Journal of Cleaner Production 519 (2025) 146002

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Introducing a comprehensive and configurable tool for calculating environmental and social footprints for use in dietary assessments

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ARTICLE INFO

Keywords:
Diet analysis
Environmental pressure
Food consumption
Food systems
Sustainability

ABSTRACT

The urgent need to transform dietary patterns to mitigate climate change, biodiversity loss, and other environmental challenges is well-established. While life cycle assessments and footprinting approaches provide valuable insights at the product level, comprehensive evaluations of entire diets are necessary to inform sustainable food choices. This paper presents the Sustainability Assessment of Foods And Diets (SAFAD)-tool, an open-source platform designed to assess the environmental and social impacts of foods and diets across nine European countries. SAFAD extends existing methodologies by offering expanded data coverage, multi-dimensional sustainability indicators, and customizable parameters for enhanced applicability. In its basic configuration, the tool includes footprints of 1804 food items, ranging from raw primary commodities like tomatoes, bananas and chicken meat, to composite foods, meals and drinks compatible with those used in dietary surveys, like different types of bread, pizza and ready-to-drink coffee. We describe the underlying methodology and demonstrate the tool's capability to evaluate dietary transitions. The tool integrates ten key indicators, including carbon footprint, biodiversity loss, and novel metrics for animal welfare and antibiotic use, enabling a comprehensive assessment of dietary sustainability. The tool's configurability allows users to adjust food waste levels, countries of origin, recipes, and emission factors, facilitating scenario analyses of mitigation strategies. Future research should focus on expanding geographic coverage, refining sustainability metrics, and integrating health-related indicators to provide a more comprehensive evaluation of dietary patterns. The SAFAD-tool simplifies the assessment of the environmental sustainability of different dietary patterns captured in dietary surveys, while also enabling the assessment of any diet, defined either as ready to eat meals or raw commodities, or a mix.

1. Introduction

The urgency of transforming dietary patterns to mitigate climate change, biodiversity loss and other environmental challenges is well-established in food systems and environmental research (Foley et al., 2011; Hallström et al., 2015; Poore and Nemecek, 2018). Dietary change, especially the reduction of animal sourced foods, is crucial as technical and management improvements in production will not be enough to reach environmental targets (Arrieta and Aguiarb, 2023; Clark et al., 2020; Herzon et al., 2024; Willett et al., 2019). This is especially relevant in high-income settings; Sun et al. (2022) demonstrated that adopting a healthy and predominantly plant-based diet in high-income nations could reduce global agricultural emissions by 61%. To effectively reduce environmental pressures from the food system, robust assessment methods are needed to capture the complex trade-offs between environmental, social, and health-related sustainability dimensions. These methods should be tailored to different decision contexts, enabling informed decision-making for policymakers, industry stakeholders, and consumers alike.

One commonly used methodology for assessing the environmental impact of food products is life cycle assessment (LCA) and footprinting approaches, typically quantifying impacts per kilogram of food product

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https://doi.org/10.1016/j.jclepro.2025.146002
Received 21 July 2024; Received in revised form 7 June 2025; Accepted 14 June 2025
Available online 24 June 2025

(Matuštík and Kočí, 2021; Harrison et al., 2022; Poore and Nemecek, 2018; Ran et al., 2024). Assessments per kg of food are crucial for various applications. These include food labelling practices such as carbon footprint labelling (Taufique et al., 2022) and information-based interventions to guide consumers towards more environmentally sustainable food choices (Kwasny et al., 2022; Karlsson Potter and Röös, 2021). Per kg of food assessments are also needed for implementation and evaluation of fiscal policies like carbon-based food taxation (Mészáros et al., 2024) or assessing environmental impacts of VAT alterations (Springmann et al., 2025). They are also integral to industry-level strategies for mitigating environmental impacts (Ingrao et al., 2015). However, for the food system as a whole, total impact is determined by the population-level consumption in combination with the per-kilogram environmental footprint of individual products. Therefore, approaches that go beyond product-level assessments and evaluate the sustainability of entire diets are particularly relevant.

The growing recognition of the importance of the environmental and social sustainability of diets has prompted integration of environmental considerations into fields such as nutrition, public health, and food policy (Sabaté et al., 2016; Guo et al., 2022). Studies often employ LCA data or footprinting data to estimate diet level environmental burdens by multiplying food consumption data by corresponding product-level impact factors. This methodology has been widely used across various global contexts (Hallström et al., 2015), including the Nordic countries (Bruno et al., 2019; Hallström et al., 2022), Mexico (Curi-Quinto et al., 2022), and China (Cai et al., 2024). Another common approach involves mathematical optimization techniques to design diets that minimize environmental footprints while maintaining nutritional adequacy (Gazan et al., 2018; Eustachio Colombo et al., 2023). More complex models, such as food system and land-use models, provide broader insights into agricultural sustainability but often lack product-specific granularity needed for diet assessment based on individual food consumption data (Karlsson and Röös, 2019; Muller et al., 2017; van Zanten et al., 2022; Erb et al., 2016).

Assessing the environmental impacts of diets presents unique challenges due to specific data requirements. Food consumption data typically comes from cohort studies (*e.g.*, Hjorth et al., 2020; Hallström et al., 2021), dietary surveys (*e.g.*, Rose et al., 2019; Lindroos et al., 2023; Scarborough et al., 2023), or food supply statistics (*e.g.*, Moberg et al., 2020). These sources generally provide information on the quantities of various foods consumed but often lack details regarding the origin of commodities or the production methods employed. While trade statistics can offer insights into the countries of origin for certain commodities, many environmental impact indicators require more granular, site-specific data (*e.g.*, level of water stress, and status of local waterways). Without such detailed information, the application of certain indicators becomes either unfeasible or irrelevant, compelling researchers to rely on broader, less precise measures (Ran et al., 2024). This limitation highlights the need for tools that include indicators specifically tailored for assessing diets described in food intake data, capable of providing meaningful results even with limited information on food origins and production methods. The challenge is to balance the need for precise, site-specific assessments with the practical limitations of available data.

In addition, food intake data from cohort studies, dietary surveys etc. often describe foods in the form in which they are consumed (*e.g.*, lasagna, mixed salad, or orange juice), whereas LCA data is typically available at the raw commodity level or only for a limited number of food items and meals. Bridging this gap requires decomposition of complex food items into their base ingredients, often through labor-intensive manual processes. For example, Hallström et al. (2021) used recipes from the Swedish National Food Agency, online resources and scientific literature to convert food items and meals into raw commodities.

A limitation of most studies on the sustainability of foods and diets is the use of only one or a few indicators (Aldaya et al., 2021; Harrison et al., 2022; Ran et al., 2024; van Dooren et al., 2018), most commonly the carbon footprint. Although reducing greenhouse gas emissions is a crucial goal, food production impacts a broad range of environmental dimensions, including biodiversity, land use, freshwater consumption, eutrophication, and pesticide pollution (Willett et al., 2019; Ran et al., 2024). Relying solely on carbon footprint assessments risks oversimplification and potential trade-offs, as optimizing for one impact may exacerbate another. Furthermore, social sustainability dimensions, such as labor rights, fair trade, and especially animal welfare, are frequently omitted despite their ethical relevance (Lanzoni et al., 2023). Animal welfare is particularly pertinent in sustainability discourse as intensive livestock production systems, while often more carbon-efficient, tend to score poorly in terms of welfare outcomes (Rydhmer and Röös, forthcoming). In general, a more efficient animal production system will have lower environmental impacts per kg of product. High efficiency at farm level can be the result of good management improving animal health and survival, thereby also improving animal welfare (Barnes et al., 2011). There are, however, trade-offs between efficiency and animal welfare (Verkuijl et al., 2024). Selection for high growth rate increases efficiency but for chicken, for example, the genetic correlation between growth rate and leg health is unfavorable (Hartcher and Lum, 2020). Hence, there is a trade-off between environmental impact and animal welfare when replacing red meat with chicken that risks being omitted if animal welfare is not included in the assessment.

Antimicrobial resistance due to antibiotic overuse in animal husbandry poses significant public health risks (Tang et al., 2017), yet it is rarely included in dietary sustainability assessments although the amount of antibiotics varies substantially between countries and production systems. There are also trade-offs between efficiency and the use of antibiotics. Using antibiotics for disease prevention and as growth promoters increases growth rate and efficiency and thus decreases the environmental impact of meat. On the other hand, high use of antibiotics in animal production increases the risk of antibiotics resistance which threatens the health of humans as well as animals (Tang et al., 2017). The use of antibiotics as growth promoters is forbidden in the EU but common in other countries, for example in the USA (Patel et al., 2020). Furthermore, use of antibiotics by routine for prevention and as growth promoters can mask issues related to hygiene, stocking density and bad management which can decrease animal welfare.

As a response to the increased interest in environmental assessments of foods and diets, a range of datasets have been developed. Some are published in research papers, one of the most comprehensive being the paper by Poore and Nemecek (2018) synthesizing results from 570 LCA studies including five environmental indicators. There are also open-access (*e.g.* Agribylase®, 2025) and proprietary (*e.g.* the RISE climate and biodiversity databases; RISE, 2025; the ESU World Food Database; ESU-services Ltd, 2025; Agri-footprint; website) databases containing a variety of indicator data for foods. However, most databases tend to lack coverage of food items found in dietary surveys, often include a limited set of indicators and are tailored to specific geographic contexts, and limiting their generalizability and adaptability for other contexts. The French Agribalyse® (2025) database, one of the more comprehensive LCA databases on food products, includes 2500 ready-to-eat foods and 16 indicators but data correspond to products produced and consumed in France. Similarly, the ESU World Food Database (ESU-services Ltd, 2025) contains data for food products relevant for the Swiss market, and it comes with a licensing cost. Configuration of most such datasets, including changing *e.g.* recipes, country of origin of food commodities, or assumed waste levels, requires specific LCA software, which might present a barrier to users not familiar with such tools. Other initiatives, such as the Product Environmental Footprints (PEF) initiative within the European Union, also offer methodology and data for assessing the environmental impacts of food, but do not cover all food products and are more aimed at industry use cases. No database currently contains data on animal welfare loss and the use of antibiotics associated with different food products.

Consequently, there is a pressing need for tools and datasets specifically designed to evaluate a broad set of impacts (including animal welfare and use of antibiotics) of dietary patterns. Developing such resources would enhance the accuracy and relevance of diet-related assessments, facilitating more informed decision-making in nutrition and sustainability research.

In response to this need, we present the Sustainability Assessment of Foods And Diets (SAFAD) tool, an open-source platform designed to provide comprehensive environmental and social impact assessments of foods and diets covering nine European countries. SAFAD extends beyond existing methodologies and tools by offering expanded data coverage (*i.e.* providing impact data for food items commonly found in dietary surveys), multi-dimensional indicators (*i.e.* incorporating eight environmental indicators and indicators for animal welfare and antibiotic use) and extensive user customization (*i.e.* allowing modification of parameters such as food waste levels, recipes, conversion factors, and emission factors to enhance applicability). This paper presents the tool's functionalities, demonstrates its application through footprint calculations for individual food items and entire diets, and explores its utility in assessing dietary transitions towards more sustainable food consumption patterns.

2. Method and data

2.1. Overview of the SAFAD tool

The SAFAD tool is built on work by Moberg et al. (2019, 2020, 2021). While their work only contains data representative for the Swedish market, the SAFAD tool includes data for nine European countries. In addition, the default version of the SAFAD tool contains footprints for 1805 food commodities, food products and meals, in comparison with the 52 food groups in Moberg et al. (2021). Furthermore, the transparency and configurability of the footprint data enabled by the SAFAD tool (on the https://safad.se/website) brings substantial innovation to this type of database.

The model consists of i) the SAFAD engine, ii) two data input files, one containing the indicator values of raw primary commodities (RPC) (*e.g.* beef meat, wheat grain, oranges), and the other containing the data of the diet (or meal) to be assessed, and iii) a number of parameter and emission factor files (see Supplementary Material (SM) section S1 for more details). The data can be configured and downloaded by non-experts from a webpage (https://safad.se/). All model code is provided under the MIT license (https://github.com/SLU-foodsystems/safad).

The SAFAD engine is a web-application that calculates food item footprints and performs the diet assessment of a chosen diet or meal. By default, the web-application shows results for typical example diets for each country, derived from the national dietary surveys for different populations (*e.g.* adults or children). To assess the impact of any diet (or meal), the user uploads any consumption data (in the stipulated format). This allows for the assessment of any diet - existing or hypothetical - as user-defined inputs, thus enabling comprehensive dietary sustainability evaluations across diverse scenarios.

2.2. Indicators

Data on eight environmental indicators and two social indicators are provided. The environmental indicators are chosen to be relevant and feasible for dietary assessments, following expert-informed recommendations in Ran et al. (2024). These are carbon footprint, cropland use, new nitrogen (N) input, new phosphorous (P) input, blue water use, pesticide use, biodiversity loss from land use and ammonia emissions. The social indicators are related to animal welfare and the use of antibiotics. See SM S2 for more information on the indicators.

The carbon footprints include emissions of greenhouse gases from farming/fishing (including the production of farm inputs), fuel and electricity used in processing (*e.g.*, milling, cheese-making), preparation (*e.g.*, cooking, roasting), packaging and transport (to the warehouse). Emissions from land use change are also included, based on data from Pendrill et al. (2022). To convert methane and nitrous oxide emissions to CO_2-equivalents (CO_2e) the values from the IPCC AR6-report (Forster et al., 2021) were used, *i.e.* 27.0 for biogenic methane, 29.8 for fossil methane and 273 for nitrous oxide. Results are also provided disaggregated for the different greenhouse gases, enabling the use of any other climate metric. Only emissions and resource use at the farming/fishing stage are included for the rest of the indicators, as the contribution at other life cycle stages for these indicators is small.

2.3. Functional unit and system boundaries

The footprints for the food items are calculated per 1 kg of food (*e.g.*, tomatoes, bread) or dish (*e.g.*, lasagna, meat stew, pizza). For meat, fish, and seafood, footprints are given per kg of bone-free edible weight.

The assessment of the carbon footprint for all food items includes emissions related to primary production (including the production of inputs), processing, packaging and transport. In terms of processing emissions, what is included in the carbon footprint depends on the food item. For example, for roots, vegetables and fruits sold raw, there are no processing emissions included (except for washing which is included in primary production), while composite foods (*e.g.* bread) includes several processing steps (for bread milling, baking). Hence, when the diet is specified as meals or processed foods, the carbon footprint includes emissions from food processing, while if the diet is specified as raw commodities, food processing will not be included. In addition, how diets are specified also affects packaging types. The default configuration in the tool assumes that foods are packaged as they are specified in the diet. For example, raw potatoes are typically sold in paper bags, but boiled potatoes are commonly sold in a tin or glass jar. Naturally, potatoes can also be boiled at home, not requiring this packaging, but for consistency, the default data configuration treats packaging of all foods equally. This can, however, be easily configured according to the ways different commodities are typically sold and eaten in different regions (see SM S9).

2.4. Footprint of raw primary commodities

The tool allows for the use of any footprint data for RPCs. These should be given per kg of commodity produced in a certain country without considering waste or conversion to edible products. The inventory data used to calculate the default footprints of the RPC (*i.e.* those provided on the website https://safad.se/) were gathered from a variety of sources. Where possible, national and international official and publicly available statistics (*e.g.* from FAOSTAT, Eurostat and national inventory reports) were used. This data was complemented with openly available data from *e.g.* trade organizations and from scientific literature. Large gaps were found for several types of inventory data which were addressed through extrapolations and approximations (see SM S4 for details). Here, we briefly describe the default RPC-dataset accompanying the SAFAD tool version 1.245 (24-10-30). Information on updates and following versions of the tool and data are available on https://github.com/SLU-foodsystems/safad.

2.4.1. Crops

A total of 113 crops were included. Country-specific footprints were calculated for crops produced within the nine target countries, as well as for crops grown in countries that export substantially to these nine countries. Export countries were included if they held a market share exceeding 10% in any of the nine target countries. For crops consumed in low quantities in Europe (*e.g.*, areca nuts, canary seeds, etc.), footprints were approximated using the footprints of similar crops grown in the same country or region. Similarly, for countries providing smaller shares of a product, footprints were approximated with those of the

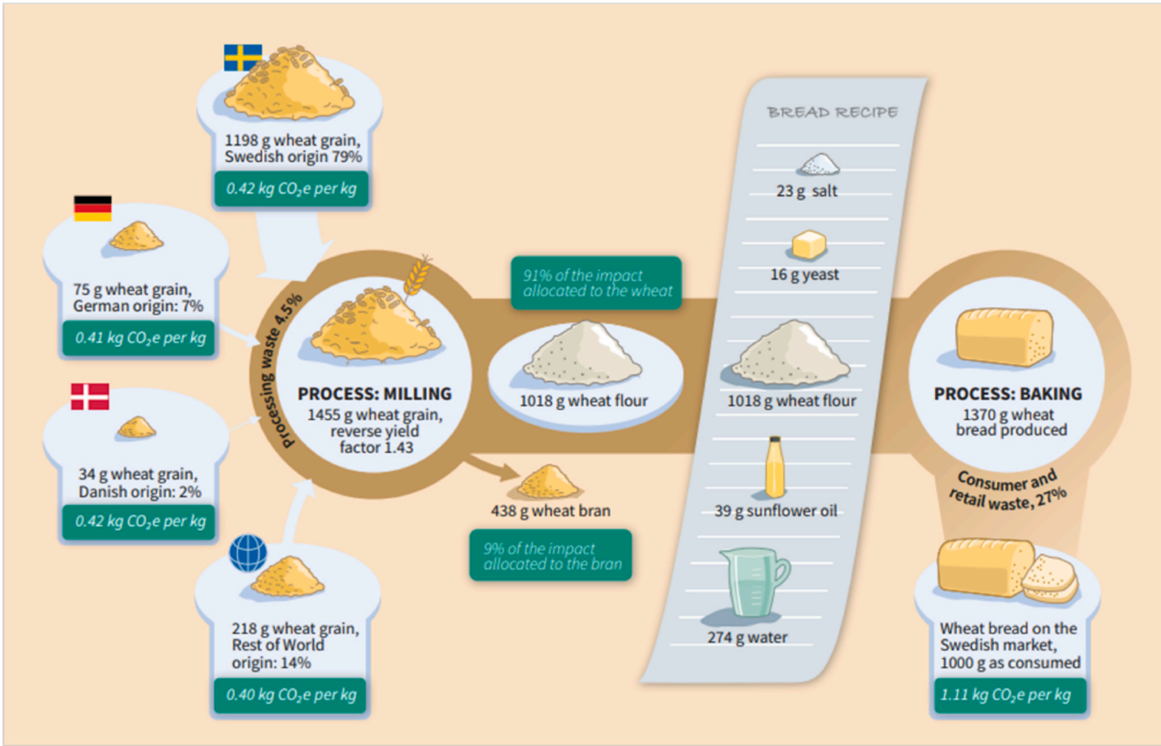

Fig. 1. Carbon footprint calculations for wheat bread in Sweden using the SAFAD-tool. Sourcing of raw commodities is based on import shares of wheat on the Swedish market and the amount required of the related ingredient ('reverse yield factor'). Carbon footprints and allocation of impacts between the main product and by-products is depicted in green squares. The final carbon footprint of consumed bread includes emissions from raw primary commodities, transportation of these commodities, processing (milling, baking), and packaging. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

same product from a country in the same region (*e.g.*, bananas from Colombia were approximated using bananas from Costa Rica). In the current version (version 1.245), the footprints of 783 unique crop-country combinations were included, after making the above-mentioned approximations.

2.4.2. *Terrestrial livestock products*

For pig, chicken, cattle, lamb and rabbit meat, hen eggs and cattle milk, we calculated country-specific footprints based on country-specific livestock diets, manure management and production parameters (*e.g.*, milk yields, mortality rates, slaughtering weights, etc.) where available (see SM S4.3 for details on methods and data). Beef meat is produced in a wide variety of systems with considerable variation in environmental impacts (Poore and Nemecek, 2018). Here we divided the production of beef in the European countries across four different systems: i) meat from culled dairy cows, ii) meat from dairy calves raised intensively indoors and slaughtered at a young age (9 months), iii) meat from dairy calves raised more extensively and slaughtered at an age of 24 months, and iv) meat from cows and their offspring in suckler herds. We established the share of meat coming from the different systems in the different countries based on slaughtering statistics and the number of dairy and suckler cows across countries (Eurostat, 2022) and used a weighted average to aggregate the footprints. We also used these shares of production systems to calculate the average animal welfare index and the use of antibiotics for beef from different countries.

For other terrestrial livestock products (those consumed in much smaller quantities), we approximated their footprints using the products mentioned above, *e.g.*, eggs from other birds were approximated with hen eggs, and sheep milk was approximated with cattle milk.

2.4.3. *Aquatic products*

For aquatic products, *i.e.* fish and other seafood products, we used data from Gephart et al. (2021) who provide standardized estimates for the carbon footprint of 23 species groups, drawing from 1690 farms and 1000 unique fishery records worldwide. As Gephart et al. (2021) only provide aggregated values, we used the shares for different greenhouse gases and life cycle stages from Moberg et al. (2019) to disaggregate emissions across carbon footprint indicators for seafood produced in aquaculture.

2.4.4. *Novel foods*

For novel food products such as cell-cultured meat and milk, precision fermented proteins, algae, and microbial fats, we derived data from published LCAs (details in SM S4.4). We collected data on the energy requirements for producing each novel food item, categorized by process type (*e.g.*, bioreactor energy, bioreactor cleaning, water filtration, drying, fermentation, separation). For agricultural inputs, we used the footprints for each ingredient from our list of crop and livestock products (*e.g.*, glucose, wheat, egg white). For non-agricultural inputs (*e.g.* synthetic agents, sulfates/phosphates, vitamins, minerals, and oxygen required for fermentation or cell cultivation in bioreactors), we categorized these as 'other' inputs and used the impact data from the original studies for these inputs.

2.5. *Food recipes and conversion factors*

Approximately 1800 recipes supplied by the European Food Safety Authority (EFSA) have been incorporated into the SAFAD tool. These recipes represent commonly consumed foods and dishes, providing a general representation of the culinary landscape in Europe. EFSA developed these data to enable the breakdown of composite foods,

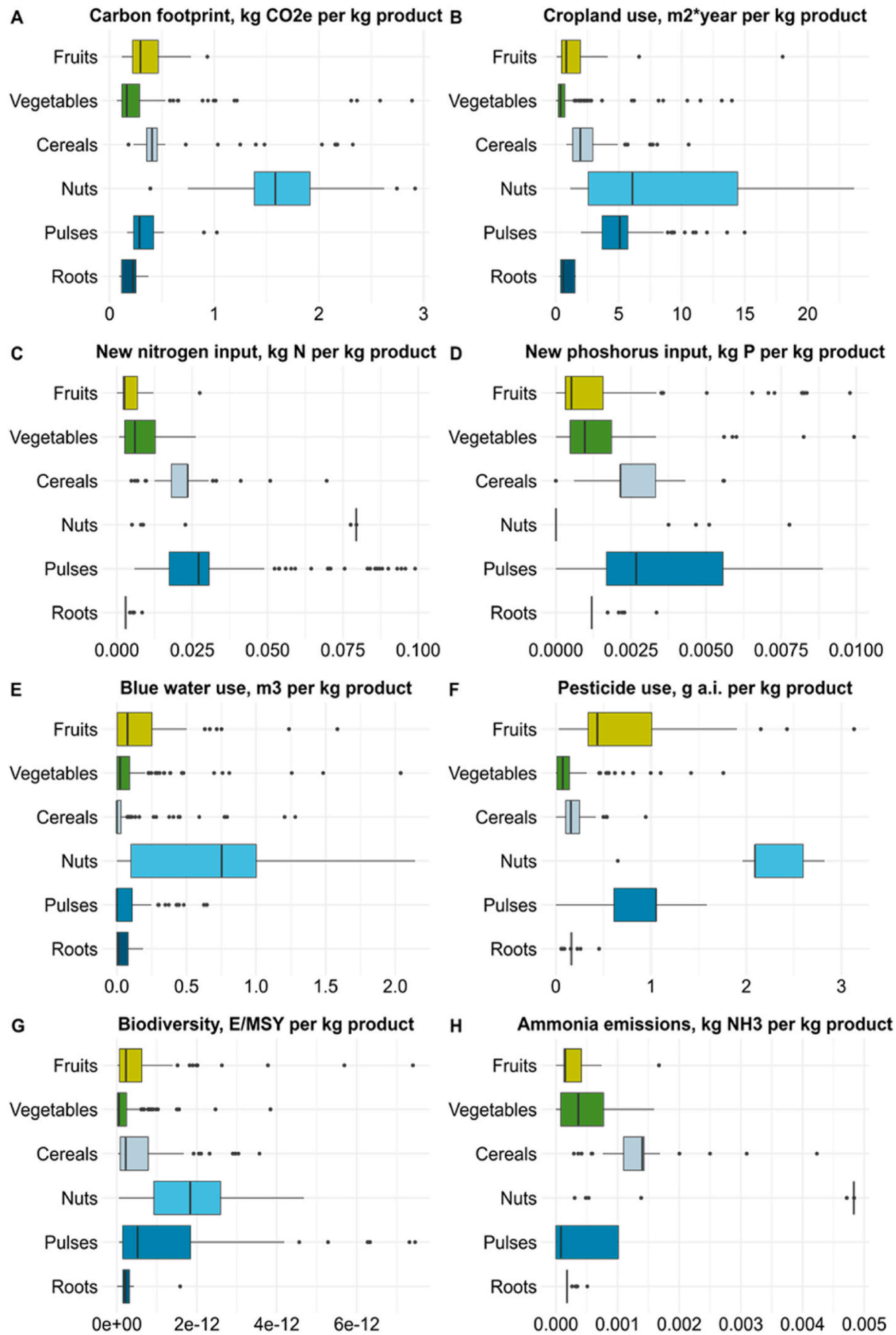

Fig. 2. Indicator values for selected plant-based RPC categories and eight sustainability indicators. Centerlines show the median; box limits indicate the 25th and 75th percentiles; whiskers extend 1.5 times the interquartile range from the 25th and 75th percentiles; and presented outliers are represented by dots. Some outliers excluded for carbon footprint, new nitrogen and phosphorus, water, pesticides and biodiversity loss when plotting graphs.

present in their food consumption database, into their constituent parts (RPCs) to facilitate assessment of dietary exposures (EFSA, 2019). A 'reverse yield factor' specify the amount of an RPC that is needed to produce one unit of an edible-RPC (*e.g.*, the amount of rape seeds that is needed to produce one unit of rape seed oil). We used these ingredient lists and reverse yield factors for all countries. However, to exemplify how country specific recipe files can be used in the tool, we also included data based on food recipes for Swedish foods supplied by the Swedish Food Agency.

We applied economic allocation factors from Moberg et al. (2019) to divide emissions and resource use across products that come out of the same RPC where applicable. For example, for rapeseed oil, 72% of the impact from rapeseed cultivation is allocated to oil and 28% to rapeseed cake (used as animal feed), based on the economic value of the oil and cake.

The food item footprints are determined using a recursive, divide-and-conquer algorithm that breaks down foods into country specific RPCs based on import shares, records food processing methods, yields, and economic allocation factors along the way, as well as packaging and transports. The energy requirements of food processing are translated to greenhouse gas emissions per unit of weight using energy related emission factors. Similarly, different packaging types are mapped to greenhouse gas emissions per unit of weight. Generalized emission factors per kg of food transported between consumption and production

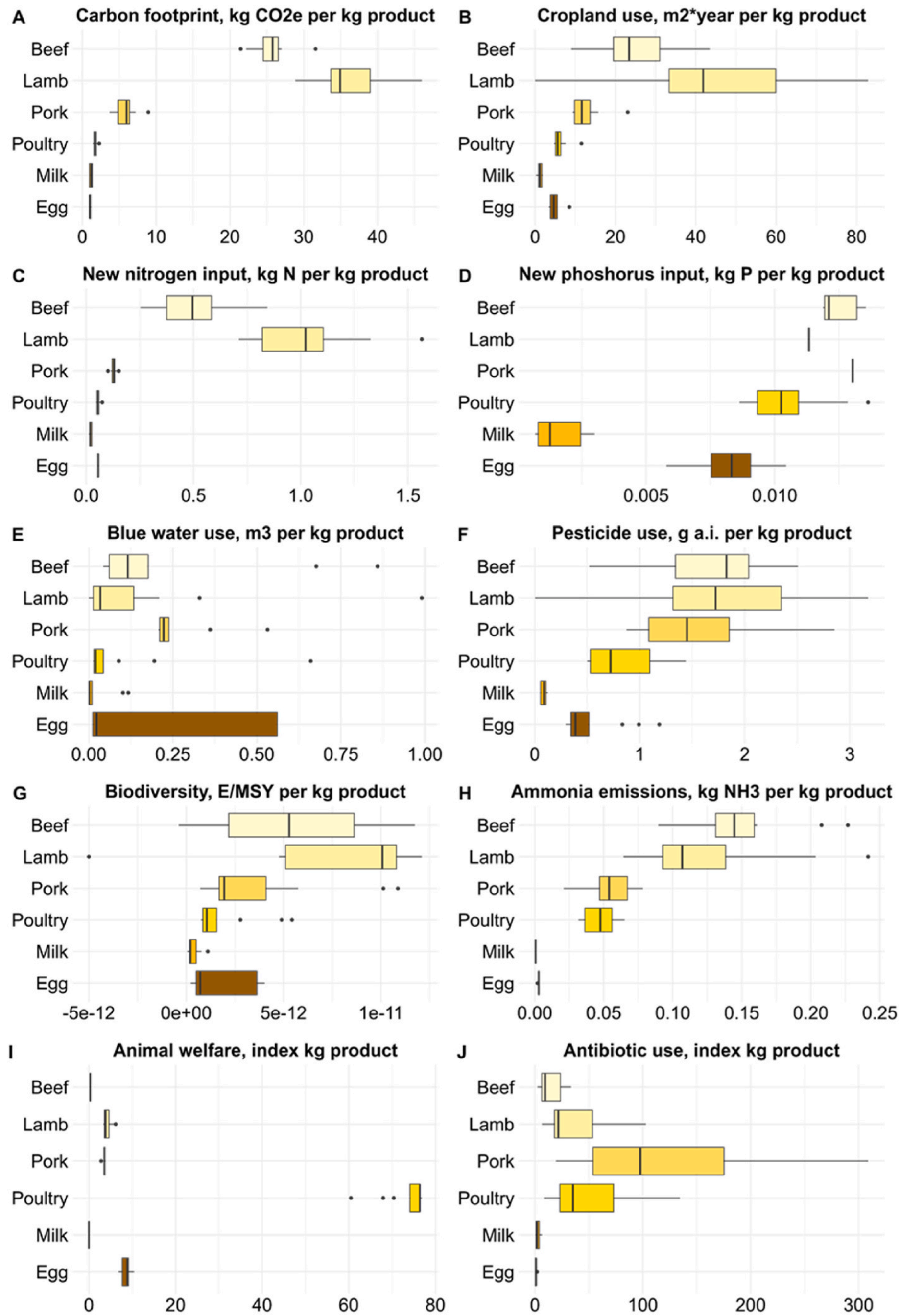

Fig. 3. Indicator values for selected animal sourced commodity categories and ten sustainability indicators. Centerlines show the median; box limits indicate the 25th and 75th percentiles; whiskers extend 1.5 times the interquartile range from the 25th and 75th percentiles; and presented outliers are represented by dots. Some outliers excluded for water, pesticides, biodiversity loss and animal welfare when plotting graphs.

countries are applied to include greenhouse gas emissions from transport. Three types of waste, from production (from harvest to retail), from retail and from consumption, are taken into account (Fig. 1).

The footprint calculations take a mostly attributional approach. They assess the anthropogenic impacts associated with the processes involved in a food product's life cycle, following normative rules that define the inventory boundary based on the physical processes of production, consumption, and disposal (Brander, 2016).

2.6. Food origin and transports

Foods and raw commodities in a diet are typically sourced from many different places globally. We account for this by using a weighted average of the footprints of RPCs from different countries based on trade data from Schwarzmueller and Kastner (2022). Trade data for some crops, *e.g.* rice and palm oil, was missing and was complemented using data from FAOSTAT and Eurostat (see SM S6). In cases where environmental data for a commodity in a given country was missing, a 'Rest of World' approximation was used constituting the average of the footprint of the countries for which data does exist.

Greenhouse gas emissions from transport were determined for each combination of producing and consuming country. Firstly, the total distance transported per transportation type (boat, truck, and train) within and between countries was determined (see SM S10) and total emissions were calculated with vehicle-specific emission factors from NTMCalc 4.0 (2023).

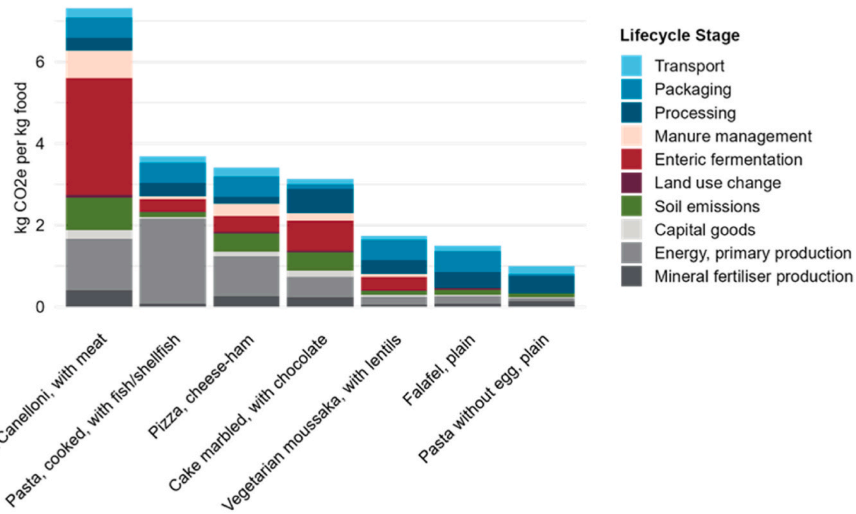

Fig. 4. Carbon footprint of composite foods in their cooked form, including waste.

We assume that the RPCs, rather than the processed products, are transported (*e.g.*, wheat rather than wheat flour or bread) but make exceptions for some types of processing which typically take place close to the production site, including winemaking, juicing and oil extraction. Transport from the retailer to the consumer is not included.

2.7. Processing and packaging

We added the emissions associated with processing of food items based on the processes provided per ingredient as specified by EFSA (2019). Carbon footprints for these processes were found in the literature (see SM S8). In addition, we specified additional processes to account for processes applied to ready-to-eat meals and foods (*e.g.*, cooking the food or baking the bread). We assume that all food processing takes place in the consumption country using national electricity mixes.

Foods and raw commodities are packaged in many ways. We account for packaging based on modified packaging weight data from Castellani et al. (2017) and Notarnicola et al. (2017) (Table S9). We created general packaging categories based on the presented foods and raw commodities and calculated the average weights of associated packaging materials. By doing so, we can assume general packages relevant to the European market (*e.g.*, fruit and vegetable packaging are assumed to be the average packaging materials present in the literature for tomatoes, bananas, apples, oranges, and potatoes). The carbon footprint of the packaging materials was retrieved from the ecoinvent database (Ecoinvent centre, 2023) (Table S10). In our methodology, we assume all consumed products are pre-packaged for retail. This avoids double-counting of packaging but results in attributing packaging to home-prepared items while omitting packaging for their constituent ingredients. For instance, a homemade pizza is assigned packaging (*e.g.*, a box) and its ingredients (such as flour, tomato sauce, and cheese) are considered unpackaged.

3. Results

3.1. Footprints per kg of raw primary commodities

Indicator values for the RPCs from various countries serve as input to the SAFAD tool. Figs. 2 and 3 illustrate the magnitude and distribution of these indicator values as provided in the default input file (version 1.245).

Most plant-based RPCs exhibit substantially lower climate impacts compared to animal-based ones, except for nuts. Specifically, 88% of plant-based RPCs have a climate impact below 1 kg CO_2e per kg, and 74% fall below 0.5 kg CO_2e per kg. High carbon footprints of plant-based RPCs is commonly a reflection of substantial deforestation-related emissions, as seen in coffee beans sourced from Indonesia and Peru. Among animal-based RPCs, ruminant meat stands out as having one of the highest carbon footprints. Beef from dairy systems exhibits a lower carbon footprint than beef from meat-only systems, as emissions are allocated between milk and meat. Chicken meat has a relatively low carbon footprint but is associated with high animal welfare losses (Fig. 3).

Animal-based RPCs also require higher inputs of new nitrogen and phosphorus, primarily due to the substantial feed quantities needed per kg of product produced. This feed demand also results in greater cropland use, particularly for ruminant meat. However, in countries like Ireland and New Zealand, much of the feed comes from pasture rather than cropland, mitigating cropland pressure. Antibiotic use varies substantially across countries and production systems, especially for pork, as indicated by the wide range in Fig. 3.

Most fruits, vegetables, and root crops have high yields per unit area, leading to low cropland use. Nuts and legumes vary widely in land use efficiency due to differences in yield. For example, cashew nuts have low yields and therefore high cropland use, whereas coconuts, with higher yields, require less cropland per kg. Among legumes, lentils exhibit the lowest yields and highest land use, while peas, fava beans, and soybeans demonstrate higher yields and lower land use (Fig. 2).

For blue water use, pesticide application, and biodiversity impacts from land use, the differences between ruminant meat and other commodities are less pronounced (Figs. 2 and 3). Nut production, however, often demands substantial irrigation, resulting in high blue water use per kg produced. Pesticide use is particularly high for nuts, although data on this indicator is highly uncertain (Fig. 2).

Biodiversity impact from land use is influenced by both the land area required and the geographic location of crop (including feed) production. Ruminant meat and low-yielding crops such as certain nuts, seeds, and legumes from countries like Greece, Spain, and Italy exhibit the highest biodiversity loss due to extensive land requirements and high biodiversity loss factors in these countries. In contrast, ruminant meat produced in Northern Europe tends to have lower biodiversity impacts. Notably, beef and lamb from Sweden demonstrates negative biodiversity loss values, reflecting a net gain in species richness (compared to the ‘natural’ baseline) due to the use of biodiversity-rich semi-natural grasslands (Fig. 3; see Eriksson, 2022 for a discussion of the biodiversity value of such pastures).

Other commodities with substantial biodiversity loss include tropical

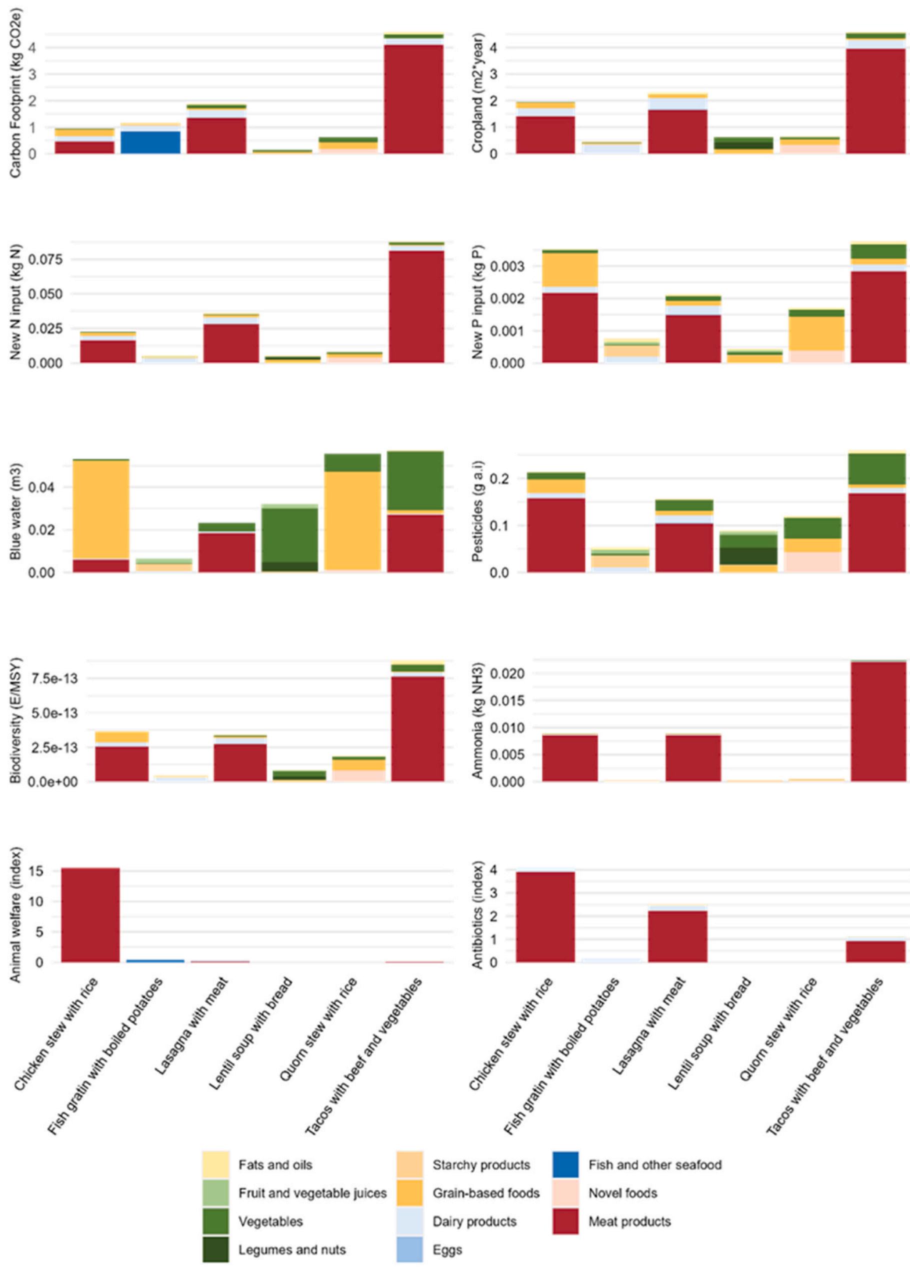

Fig. 5. Environmental impacts (per 1 standard portion) of composite foods on the Swedish market. Portion sizes are retrieved from the food database from the Swedish National Food Agency (SFA, 2023).

products such as coffee and bananas from Africa and South America. Conversely, high-yielding crops like tomatoes, cucumbers, carrots, and cabbages from Northern Europe show some of the lowest biodiversity impacts associated with land use.

3.2. Footprint of food items and meals

The carbon footprint of food products and meals is given as the total footprint in kg CO_2e, but emissions are also disaggregated across different life cycle stages, including primary production (*e.g.*, mineral fertilizer production, capital goods, soil emissions, energy use, and enteric fermentation), land use change, and post-farm emissions (*e.g.*, processing, packaging, and transport). Fig. 4 illustrates this breakdown using examples of cooked composite foods.

Consistent with findings on the high environmental impact of red meat (*e.g.*, Moberg et al., 2019; Poore and Nemecek, 2018), meals with substantial quantities of red meat exhibit high indicator values for carbon footprint, cropland use, new nitrogen and phosphorus inputs, water use, and ammonia emissions (Fig. 5). For instance, the taco meal and lasagna in Fig. 5 both contain beef, with the taco meal showing a higher carbon footprint due to a greater proportion of meat in its recipe.

The inclusion of multiple indicators in the SAFAD tool facilitates an analysis of trade-offs among various environmental impacts, and between environmental impacts and animal welfare and antibiotic use. Replacing red meat with chicken can reduce the carbon footprint of a meal. However, this substitution introduces trade-offs, as chicken-based meals are associated with substantially greater animal welfare loss. This example illustrates the importance of including multiple sustainability indicators when assessing the sustainability of meals and diets.

Table 1
Results from the assessment of the Swedish average diet as captured by supply data from the Swedish Board of Agriculture (2024), and percentage change through different changes through different mitigation options.

Indicator	Average Swedish Diet	Consumer food waste reduced by 50 %	Change half of beef for chicken	Domestic production of all product currently grown in Sweden
Carbon footprint	1.7 t CO_2e	−6.1%	−12%	−5.1%
Cropland use	0.24 ha	−5.9%	−6.6%	+8.9%
New nitrogen input	31 kg N	−6.2%	−12%	−1.9%
New phosphorus input	3.9 kg P	−6.1%	−1.8%	−3.8%
Blue water use	54 m^2	−6.2%	−2.2%	−14%
Pesticide use	489 g a.i.	−5.4%	-<1%	−10%
Biodiversity loss	5.6E-10 E/MSY	−5.9%	−5.5%	−27%
Ammonia emissions	5.2 kg NH_3	−6.0%	−16%	−3.2%
Animal welfare loss	1735 (index)	−5.5%	+30%	−6.1%
Use of antibiotics	1832 (index)	−5.6%	+5%	−51%

3.3. Diet assessments

The indicator results from assessing the average Swedish adult diet as captured by the latest food supply data (2022) as measured by the Swedish Board of Agriculture (SBA, 2024) is shown in Table 1.

The SAFAD tool also shows results from all indicators disaggregated across food groups (Fig. 6 top) or divided among different commodity groups (Fig. 6 bottom). In the latter case, the commodity groups contain the footprints associated with primary production of the raw material only and do not include the processing, packaging and transport footprints (greenhouse gas emissions from these stages are included in the total, but not shown in the figure; Fig. 6 bottom). In addition, the carbon footprint can be displayed disaggregated into the share of emissions from different lifecycle stages (Fig. 7 top) and different greenhouse gases (Fig. 7 bottom).

The SAFAD tool allows for adjustments of a range of parameters, enabling scenario analyses of dietary change and other mitigation options. Here, we demonstrate this capability using three examples applied to the average Swedish diet (based on food supply data from the Swedish Board of Agriculture; SBA, 2024): (1) reducing consumer food waste by 50%, (2) replacing half of the beef in beef dishes with chicken, and (3) shifting all commodities in the diet currently grown in Sweden to 100% domestic production (*e.g.* tomatoes which are grown in Sweden are assumed to be sourced only from Sweden, while for *e.g.* bananas which are not grown in Sweden current import shares are maintained). The results are summarized in Table 1.

Reducing consumer food waste by 50% results in a 5–6% reduction across all environmental indicators, under the assumption that with less consumer waste, less food is required to be produced, processed, transported, and packaged. Replacing half of the beef with chicken substantially reduces the carbon footprint (−12%), new nitrogen input (−12%) and ammonia emissions (−16%), but comes at the expense of a notable increase in animal welfare loss (+30%) (Table 1).

Switching to entirely domestic production for all commodities currently grown in Sweden yields mixed results across indicators. The carbon footprint decreases by approximately 5%, because of lower greenhouse gas emissions for some Swedish-produced commodities and a 31% reduction in transport emissions. However, since transport accounts for only 6% of the total emissions, this reduction has a modest impact on the overall carbon footprint. Land use increases due to the generally lower yields of some Swedish crops compared to their imported counterparts. Biodiversity impacts from land use, however, decrease substantially (27%; Table 1), as sourcing foods from domestic production reduces reliance on sensitive ecosystems, such as those in Southern Europe. Animal welfare loss is also reduced, due to Sweden's more stringent animal welfare regulations, and antibiotic use drops considerably, reflecting Sweden's minimal reliance on antibiotics in livestock production compared to other countries (ESVAC, 2023).

4. Discussion

4.1. Relevance of the findings and their application

This paper presents, to our knowledge, the first configurable, open-source tool designed to calculate both the environmental and social footprints of food and diets. The tool includes a large and diverse database of food items and meals, ensuring compatibility with European dietary survey data. It integrates ten key sustainability indicators, including those related to animal welfare and antibiotic use, allowing for a comprehensive assessment of food system impacts. This tool is designed to facilitate the sustainability assessment of various dietary patterns captured in dietary surveys. It also enables the evaluation of any diet, whether defined as ready-to-eat meals (as in dietary surveys), raw commodities, or a combination of both, such as in the FAOSTAT Food Balance Sheets (FAOSTAT, 2024). The broad set of indicators highlights trade-offs and synergies, as shown in the assessment of mitigation strategies for a more sustainable Swedish diet (section 3.3); reducing waste benefits all indicators, while replacing beef with chicken improves several environmental metrics but increases animal welfare concerns substantially. Prioritizing domestic production is generally beneficial, with particularly positive effects on biodiversity (Table 1).

The tool and the data it provides can be used in a multitude of use cases. It has already been used by the Swedish Food Agency for assessing the sustainability of adolescent diets (Lindroos et al., 2025) and children (Jacobsen et al., 2025). It has also been used to assess the environmental consequences of tax reforms (Larsson et al., forthcoming) and to evaluate future scenarios (Mazac et al., forthcoming). In a forthcoming study by Karlsson et al., data from the SAFAD tool was used to illustrate trade-offs between the climate impact and animal welfare when establishing a 'sustainable limit' to meat consumption. In a study measuring food intake and waste in preschools, the tool was used to assess the environmental impact of different serving styles (Jacobsen et al., forthcoming). Since recipes and waste levels were explicitly measured in this study, configuring them accordingly was essential. This was easily achieved using the SAFAD configuration files, demonstrating the tool's flexibility and its adaptability for diverse applications. The SAFAD webpage (https://safad.se/) provides an interactive platform where users can explore the environmental impact of foods and diets through a user-friendly interface. The tool allows visitors to search for specific food items and view the results on a wide range of indicators. Users can compare different foods side by side and gain insight into more sustainable choices. The presentation of carbon footprint results in multiple disaggregated formats enhances a comprehensive understanding of the sources and drivers of emissions. By disaggregating results based on food groups or raw commodities (Fig. 6), users can better identify the specific types of foods and ingredients that contribute to varying environmental pressures. This level of detail is particularly valuable for recognizing high-impact food categories and designing targeted strategies for

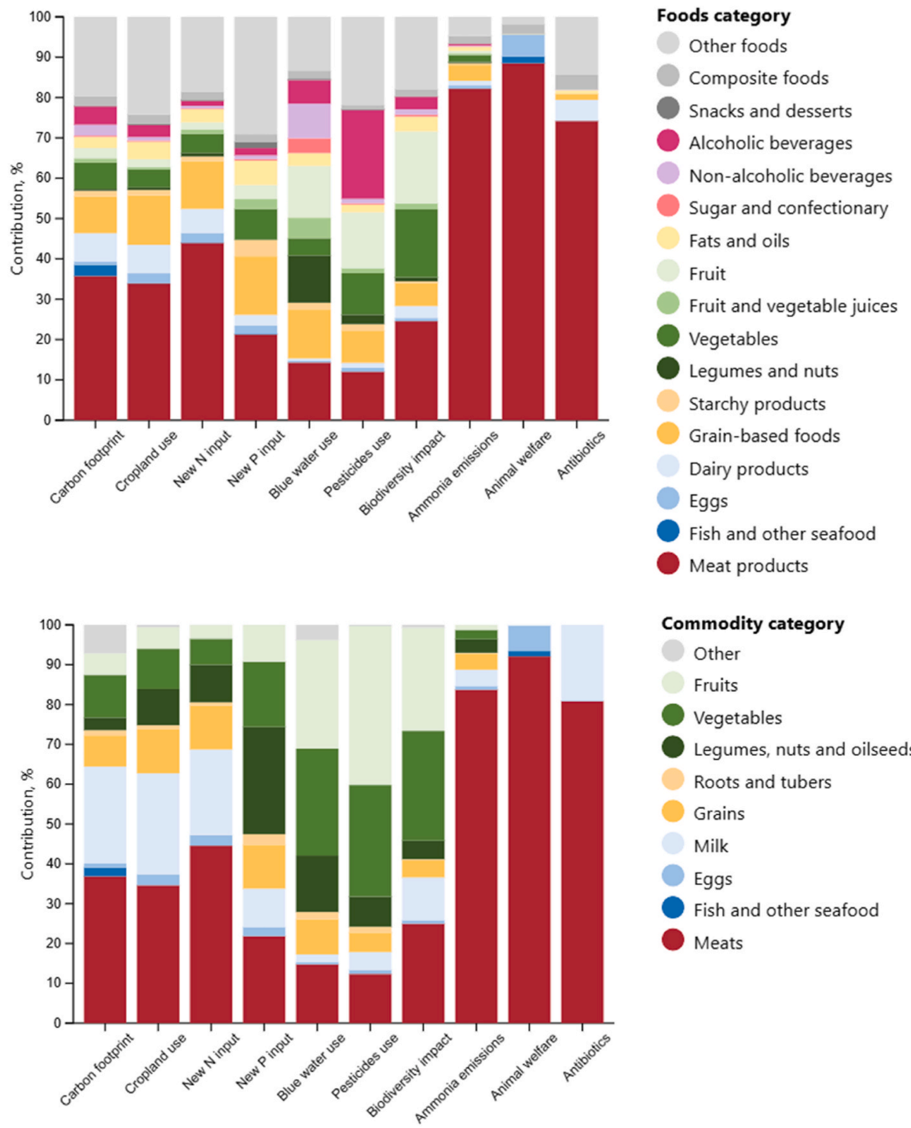

Fig. 6. Footprint contributions across indicators. Disaggregated into food groups (top) and different raw commodity groups (bottom).

emission reduction. Furthermore, breaking down the carbon footprint across different life cycle stages (Fig. 7) provides crucial insights into the relative contributions of various processes, such as primary production, processing, packaging and transport. Understanding these distinctions allows for a more nuanced approach to mitigation efforts, enabling consumers, policymakers, and industry stakeholders to prioritize actions that address the most emission-intensive stages of the supply chain. By offering multi-dimensional analyses, this approach supports informed decision-making in food sustainability.

The data provided by the SAFAD tool is of the accounting or attributional type and thus represents current production systems. As such, they provide a snapshot of the current situation but do not show the consequences, feasibility, or probability of a change of diets, and do not capture systemic effects (van der Werf et al., 2020). For example, a lacto-ovo-vegetarian diet including milk and eggs typically has a lower carbon footprint than a diet containing beef. However, it's crucial to recognize that beef is an inevitable byproduct of dairy farming. Hence, if a substantial portion of the population adopted a lacto-ovo-vegetarian diet, and the beef resulting from dairy production was not consumed, two interpretations are possible: either the scenario becomes infeasible due to excess beef production, or the actual environmental impact becomes higher than what the assessment in the SAFAD tool would suggest as the tool would not account for the unconsumed beef from dairy production. To mitigate similar discrepancies, we made modeling decisions aimed at reducing such inconsistencies, such as uniformly allocating environmental impacts across meat and offal, acknowledging that offal cannot be produced independently from meat.

Furthermore, a country may exhibit low values for certain indicators, but its production potential for that specific low-impact output may already be maximized. In other words, increasing sourcing from that country may not be a viable solution for reducing impacts, as production cannot expand beyond current levels. For example, in our dataset, beef from the Netherlands has the lowest carbon footprint among all countries. However, the Netherlands faces significant challenges related to nutrient pollution due to high livestock stocking densities and substantial feed imports, making further production increases environmentally unsustainable (Government of the Netherlands, 2023). It is fair to question the relevance of country-specific data for this reason, but country-specific data can be important for trust. For example, recently, the development of revised Nordic Nutritional Recommendations (Blomhoff et al., 2023) was criticized for not using locally applicable data (Wood et al., 2024). It is important to accept that no tool will be perfect and able to capture all important aspects. The feasibility of proposed dietary changes identified from indicator-based assessments

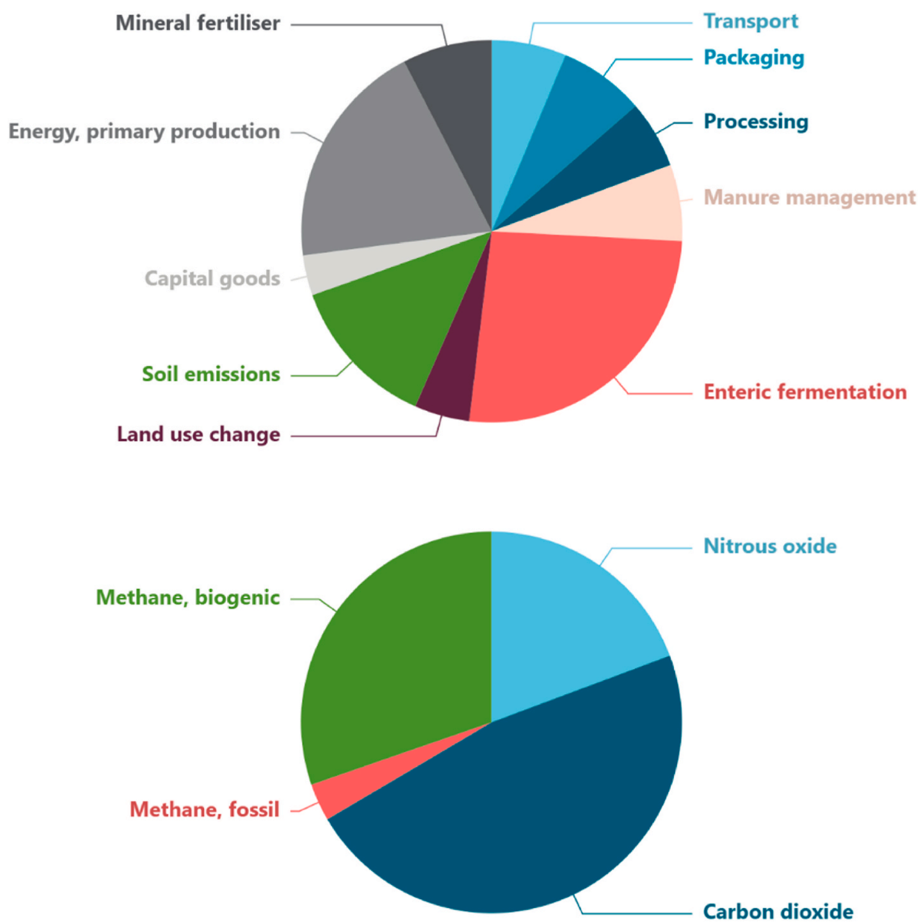

Fig. 7. Composition of the carbon footprint of the Swedish diet. Disaggregated across the different lifecycle stages and processes contributing to emissions (top), and across the different greenhouse gases making up the carbon footprint (bottom).

like those performed by the SAFAD tool can be tested using additional food systems or land use models (Muller et al., 2017; Röös et al., 2022) which can give valuable complementary information on the sustainability and biophysical feasibility of a certain change to diets.

4.2. Limitations

The SAFAD tool, while comprehensive, has inherent limitations that warrant consideration. The environmental indicators employed in this study offer valuable insights but possess intrinsic challenges. For example, the blue water use indicator does not account for local water stress, and biodiversity loss estimates are associated with substantial uncertainties (Ran et al., 2024). Assessing the environmental performance of diets is complicated by model and data uncertainties. The carbon footprint, for example, arises from multiple processes and depends on factors such as climate conditions, assumptions of farming practices across scales, and soil characteristics. Additionally, methodological choices in emission accounting can substantially influence the results (Moberg et al., 2019).

The SAFAD tool calculations rely on large amounts of inventory data, including crop yields, use of fertilizers, pesticides, water and energy use in cropping, livestock feeding, and performance, as well as processing, packaging and transport types, and energy use data. For many of these data, data availability presents a major limitation (*e.g.*, data on pesticide and fertilizer use per crop is not collected regularly for most crops and countries), and many extrapolations and approximations were needed (see SM 4 for more details). Therefore, detailed comparisons between individual food items should be made with great care or be avoided when differences are small. However, the patterns in the results for different indicators are consistent with previous research (Clune et al., 2017; Poore and Nemecek, 2018; Moberg et al., 2019, 2020, 2021) and calculations are consistent across food groups. Therefore, diet-level results, including the magnitude of indicator values and the trade-offs and synergies among indicators, can be considered sufficiently robust for generating valuable insights into dietary sustainability. Additionally, the tool's configurable nature allows for seamless updates to the inventory data as new information becomes available.

Measuring actual food intake in dietary surveys presents significant challenges, primarily due to reliance on self-reported data, which is prone to recall bias, underreporting, and social desirability effects (Bailey, 2021). Portion size estimation and variability in eating habits over time further complicate accuracy. These limitations introduce uncertainty into assessments of the environmental impacts of diets, as dietary intake data serve as a key input. This is a challenge common to all methodological approaches used to calculate diet-related environmental impacts, as they all depend on accurate estimates of what people actually eat.

4.3. Future research directions

The broad range of environmental indicators included in the SAFAD tool enables capturing trade-offs among different environmental aspects, as well as animal welfare and the use of antibiotics, which our example of a diet assessment showed (section 3.3). For a comprehensive assessment of the environmental sustainability of diets, Ran et al. (2024) recommend that to capture important environmental trade-offs, indicators for at least the following five areas should be included: climate change, biosphere integrity, blue water consumption, novel entities, and impacts on natural resources (especially wild fish stocks). The current version of the SAFAD tool described in this paper contains indicators for all these areas except indicators related to the impacts on wild fish stocks from the inclusion of blue foods in the diet. Important trade-offs may exist, as some blue foods have low carbon footprints, but are caught using unsustainable fishing practices that threaten wild stocks, such as Baltic Sea herring (Ran et al., 2024). Therefore, an important avenue for advancing and improving the SAFAD tool in the future involves adding indicators that can capture impacts on this valuable aquatic natural resource. Another valuable indicator that could be added is an indicator measuring energy requirements for producing the foods in the diet, as clean renewable energy is a limited resource. In addition, incorporating various health-related indicators offers further opportunities for enhancing the tool. Several such indicators are available, *e.g.* the Healthy Eating Index, which has been used by Shams-White et al. (2023) and the Nutrient Rich Food Index, proposed by Bianchi et al. (2020) for the Swedish context.

In future versions of the tool, the risk of imbalance in consumed amounts of associated RCPs (such as beef and milk, or pork and blood sausage) could, to some extent, be overcome by equipping the tool with checks that test for such systemic effects (Wood et al., 2023). Adding more countries is straight-forward and could be valuable but would require additional data collection for these countries.

5. Conclusions

The SAFAD tool provides a configurable, open-source platform that enables detailed evaluations of the environmental and social footprints of foods and diets across multiple sustainability indicators. By incorporating ten key indicators, including animal welfare and antibiotic use, SAFAD extends beyond conventional carbon footprint assessments, allowing for a more nuanced understanding of trade-offs and synergies in dietary sustainability. The tool enables assessing entire diets, as well as individual food products, making it valuable for researchers, policymakers, industry stakeholders, and consumers seeking science-based guidance on sustainable food choices. The ability to disaggregate results by food groups, raw commodities, and life cycle stages enhances transparency, enabling users to identify high-impact food categories and mitigation strategies. While SAFAD represents an advancement in dietary sustainability assessments, limitations remain, particularly regarding data granularity and systemic effects. Future enhancements should focus on expanding geographic coverage, refining sustainability indicators, and incorporating additional health-related metrics to provide a more comprehensive evaluation of dietary patterns. As dietary sustainability continues to gain prominence in public discourse, tools like SAFAD will play an important role in informing and guiding efforts toward more sustainable and ethical food systems.

CRediT authorship contribution statement

E. Röös: Writing – original draft, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **M. Jacobsen:** Writing – review & editing, Validation, Methodology, Investigation, Formal analysis, Conceptualization. **L. Karlsson:** Writing – review & editing, Methodology, Investigation, Formal analysis. **W. Wanecek:** Writing – review & editing, Validation, Software, Methodology, Formal analysis. **J. Spångberg:** Writing – review & editing, Methodology, Investigation, Formal analysis. **R. Mazac:** Writing – review & editing, Methodology, Investigation, Formal analysis. **L. Rydhmer:** Writing – review & editing, Methodology, Investigation, Formal analysis, Conceptualization.

Declaration of the use of AI

During the preparation of this work the authors used ChatGPT 4o order to improve the language. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

Acknowledgements

Funding for MJ, LK, WW, JS, LR and part of ER comes from the project "*Food systems transformation towards healthy and sustainable dietary behaviour - PLAN'EAT*" granted by the European Union's Horizon Europe Research and Innovation Programme under the Grant Agreement n° 101061023. RM was funded by Mistra Food Futures (Grant number DIA 2018/24 #8), a research program financed by the Stiftelsen för miljöstrategisk forskning (MISTRA), Sweden. ER was also funded by the research project "*Economic policy instruments to reduce greenhouse gas emissions from the Swedish food sector – EPIC*" (Grant number 2020-00187) funded by the governmental research council for sustainable development FORMAS. All funding is gratefully acknowledged.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2025.146002.

Data availability

The tool and data is available at https://safad.se/. Code is available at https://github.com/SLU-foodsystems

References

Agribylase®, 2025. Agribalyse documentation (EN). https://doc.agribalyse.fr/documentation-en/[2025-01-27.

Aldaya, M.M., Ibañez, F.C., Domínguez-Lacueva, P., Murillo-Arbizu, M.T., Rubio-Varas, M., Soret, B., Beriain, M.J., 2021. Indicators and recommendations for assessing sustainable healthy diets. Foods 10 (5), 999. https://doi.org/10.3390/foods10050999.

Arrieta, E.M., Aguiarb, S., 2023. Healthy diets for sustainable food systems: a narrative review. Environ. Sci. Adv. 2, 684–694. https://doi.org/10.1039/D2VA00214K.

Bailey, R.L., 2021. Overview of dietary assessment methods for measuring intakes of foods, beverages, and dietary supplements in research studies. Curr. Opin. Biotechnol. 70, 91–96. https://doi.org/10.1016/j.copbio.2021.02.007.

Barnes, A.P., Rutherford, K.M.D., Langford, F.M., Haskell, M.J., 2011. The effect of lameness prevalence on technical efficiency at the dairy farm level: an adjusted data envelopment analysis approach. J. Dairy Sci. 94 (11), 5449–5457. https://doi.org/10.3168/jds.2011-4262.

Bianchi, M., Strid, A., Winkvist, A., Lindroos, A.-K., Sonesson, U., Hallström, E., 2020. Systematic evaluation of nutrition indicators for use within food LCA studies. Sustainability 12 (21), 8992. https://doi.org/10.3390/su12218992.

Blomhoff, R., Andersen, R., Arnesen, E.K., Christensen, J.J., Eneroth, H., Erkkola, M., Gudanaviciene, I., Halldórsson, þ.I., Höyer-Lund, A., Lemming, E.W., 2023. Nordic Nutrition Recommendations 2023: Integrating Environmental Aspects. Nordic Council of Ministers.

Brander, M., 2016. Conceptualising attributional LCA is necessary for resolving methodological issues such as the appropriate form of land use baseline. Int. J. Life Cycle Assess. 21 (12), 1816–1821. https://doi.org/10.1007/s11367-016-1147-0.

Bruno, M., Thomsen, M., Pulselli, F.M., Patrizi, N., Marini, M., Caro, D., 2019. The carbon footprint of Danish diets. Clim. Change 156 (4), 489–507. https://doi.org/10.1007/s10584-019-02508-4.

Cai, H., Talsma, E.F., Chang, Z., Wen, X., Fan, S., Van 't Veer, P., Biesbroek, S., 2024. Aligning health, environment, and cost aspects of diets: identifying sustainable dietary patterns in China. Environ. Impact Assess. Rev. 106, 107531. https://doi.org/10.1016/j.eiar.2024.107531.

Castellani, V., Fusi, A., Sala, S., 2017. Consumer Footprint. Basket of Products Indicator on Food. Publications Office of the European Union. https://data.europa.eu/doi/10.2760/668763[2023-12-12.

Clark, M., Domingo, N., Colgan, K., Thakrar, S., Tilman, D., Lynch, J., Azevedo, I., Hill, J., 2020. Global food system emissions could preclude achieving the 1.5° and 2°C climate change targets. Science 370, 705–708. https://doi.org/10.1126/science.aba7357.

Clune, S., Crossin, E., Verghese, K., 2017. Systematic review of greenhouse gas emissions for different fresh food categories. J. Clean. Prod. 140, 766–783. https://doi.org/10.1016/j.jclepro.2016.04.082.

Curi-Quinto, K., Unar-Munguía, M., Rodríguez-Ramírez, S., Rivera, J.A., Fanzo, J., Willett, W., Röös, E., 2022. Sustainability of diets in Mexico: diet quality, environmental footprint, diet cost, and sociodemographic factors. Front. Nutr. 9, 855793. https://www.frontiersin.org/journals/nutrition/articles/10.3389/fnut.2022.855793.

Ecoinvent centre, 2023. Ecoinvent Database Version 3.9.1. Swiss Centre for Life Cycle Inventories, Dübendorf, Switzerland.

EFSA, 2019. The raw primary commodity (RPC) model: strengthening EFSA's capacity to assess dietary exposure at different levels of the food chain, from raw primary commodities to foods as consumed. EFSA Supporting Publications 16 (1), 1532E. https://doi.org/10.2903/sp.efsa.2019.EN-1532.

Erb, K.-H., Lauk, C., Kastner, T., Mayer, A., Theurl, M.C., Haberl, H., 2016. Exploring the biophysical option space for feeding the world without deforestation. Nat. Commun. 7 (1), 11382. https://doi.org/10.1038/ncomms11382.

Eriksson, O., 2022. Coproduction of food, cultural heritage and biodiversity by livestock grazing in Swedish semi-natural grasslands. Front. Sustain. Food Syst. 6, 801327. https://dx.doi.org/10.3389/fsufs.2022.801327.

ESU-services Ltd, 2025. ESU world food database – LCIs for LCA of nutrition. https://esu-services.ch/data/fooddata/[2025-01-27].

ESVAC, 2023. Sales of Veterinary Antimicrobial Agents in 31 European Countries in 2022: Trends from 2010 to 2022 : Thirteenth ESVAC Report. Publications Office. https://data.europa.eu/doi/10.2809/895656, 2024-07-15.

Eurostat, 2022. Data browser. https://ec.europa.eu/eurostat/databrowser/explore/all/agric?lang=en&subtheme=agr.apro&display=list&sort=category.

Eustachio Colombo, P., Elinder, L.S., Nykänen, E.-P.A., Patterson, E., Lindroos, A.K., Parlesak, A., 2023. Developing a novel optimisation approach for keeping heterogeneous diets healthy and within planetary boundaries for climate change. Eur. J. Clin. Nutr. https://doi.org/10.1038/s41430-023-01368-7.

FAOSTAT, 2024. Food balance sheets. https://www.fao.org/faostat/en/#data/FBS. (Accessed 17 July 2024).

Foley, J.A., Ramankutty, N., Brauman, K.A., Cassidy, E.S., Gerber, J.S., Johnston, M., Mueller, N.D., O'Connell, C., Ray, D.K., West, P.C., Balzer, C., Bennett, E.M., Carpenter, S.R., Hill, J., Monfreda, C., Polasky, S., Rockström, J., Sheehan, J., Siebert, S., Tilman, D., Zaks, D.P.M., 2011. Solutions for a cultivated planet. Nature 478 (7369), 337–342. https://doi.org/10.1038/nature10452.

Forster, P., Storelvmo, T., Armour, K., Collins, W., Dufresne, J.-L., Frame, D., Lunt, D.J., Mauritsen, T., Palmer, M.D., Watanabe, M., Wild, M., Zhang, H., 2021. The earth's energy budget, climate feedbacks, and climate sensitivity. In: Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S.L., Péan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M.I., Huang, M., Leitzell, K., Lonnoy, E., Matthews, J.B.R., Maycock, T.K., Waterfield, T., Yelekçi, O., Yu, R., Zhou, B. (Eds.), Climate Change 2021: the Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 923–1054. https://doi.org/10.1017/9781009157896.009.

Gazan, R., Brouzes, C.M.C., Vieux, F., Maillot, M., Lluch, A., Darmon, N., 2018. Mathematical optimization to explore tomorrow's sustainable diets: a narrative review. Adv. Nutr. 9 (5), 602–616. https://doi.org/10.1093/advances/nmy049.

Gephart, J.A., Henriksson, P.J.G., Parker, R.W.R., Shepon, A., Gorospe, K.D., Bergman, K., Eshel, G., Golden, C.D., Halpern, B.S., Hornborg, S., Jonell, M., Metian, M., Mifflin, K., Newton, R., Tyedmers, P., Zhang, W., Ziegler, F., Troell, M., 2021. Environmental performance of blue foods. Nature 597 (7876), 360–365. https://doi.org/10.1038/s41586-021-03889-2.

Government of the Netherlands, 2023. The nitrogen strategy and the transformation of the rural areas [onderwerp][2024-05-09]. https://www.government.nl/topics/nature-and-biodiversity/the-nitrogen-strategy-and-the-transformation-of-the-rural-areas.

Guo, A., Bryngelsson, S., Strid, A., Bianchi, M., Winkvist, A., Hallström, E., 2022. Choice of health metrics for combined health and environmental assessment of foods and diets: a systematic review of methods. J. Clean. Prod. 365, 132622. https://doi.org/10.1016/j.jclepro.2022.132622.

Hallström, E., Carlsson-Kanyama, A., Börjesson, P., 2015. Environmental impact of dietary change: a systematic review. J. Clean. Prod. 91, 1–11. https://doi.org/10.1016/j.jclepro.2014.12.008.

Hallström, E., Bajzelj, B., Håkansson, N., Sjons, J., Åkesson, A., Wolk, A., Sonesson, U., 2021. Dietary climate impact: contribution of foods and dietary patterns by gender and age in a Swedish population. J. Clean. Prod. 306, 127189. https://doi.org/10.1016/j.jclepro.2021.127189.

Hallström, E., Davis, J., Håkansson, N., Ahlgren, S., Åkesson, A., Wolk, A., Sonesson, U., 2022. Dietary environmental impacts relative to planetary boundaries for six environmental indicators – a population-based study. J. Clean. Prod. 373, 133949. https://doi.org/10.1016/j.jclepro.2022.133949.

Harrison, M.R., Palma, G., Buendia, T., Bueno-Tarodo, M., Quell, D., Hachem, F., 2022. A scoping review of indicators for sustainable healthy diets. Front. Sustain. Food Syst. 5, 822263. https://doi.org/10.3389/fsufs.2021.822263.

Hartcher, K.M., Lum, H.K., 2020. Genetic selection of broilers and welfare consequences: a review. Worlds Poult. Sci. J. 76 (1), 154–167. https://doi.org/10.1080/00439339.2019.1680025.

Herzon, I., Mazac, R., Erkkola, M., Garnett, T., Hansson, H., Jonell, M., Kaljonen, M., Kortetmäki, T., Lamminen, M., Lonkila, A., Niva, M., Pajari, A.-M., Tribaldos, T., Toivonen, M., Tuomisto, H., Koppelmäki, K., Röös, E., 2024. Both downsizing and improvements to livestock systems are needed to stay within planetary boundaries. Nat. Food 5, 642–645. https://doi.org/10.1038/s43016-024-01030-w.

Hjorth, T., Huseinovic, E., Hallström, E., Strid, A., Johansson, I., Lindahl, B., Sonesson, U., Winkvist, A., 2020. Changes in dietary carbon footprint over ten years relative to individual characteristics and food intake in the Västerbotten intervention programme. Sci. Rep. 10 (1), 20. https://doi.org/10.1038/s41598-019-56924-8.

Ingrao, C., Matarazzo, A., Tricase, C., Clasadonte, M.T., Huisingh, D., 2015. Life cycle assessment for highlighting environmental hotspots in Sicilian peach production systems. J. Clean. Prod. 92, 109–120. https://doi.org/10.1016/j.jclepro.2014.12.053.

Jacobsen, M., Moraeus, L., Patterson, E., Lindroos, A.-K., Eriksson, M., 2025. Fostering unsustainability? An analysis of 4-year-olds' dietary impacts in Sweden. Curr Res Environ Sustain 9, 100281. doi: 10.1016/j.crsust.2025.100281.

Karlsson, J.O., Röös, E., 2019. Resource-efficient use of land and animals—Environmental impacts of food systems based on organic cropping and avoided food-feed competition. Land Use Policy 85, 63–72. https://doi.org/10.1016/j.landusepol.2019.03.035.

Karlsson Potter, H., Röös, E., 2021. Multi-criteria evaluation of plant-based foods –Use of environmental footprint and LCA data for consumer guidance. J. Clean. Prod. 280, 124721. https://doi.org/10.1016/j.jclepro.2020.124721.

Kwasny, T., Dobernig, K., Riefler, P., 2022. Towards reduced meat consumption: a systematic literature review of intervention effectiveness, 2001–2019. Appetite 168, 105739. https://doi.org/10.1016/j.appet.2021.105739.

Lanzoni, L., Whatford, L., Atzori, A.S., Chincarini, M., Giammarco, M., Fusaro, I., Vignola, G., 2023. Review: the challenge to integrate animal welfare indicators into the life cycle assessment. Animal 17 (5), 100794. https://doi.org/10.1016/j.animal.2023.100794.

Lindroos, A.K., Hallström, E., Moraeus, L., Strid, A., Winkvist, A., 2023. Dietary greenhouse gas emissions and diet quality in a cross-sectional study of Swedish adolescents. Am. J. Clin. Nutr. S0002916523661246. https://doi.org/10.1016/j.ajcnut.2023.09.001.

Matuštík, J., Kočí, V., 2021. What is a footprint? A conceptual analysis of environmental footprint indicators. J. Clean. Prod. 285, 124833. https://doi.org/10.1016/j.jclepro.2020.124833.

Lindroos, A.K., Winkvist, A., Röös, E., Hallström E. (2025). The environmental impact of Swedish adolescents' diets. Environ. res. food syst (in press). doi: 10.1088/2976-601X/adde63.

Mérieux NutriSciences, Blonk, 2025. Agri-footprint. https://blonksustainability.nl/tools-and-databases/agri-footprint [2025-01-27].

Mészáros, Á., Dósa, N., Péterfi, A., Horváth, K., Szarvas, Z., Balogh, J.M., Munkácsy, B., Vokó, Z., 2024. Prospects of food taxes for planetary health: a systematic review of modeling studies. Nutr. Rev. https://doi.org/10.1093/nutrit/nuae111.

Moberg, E., Walker Andersson, M., Säll, S., Hansson, P.-A., Röös, E., 2019. Determining the climate impact of food for use in a climate Tax—Design of a consistent and transparent model. Int. J. Life Cycle Assess. 24 (9), 1715–1728. https://doi.org/10.1007/s11367-019-01597-8.

Moberg, E., Karlsson Potter, H., Wood, A., Hansson, P.-A., Röös, E., 2020. Benchmarking the Swedish diet relative to global and national environmental targets—identification of indicator limitations and data gaps. Sustainability 12 (4), 1407. https://doi.org/10.3390/su12041407.

Moberg, E., Säll, S., Hansson, P.-A., Röös, E., 2021. Taxing food consumption to reduce environmental impacts – identification of synergies and goal conflicts. Food Policy 101, 102090. https://doi.org/10.1016/j.foodpol.2021.102090.

Muller, A., Schader, C., El-Hage Scialabba, N., Brüggemann, J., Isensee, A., Erb, K.-H., Smith, P., Klocke, P., Leiber, F., Stolze, M., Niggli, U., 2017. Strategies for feeding the world more sustainably with organic agriculture. Nat. Commun. 8 (1), 1290. https://doi.org/10.1038/s41467-017-01410-w.

Notarnicola, B., Tassielli, G., Renzulli, P.A., Castellani, V., Sala, S., 2017. Environmental impacts of food consumption in Europe. J. Clean. Prod. 140, 753–765. https://doi.org/10.1016/j.jclepro.2016.06.080.

NTMCalc 4.0, 2023. Environmental performance calculator. Network for transport measures. https://www.transportmeasures.org/ntmcalc/v4/basic/index.html#/[2024-05-27.

Patel, S.J., Wellington, M., Shah, R.M., Ferreira, M.J., 2020. Antibiotic stewardship in food-producing animals: challenges, progress, and opportunities. Clin. Ther. 42 (9), 1649–1658. https://doi.org/10.1016/j.clinthera.2020.07.004.

Pendrill, F., Persson, U.M., Kastner, T., Wood, R., 2022. Deforestation Risk Embodied in Production and Consumption of Agricultural and Forestry Commodities 2005-2018. Zenodo. https://doi.org/10.5281/ZENODO.5886600.

Poore, J., Nemecek, T., 2018. Reducing food's environmental impacts through producers and consumers. Science 360 (6392), 987–992. https://doi.org/10.1126/science.aaq0216.

Ran, Y., Cederberg, C., Jonell, M., Bergman, K., De Boer, I.J.M., Einarsson, R., Karlsson, J., Potter, H.K., Martin, M., Metson, G.S., Nemecek, T., Nicholas, K.A., Strand, Å., Tidåker, P., Van Der Werf, H., Vanham, D., Van Zanten, H.H.E., Verones, F., Röös, E., 2024. Environmental assessment of diets: overview and guidance on indicator choice. Lancet Planet. Health 8 (3), e172–e187. https://doi.org/10.1016/S2542-5196(24)00006-8.

RISE, 2025. RISE food climate database. Research institutes of sweden., gothenburg, Sweden. https://www.ri.se/en/expertise-areas/expertises/rise-food-climate-database [2025-01-27].

Röös, E., Mayer, A., Muller, A., Kalt, G., Ferguson, S., Erb, K.-H., Hart, R., Matej, S., Kaufmann, L., Pfeifer, C., Frehner, A., Smith, P., Schwarz, G., 2022. Agroecological practices in combination with healthy diets can help meet EU food system policy targets. Sci. Total Environ. 847, 157612. https://doi.org/10.1016/j.scitotenv.2022.157612.

Rose, D., Heller, M.C., Willits-Smith, A.M., Meyer, R.J., 2019. Carbon footprint of self-selected US diets: nutritional, demographic, and behavioral correlates. Am. J. Clin. Nutr. 109 (3), 526–534. https://doi.org/10.1093/ajcn/nqy327.

Sabaté, J., Harwatt, H., Soret, S., 2016. Environmental nutrition: a new frontier for public health. Am. J. Publ. Health 106 (5), 815–821. https://doi.org/10.2105/AJPH.2016.303046.

SBA, 2024. Direktkonsumtion efter vara, variabel och År. PxWeb. http://statistik.sjv.se/PXWebPXWeb/pxweb/sv/Jordbruksverketsstatistikdatabas/Jordbruksverketsstatistikdatabas_Konsumtionavlivsmedel/JO1301K1.px/[2024-07-15.

Scarborough, P., Clark, M., Cobiac, L., Papier, K., Knuppel, A., Lynch, J., Harrington, R., Key, T., Springmann, M., 2023. Vegans, vegetarians, fish-eaters and meat-eaters in the UK show discrepant environmental impacts. Nat. Food 4, 565–574. https://doi.org/10.1038/s43016-023-00795-w.

Schwarzmueller, F., Kastner, T., 2022. Agricultural trade and its impacts on cropland use and the global loss of species habitat. Sustain. Sci. 17 (6), 2363–2377. https://doi.org/10.1007/s11625-022-01138-7.

SFA, 2023. Search for nutrients. Swedish food agency, Uppsala, Sweden. https://soknaringsinnehall.livsmedelsverket.se/[2024-05-24.

Shams-White, M.M., Pannucci, T.E., Lerman, J.L., Herrick, K.A., Zimmer, M., Meyers Mathieu, K., Stoody, E.E., Reedy, J., 2023. Healthy eating Index-2020: review and update process to reflect the dietary guidelines for Americans, 2020-2025. J. Acad. Nutr. Diet. 123 (9), 1280–1288. https://doi.org/10.1016/j.jand.2023.05.015.

Springmann, M., Dinivitzer, E., Freund, F., Dejgård Jensen, J., Bouyssou, C.G., 2025. A reform of value-added taxes on foods can have health, environmental and economic benefits in Europe. Nat. Food. https://doi.org/10.1038/s43016-024-01097-5.

Sun, Z., Scherer, L., Tukker, A., Spawn-Lee, S.A., Bruckner, M., Gibbs, H.K., Behrens, P., 2022. Dietary change in high-income nations alone can lead to substantial double climate dividend. Nat. Food 3, 29–37. https://doi.org/10.1038/s43016-021-00431-5.

Tang, K.L., Caffrey, N.P., Nóbrega, D.B., Cork, S.C., Ronksley, P.E., Barkema, H.W., Polachek, A.J., Ganshorn, H., Sharma, N., Kellner, J.D., Ghali, W.A., 2017. Restricting the use of antibiotics in food-producing animals and its associations with antibiotic resistance in food-producing animals and human beings: a systematic review and meta-analysis. Lancet Planet. Health 1 (8), e316–e327. https://doi.org/10.1016/S2542-5196(17)30141-9.

Taufique, K.M.R., Nielsen, K.S., Dietz, T., Shwom, R., Stern, P.C., Vandenbergh, M.P., 2022. Revisiting the promise of carbon labelling. Nat. Clim. Change 12 (2), 132–140. https://doi.org/10.1038/s41558-021-01271-8.

van der Werf, H.M.G., Knudsen, M.T., Cederberg, C., 2020. Towards better representation of organic agriculture in life cycle assessment. Nat. Sustain. 3 (6), 419–425. https://doi.org/10.1038/s41893-020-0489-6.

van Dooren, C., Aiking, H., Vellinga, P., 2018. In search of indicators to assess the environmental impact of diets. Int. J. Life Cycle Assess. 23, 1297–1314. https://doi.org/10.1007/s11367-017-1371-2.

van Zanten, 2022. In: Peters, C.J., Thilmany, D.D., Peters, C.J., Thilmany, D.D. (Eds.), Food Systems Modelling, Chapter 5, Academic Press, an Imprint of. Elsevier.

Verkuijl, C., Smit, J., Green, J., Nordquist, R., Sebo, J., Hayek, M., Hötzel, M.J., 2024. Climate change, public health, and animal welfare: towards a one health approach to reducing animal agriculture's climate footprint. Frontier in Animal Science 5, 1281450. https://doi.org/10.3389/fanim.2024.1281450.

Willett, W., Rockström, J., Loken, B., Springmann, M., Lang, T., Vermeulen, S., Garnett, T., Tilman, D., DeClerck, F., Wood, A., Jonell, M., Clark, M., Gordon, L.J., Fanzo, J., Hawkes, C., Zurayk, R., Rivera, J.A., De Vries, W., Majele Sibanda, L., Afshin, A., Chaudhary, A., Herrero, M., Agustina, R., Branca, F., Lartey, A., Fan, S., Crona, B., Fox, E., Bignet, V., Troell, M., Lindahl, T., Singh, S., Cornell, S.E., Srinath Reddy, K., Narain, S., Nishtar, S., Murray, C.J.L., 2019. Food in the anthropocene: the EAT–lancet commission on healthy diets from sustainable food systems. Lancet 393 (10170), 447–492. https://doi.org/10.1016/S0140-6736(18)31788-4.

Wood, A., Moberg, E., Curi-Quinto, K., Van Rysselberge, P., Röös, E., 2023. From "good for people" to "good for people and planet" – placing health and environment on equal footing when developing food-based dietary guidelines. Food Policy 117, 102444. https://doi.org/10.1016/j.foodpol.2023.102444.

Wood, A., Swan, J., Masino, T., Tørnqvist, B., Herzon, I., Röös, E., 2024. Clearing the Confusion - a Review of the Criticisms Relating to the Environmental Analysis of the Nordic Nutrition Recommendations 2023. A policy report from Stockholm Resilience Centre at Stockholms University and the Swedish University of Agricultural Sciences. https://su.figshare.com/articles/report/Clearing_the_confusion_a_review_of_the_criticisms_relating_to_the_environmental_analysis_of_the_Nordic_Nutrition_Recommendations_2023/25429057.