Hoekstra (2016) that volumetric water use, including rainwater, is an indication of how efficiently the water resource is being used. Blue water use is an indicator of irrigation water, comparable to the global sustainability boundaries for the food system (Willett et al., 2019) (section 4.2). A water scarcity indicator (AWARE) was used as an indicator of potential

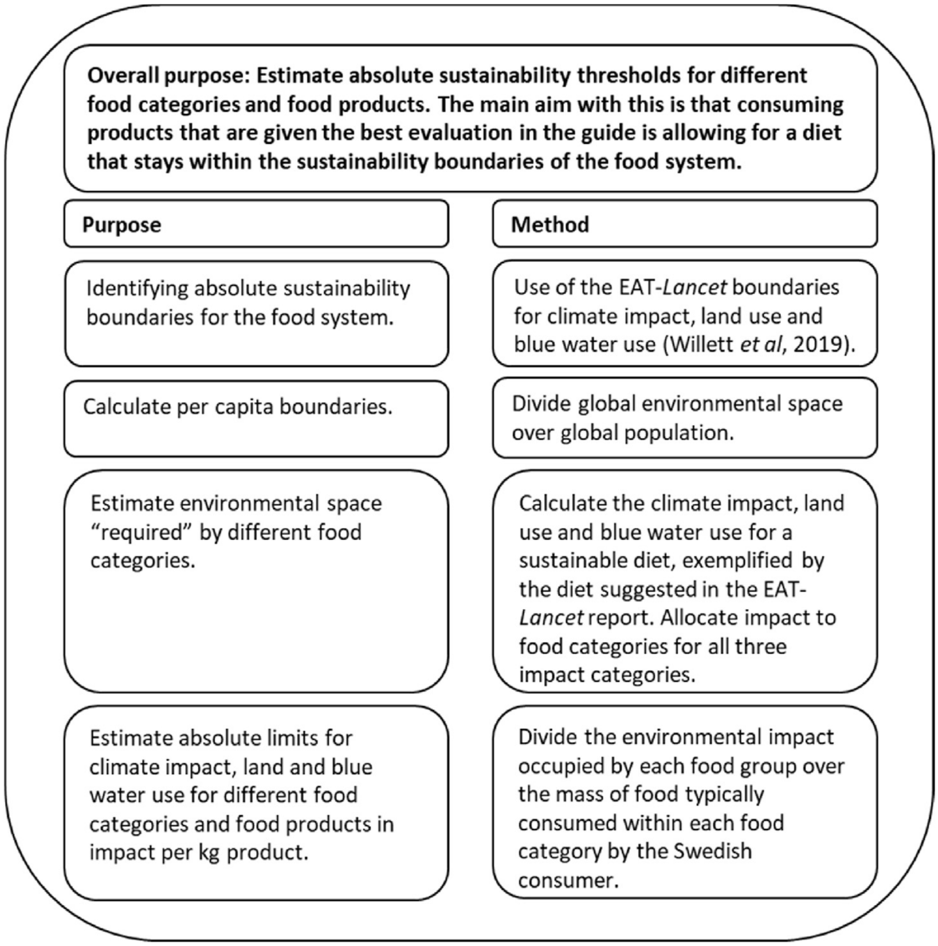

Fig. 3. Methodology used for calculating absolute thresholds for food products in different food groups.

impact locally of (blue) water use. AWARE emerged from the UNEP-SETAC Life Cycle Initiative (Boulay et al., 2018), and is recommended for use in water scarcity impact assessment by Jolliet et al. (2018), who also recommend using a different water scarcity indicator in sensitivity analysis. Here, the water scarcity impact method (water stress index, WIS) (Pfister et al., 2009) was used in combination with AWARE for most products included in the guide (Lundmark, 2019).

WWF-Sweden decided not to use the 'green star' level for water use in the Vego-guide, due to uncertainty in the underlying data.

2.4.4. Pesticide use

There is little or no statistical information on pesticide use for different crops produced world-wide. The FAO keeps records on total pesticide use per country, but not coupled to specific crops, while existing data on European Union (EU) level for crop groups are outdated (EUROSTAT, 2007). Due to this lack of data, pesticide use was evaluated based on certification (where certified organic always received a green star rating, as organic production uses very few toxic substances; Ascard et al., 2017) and legislation. For non-organic products, it was assumed that pesticides are likely to be used. Products produced within the EU were rated yellow, while conventional crops produced outside the EU were rated orange, based on the relatively rigid pesticide legislation in the EU harmonized for all EU countries.

Pesticide use for conventional products produced within the EU was assessed based on active substance (AS) per hectare, for which EU products and Swedish products with high pesticide use per hectare were given an orange rating in the guide (Table S3). Pesticide use per hectare was applied instead of AS per kg product, since pesticide use intensity per unit of land determines actual local pesticide leaching to freshwater. For example, it has been found that field pea, potato, and sugar beet cultivation in parts of Sweden contributes strongly to local pesticide levels in water bodies, although the area used is relatively small compared with the cereal acreage (Boye et al., 2013). For high-yielding crops such as potato, this intensity would not be captured using AS per kg product. National and EU statistics were used (see Karlsson Potter et al., 2020). No coherent data on pesticide use for individual crops were found for products produced outside the EU, and therefore no similar assessment was made for such products.

2.5. Establishing thresholds

Thresholds were the limits applied to establish whether a product received a green star, green, yellow, or orange rating for a certain impact category. This section describes how the thresholds were set.

2.5.1. Thresholds for green star

The starting point for establishing thresholds was to relate the green star level to the planetary boundaries for the food system defined by Willett et al. (2019), and hence enable evaluation of foods based on absolute sustainability boundaries, as suggested by

Table 4
Overall and product group-specific environmental impact thresholds calculated based on the planetary boundaries for a sustainable food system.

		Overall[b]	Protein sources	Carbohydrate sources	Plant-based drinks/cream	Fruit and vegetables
Climate impact	kg CO_2e per kg food product	1.1	2.9	0.7	0.9	0.8
Water use[a]	m^3 blue water per kg food product	0.2	0.2	0.1	0.03	0.2
Land use	m^2 per kg food product	2.9	7.1[c]	1.7	1.7	0.9

[a] Threshold for a green rating.
[b] Estimated thresholds per kg food products calculated for the whole diet, based on the average boundary for climate and land and the lower boundary for water use (Willett et al., 2019), to reveal differences between different products for water.
[c] Higher than the threshold for the green level in the meat guide, so changed to 5 m^2 per kg product for both the green star and green level.

Leach et al. (2016). The planetary boundaries for the food system define "allowances" of environmental pressures (climate, nitrogen and phosphorus use, species extinction) and resource use (water, land) for the global food system.

The method used for calculating thresholds is summarized in Fig. 3. First, per capita environmental boundaries for climate impact, water use (blue water), and land use were established by dividing the global boundaries (Willett et al., 2019) by the global population in 2018 (WorldBank, 2019). The calculated per capita 'environmental space' for each impact category was then distributed over different food groups based on their impact for the respective environmental categories in a sustainable diet, exemplified as the EAT-*Lancet* diet suggested by Willett et al. (2019) (see Table S2). The environmental impact of the sustainable diet was calculated using data from Moberg et al. (2020) and data collected in the present study. For example, for the EAT-*Lancet* diet the product group protein sources (meat, fish, egg, nuts, and legumes) causes 35% of the climate impact of the complete diet, while the carbohydrates group (cereals and potatoes) causes 18%. Therefore, the protein group in the Vego-guide was allowed to use 35% of the greenhouse gas emissions in the boundary case and the carbohydrate group was allowed to use 18% (Table 4). This meant that a product group with a higher (or lower) environmental impact within a specific environmental category was given a higher (or lower) environmental space for this impact category. To determine the environmental space per kg of food, the calculated environmental space for each food group and environmental category was divided by assumed amount (in kg) of each food group consumed in the average Swedish diet (Amcoff et al., 2012; Enghardt Barbieri and Lindvall, 2003).

These absolute thresholds were used as the green star criteria for land and climate impact, and as the green level criteria for water. The thresholds for biodiversity impact estimated as PDF, total water use, impact on water scarcity estimated using AWARE, and pesticide use could not be related to absolute sustainability boundaries, due to lack of boundaries for these indicators. Instead, the thresholds were set to show clear differences between product performance for the different environmental categories. Therefore, some products with an impact below the thresholds calculated from the planetary boundaries (Table 4) still ended up with a green, yellow, or orange rating for climate impact, water use, and biodiversity impact, due to higher impacts for the indicators not related to the absolute planetary boundaries (potential biodiversity impact (PDF), local impact on water scarcity (AWARE), and total water use).

2.5.2. *Thresholds for green, yellow, and orange*

The green thresholds for climate impact, land use, and blue water use were set by doubling the green star thresholds, and the yellow thresholds by doubling the green thresholds (Table S3). The only exception was the thresholds for protein sources, which were set in accordance with those in WWF's meat guide, to align evaluation of protein sources with meat, as these have similar functions in a meal.

For communicating the environmental impact in one rating (the final evaluation), the results from the four environmental impact categories were weighted equally. Each rating for the four different categories was given a score (green star 1 point, green 2, yellow 3, and orange 4). For the combined points scores, a green star was given to products with <5 points, green for 6–8 points, yellow for 9–11 points, and orange for 12–16 points. The points awarded for the different final evaluations were set so that differences between the products were revealed.

3. Results

Table 5 presents a sample of results from the environmental evaluation (for all results, see Table S4 in SM). Most products received a green star and green rating for climate impact (see S4 for vegetables), while inclusion of the other criteria gave a fuller picture of the potential environmental impact of plant-based products than an evaluation based solely on climate impact.

Several countries of origin were included for all products, as well as conventional, organic, and Swedish production when applicable. However, to reduce the complexity in the final Vego-guide, if the results for Swedish-produced and imported production were similar (*e.g.*, potatoes), WWF-Sweden decided not to show country of origin in the guide (Table 5). If the results differed (*e.g.*, strawberries, tomatoes), results for different regions of origin were included (Table 5). In total, 17 products received an orange rating, associated with the message "be careful", in the guide. Four of these (non-certified almonds, bananas, asparagus from Europe, asparagus from outside Europe) are included in Table 5. The other products with an orange rating were: non-certified cashew nuts, coconut (grated), hazelnuts, pistachio nuts, walnuts, sesame seeds, avocados, green beans from outside Europe, olives, cherries from outside Europe, dates, mangoes, and papayas (Table S4). All results shown in this paper and in SM are those selected as being of highest relevance for the Swedish market by WWF-Sweden. However, not all products shown here will be included in the final guide.

4. Discussion

The collaboration with WWF-Sweden in development of the consumer communication tool offered many possibilities, but also posed some challenges. WWF-Sweden ultimately made the final decisions, *e.g.*, on what we view as the rather inconsistent evaluation of water use (omission of the green star level for this category). However, the overall discussions in the project group were very fruitful and interesting and we believe that the outcome, i.e., the Vego-guide, benefited from combining the different experiences and knowledge of both partners.

During development of the Vego-guide, there were continuous discussions on a number of issues, especially how to compare different products with different functions in a diet, the method used for evaluation of products, *i.e.*, thresholds for different evaluations, and the challenges of including impacts from the use of

Table 5
Results from multi-criteria evaluation of selected products.

GROUP	PRODUCT	CLIMATE	BIODIVERSITY	WATER	PESTICIDE USE	FINAL EVALUATION
Protein sources						
	Beans, dried, imported	GREEN STAR	GREEN STAR	GREEN	ORANGE	GREEN
	Beans, dried, Sweden	GREEN STAR	GREEN STAR	GREEN	YELLOW	GREEN
	Beans, dried, organic	GREEN STAR	GREEN STAR	GREEN	GREEN STAR	GREEN STAR
	Beans, dried, organic, Sweden	GREEN STAR	GREEN STAR	GREEN	GREEN STAR	GREEN STAR
	Lentils, dried	GREEN STAR	GREEN STAR	GREEN	ORANGE	GREEN
	Lentils, dried, Sweden[a]	GREEN STAR	GREEN STAR	GREEN	YELLOW	GREEN
	Lentils, dried, organic	GREEN STAR	GREEN STAR	GREEN	GREEN STAR	GREEN STAR
	Lentils, dried, organic, Sweden[a]	GREEN STAR	GREEN STAR	GREEN	GREEN STAR	GREEN STAR
	Ready-made, soy-based	GREEN STAR	GREEN STAR	GREEN	ORANGE	GREEN
	Ready-made, soy-based, organic	GREEN STAR	GREEN STAR	GREEN	GREEN STAR	GREEN STAR
	Almonds	GREEN	YELLOW	ORANGE	ORANGE	ORANGE
	Almonds, organic	GREEN	YELLOW	ORANGE	GREEN STAR	YELLOW
	Peanuts	GREEN STAR	GREEN STAR	YELLOW	ORANGE	YELLOW
	Peanuts, organic	GREEN STAR	GREEN STAR	YELLOW	GREEN STAR	GREEN
Carbohydrate sources						
	Pasta	GREEN	GREEN STAR	GREEN	YELLOW	GREEN
	Pasta, Sweden	GREEN STAR	GREEN STAR	GREEN	YELLOW	GREEN
	Pasta, organic	GREEN	GREEN STAR	GREEN	GREEN STAR	GREEN
	Pasta, organic, Sweden	GREEN STAR	GREEN STAR	GREEN	GREEN STAR	GREEN STAR
	Quinoa	GREEN	YELLOW	GREEN	ORANGE	YELLOW
	Quinoa, organic	GREEN	YELLOW	GREEN	GREEN STAR	GREEN
	Potatoes	GREEN STAR	GREEN STAR	GREEN	ORANGE	GREEN
	Potatoes, organic	GREEN STAR	GREEN STAR	GREEN	GREEN STAR	GREEN STAR
Plant-based drinks/cream						
	Almond drink	GREEN STAR	GREEN STAR	YELLOW	ORANGE	YELLOW
	Almond drink, organic	GREEN STAR	GREEN STAR	YELLOW	GREEN STAR	GREEN
	Oat drink	GREEN STAR	GREEN STAR	GREEN	YELLOW	GREEN
	Oat drink, organic	GREEN STAR	GREEN STAR	GREEN	GREEN STAR	GREEN STAR
Fruit and berries						
	Apples	GREEN STAR	GREEN STAR	GREEN	ORANGE	GREEN
	Apples, Sweden	GREEN STAR	GREEN STAR	GREEN	ORANGE	GREEN
	Apples, organic	GREEN STAR	GREEN STAR	GREEN	GREEN STAR	GREEN STAR
	Bananas	GREEN	ORANGE	GREEN	ORANGE	ORANGE
	Bananas, organic	GREEN	YELLOW	GREEN	GREEN STAR	GREEN
	Oranges	GREEN STAR	GREEN STAR	YELLOW	ORANGE	YELLOW
	Oranges, organic	GREEN STAR	GREEN STAR	YELLOW	GREEN STAR	GREEN
	Pears	GREEN STAR	GREEN STAR	GREEN	ORANGE	GREEN
	Pears, organic	GREEN STAR	GREEN STAR	GREEN	GREEN STAR	GREEN STAR
	Strawberries	GREEN	GREEN STAR	YELLOW	ORANGE	YELLOW
	Strawberries, Sweden	GREEN STAR	GREEN	GREEN	ORANGE	YELLOW
	Strawberries, organic	GREEN	GREEN STAR	YELLOW	GREEN STAR	GREEN
	Strawberries, Sweden, organic	GREEN STAR	GREEN	GREEN	GREEN STAR	GREEN
Vegetables and mushrooms						
	Asparagus, Europe	YELLOW	GREEN	YELLOW	ORANGE	ORANGE
	Asparagus, Europe, organic	YELLOW	GREEN	YELLOW	GREEN STAR	YELLOW
	Asparagus, south America,	ORANGE	YELLOW	ORANGE	ORANGE	ORANGE
	Cucumber	YELLOW	GREEN STAR	YELLOW	ORANGE	YELLOW
	Cucumber, Sweden	GREEN STAR	GREEN STAR	GREEN	YELLOW	GREEN
	Cucumber, organic	YELLOW	GREEN STAR	YELLOW	GREEN STAR	GREEN
	Cucumber, Sweden, organic	GREEN STAR	GREEN STAR	GREEN	GREEN STAR	GREEN STAR
	Eggplant	YELLOW	GREEN STAR	YELLOW	ORANGE	YELLOW
	Eggplant, organic	YELLOW	GREEN STAR	YELLOW	GREEN STAR	GREEN
	Tomatoes	YELLOW	GREEN STAR	GREEN	ORANGE	YELLOW
	Tomatoes, Sweden	GREEN	GREEN STAR	GREEN	YELLOW	GREEN
	Tomatoes, organic	YELLOW	GREEN STAR	GREEN	GREEN STAR	GREEN
	Tomatoes, Sweden, organic	GREEN	GREEN STAR	GREEN	GREEN STAR	GREEN
	Mushrooms[a]	ORANGE	GREEN STAR	GREEN	ORANGE	YELLOW
	Mushrooms, organic[a]	ORANGE	GREEN STAR	GREEN	GREEN STAR	GREEN

[a] No data on water use, estimated by WWF.

pesticides. Therefore, we discuss these more in depth in section 4.2 to 4.4, respectively. We start the discussion in section 4.1 with some reflections on the use of available global LCA data in the development of a guide for the Swedish market.

4.1. Data interpretation and adaptation for specific markets

One challenge when using existing data on environmental footprints and LCA data on food products is that the data can be rather general and need to be adapted to the specific market. Here, we examined how adaptation of LCA data for the Swedish market affected the climate impact rating of the products. Climate impact estimates for the Vego-guide were based on earlier studies and their applicability to the Swedish market. The earlier studies estimated to be relevant, including impact from transportation and packaging, are shown as dots in Fig. 4. That diagram also shows the average climate impact for the studies considered relevant for the Swedish market, the average for all studies, and the range of climate impact in all studies. For all product groups, the relevant studies had a slightly lower average climate impact than all studies. This was because i) transportation to Sweden was added to all studies identified in the initial screening, while in the assessment of applicability of studies for the Swedish market these studies were removed; and because ii) technology changes over time, *e.g.*, older studies on greenhouse production of tomatoes and cucumber in Sweden generally considered fossil fuel-based heating, while heating today is mainly bioenergy-based. Use of the precautionary approach, where climate impact was not expressed as an average value, but as lower than that in the relevant study with the highest impact (highest dot in Fig. 4), for all individual products generally resulted in the climate estimate being higher than the average value, both for all studies and for relevant studies.

4.2. Comparison across foods – choice of functional unit

In comparing environmental impacts of different food products, choice of FU is important (Sonesson et al., 2019). The main challenge with using the same FU for comparing products from different product groups is that some products with relatively high environmental impact in some categories could also have high nutritional qualities that make them suitable for different functions in the diet, so that they cannot be replaced by food products from a different product group. For example, plant-based protein sources are generally associated with higher land use than carbohydrate sources, but it is not nutritionally adequate to replace all protein in the diet with carbohydrate products. When comparing different products with different functions in a diet, one option could be to use different FUs for different product groups, *e.g.*, protein content for protein sources and energy content for carbohydrates. However, for fruit and vegetables there is no such straight-forward FU and most provide several nutrients. Different options for the FU, such as dry matter content and nutrient indices (the latter discussed in Karlsson Potter et al., 2020), were tested and evaluated during the development of the guide, without satisfactory results.

To overcome this challenge, we developed the novel approach of using product group-specific thresholds for the environmental evaluation (section 2.5). This method has a similar effect as using different FUs for different product groups, *i.e.*, it reveals differences within product groups. For example, the thresholds for the carbohydrates group was lowered, so that differences between products that generally have a low environmental impact per kilogram were more visible. This can be seen for the climate impact evaluation for rice in Table S5, where rice received a yellow rating when the product group-specific thresholds were used, but a green rating when using the same thresholds for all products. Our approach

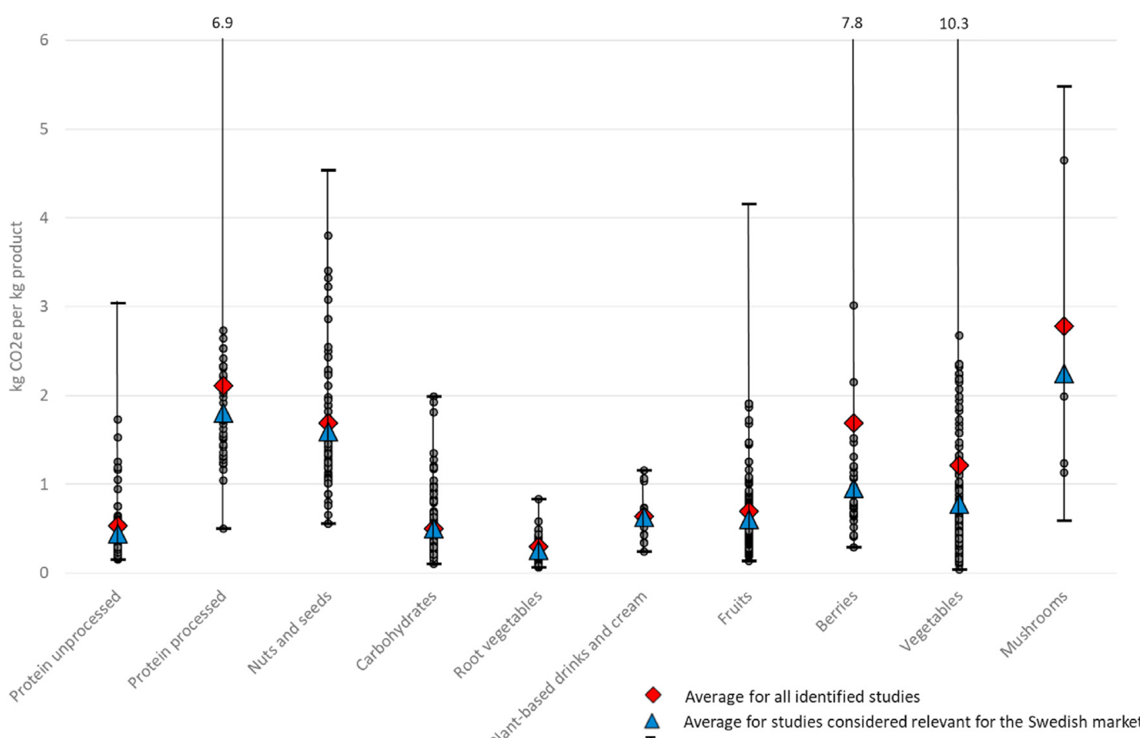

Fig. 4. Climate impact in published studies considered relevant for the Swedish market (dots), average climate impact for all studies, average for studies relevant for the Swedish market, and range reported in all studies. The climate impact figures include transport to Sweden and packaging, but not land use change. The protein sources group is sub-divided into protein unprocessed (including beans, peas, and lentils), protein processed (including *e.g.*, soy-based ready-to-eat alternatives to meat), and nuts and seeds; the carbohydrate sources group into carbohydrates (including cereals and pasta) and root vegetables; and fruit and vegetables into fruits, berries, vegetables, and mushrooms.

facilitates choices within the product group, rather than between products in different groups. Results for all products when using the FU 1 kg food and the same thresholds for all product groups, *i.e.,* the 'overall' thresholds in Table 4 for both protein and carbohydrate sources, plant-based drinks/cream, and fruit and vegetables, are shown in Table S5. In general, using the same threshold for all products gave a harsher evaluation (more yellow and orange final evaluations) for the protein sources group and a milder evaluation (more green and green star final evaluations) for the carbohydrate sources and fruit and vegetables groups. It also resulted in smaller differences between products within the product groups with generally low environmental impacts. For example, products in the carbohydrates group generally received a green star rating for climate impact when using the same thresholds for all products, while some products received a green rating when using the product group-specific thresholds (Table S5).

4.3. Limitations with absolute and relative thresholds

One alternative to using absolute sustainability boundaries as a basis for thresholds is to use relative thresholds for each product category, which would then indicate the best and worst in each product group (*e.g.*, best and worst protein source, best and worst carbohydrate source, and so on). The advantage of using the method based on absolute targets presented here is that environmental advantages of some product groups become clear, *e.g.*, there are few yellow and orange evaluations in the carbohydrate group due to generally low resource use and environmental impact in producing these products.

Using the planetary boundaries for the food system (Willett et al., 2019) to estimate the thresholds for 'best level' (green star) in the Vego-guide enabled evaluation of single products against absolute sustainability targets. Thus it offers the possibility to communicate information on products with impacts below the estimated sustainability thresholds for the climate impact, land use, and water use categories. However, this evaluation should be viewed only as an indication of what can be considered sustainable products, as identifying absolute targets for the global sustainable food system is truly a challenge associated with great uncertainty (Einarsson et al., 2019). Moreover, the final sustainabilty outcomes are a result of the total amounts of products consumed, so it is always challenging to determine the sustainability of a single product. Our new method for calculating absolute product group-specific thresholds could be extended and refined. It is also important to note that only environmental sustainability is considered, and not *e.g.*, health effects from different foods, agronomic aspects such as soil quality, or other socio-economic aspects, which could be included in a similar tool (Lukas et al., 2016).

4.4. The difficulty of including impacts from pesticide use

A major limitation with the evaluation of foods in the Vego-guide was how impacts from the use of pesticides were included. Ecotoxicity/novel entities was considered of high relevance for the production of plant-based foods and of high importance for users (Table 3). Statistics on pesticide use per hectare provided by FAOSTAT (2018) for different countries show that the use varies widely. However, no global dataset of pesticide use per *crop* is available. In general, thousands of substances are used and there is poor monitoring of these in most countries (Leclerc et al., 2019). In addition, the simple indicator kg AS per kg crop does not capture the toxic effects of the pesticide. Methods for assessing these impacts for different chemicals are available and are being improved and harmonized (Fantke et al., 2018), but require information on the substances used per crop, which is commonly not available. Hence, a global data-driven approach was not possible to use in the Vego-guide, so we chose the approach of using organic certification as an evaluation criterion, in combination with the very coarse method of judging products based on whether they were produced in the EU, and hence covered by the relatively rigid EU pesticide legislation, or not. However, some countries outside the EU have similar legislation, and hence presumably similarly low pesticide use, but no systematic evaluation system applicable to all exporting countries relevant for the Swedish market was found. The chosen approach carries the risk of harming producers in countries outside the EU, which was considered unfair and a major drawback. Therefore, the evaluation criteria for pesticide use were intensively discussed during development of the guide, including the option not to include this environmental category. However, WWF judged it impossible to release a guide for plant-based products without the inclusion of impacts from pesticide use, as this aspect is very important to consumers, and since fruit and vegetables are crops with major pesticide use. Therefore, it was decided that including this far from optimal approach was better than omitting pesticide use impacts completely. Data showing lower maximum residue levels (MRL) for foods in the EU (Handford et al., 2015) and more common transgression of MRL for products produced outside the EU and imported (EFSA, 2018) gave some support for the chosen strategy. However, improving the criteria for this category in coming updates of the guide was seen as very important. Interesting new research emerging in this area could be useful, *e.g.*, Leclerc et al. (2019) suggest use of extrapolation techniques to fill data gaps on pesticide use.

The way in which pesticide use was included in the guide influenced the results. After weighting, only certified products received a green star in the final evaluation (Table 5, Table S4). This was because the evaluation criteria for pesticide use, where only certified products with very little or no pesticide use received a green star and all non-certified products received either a yellow or an orange rating, influenced the results. The products received 3–4 points for the yellow-orange ratings, making it impossible to achieve $\leq$5 points (required for a green star) in the final evaluation. This means that, based on the final evaluation, users of the guide cannot see if a product meets the calculated thresholds based on the planetary boundaries. For that reason, we recommend displaying the results for all four environmental categories in the Vego-guide. This would also be consistent with the target group, as interested consumers are likely to want to know the underlying ratings leading to the final evaluation.

5. Conclusions

We developed a method for environmental multi-criteria evaluation of plant-based food products in terms of climate, biodiversity, water, and pesticide use impacts. Adding more impact categories than the commonly used climate impact gave a fuller and more complex picture of potential environmental impacts of plant-based products. Available environmental footprint and LCA data were adapted for the specific (Swedish) market, where the consumer communication tool (Vego-guide) will be used. For environmental evaluations, we developed a method for calculating absolute sustainability thresholds for individual plant-based food products within five product groups. Comparing the environmental impact of these products is challenging, due to their different functions (providing protein or carbohydrates etc.) in a complete diet. We used the functional unit of 1 kg product in a store in Sweden and applied different thresholds for environmental evaluation of the different food groups, hence capturing the different functions of the foods. This enabled evaluation of different products on the same grounds, *i.e.*, using the global sustainability boundaries and the same functional unit for all food products, while visualizing differences in environmental impact within the groups. The method provides a way to use extensive amounts of data of varying quality, reducing the complexity in assessing the environmental impacts of food products. It therefore facilitates choices between food products within the same food group, for more environmentally sustainable consumption of plant-based foods.

CRediT authorship contribution statement

Hanna Karlsson Potter: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Resources, Software, Visualization, Writing - original draft. **Elin Röös:** Conceptualization, Formal analysis, Investigation, Methodology, Funding acquisition, Project administration, Supervision, Validation, Writing - review & editing.

Declaration of competing interest

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

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Appendix A. Supplementary data

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