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Title	Translating environmentally optimized agri-food systems into diets: A case study
Authors	Cardinaals, Renee;Maindl, Thomas;Huppertz, Thom;Van Zanten, Hannah
Publication date	2026-06-13
Original Citation	Cardinaals, R, Maindl, T, Huppertz, T & Van Zanten, H 2026, 'Translating environmentally optimized agri-food systems into diets: A case study', Future Foods, vol. 14, 101077, pp. 1-11. https://doi.org/10.1016/j.fufo.2026.101077
Type of publication	Article (peer-reviewed)
Link to publisher's version	https://www.scopus.com/pages/publications/105041536109 - 10.1016/j.fufo.2026.101077
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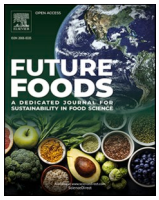
Future Foods 14 (2026) 101077



Contents lists available at ScienceDirect

Future Foods

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Translating environmentally optimized agri-food systems into diets: a case study

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ARTICLE INFO

Keywords:
Sustainable healthy diets
Food systems optimization
Sustainable production
Human health
Nutrition

ABSTRACT

Food system optimization models that allow for assessing food system redesigns in line with sustainability objectives often lack a translation from crop and livestock production into food products that make up diets. Not making the translation from commodities into food products could limit the assessment of whether redesigned agri-food systems can cater to culturally adapted diets, as well as an accurate health assessment thereof. To explore the methodological aspects that should be considered when bridging the gap between food system optimization and healthy diets, we used results from the Circular Food Systems (CiFoS) model in a case study. CiFoS results consisted of commodities (n=154) produced in a redesigned European agri-food system which were mapped to food products (n=602) that are currently included in European diets. Two different diet scenarios were explored that translated CiFoS commodities into diets that: (1) matched the current consumption, (2) could be considered to be healthier and maximized the use of available commodities. Results demonstrated that applying the objective to match current diets, the available commodities could only partially be translated into product-level diets, and more than half of the total available commodities was left unused. However, maximizing the use of commodities resulted in diets that could be considered healthier than, but also deviating considerably from, current diets. This study highlights relevant methodological aspects and emphasizes the need to look beyond commodity-level diets when optimizing agri-food systems for sustainable healthy diets as a translation into food products allows for better evaluation of these diets.

1. Introduction

European dietary patterns contributed to over 600 thousand deaths (25% of all risks) and over 11 million disability adjusted life years (22% of all risks) in 2021 (IHME, 2019). At the same time, the European food system is not sustainable in the way it is depleting natural resources and causing environmental pollution (Bajan et al., 2022). An important step toward achieving climate change targets and an overall healthier planet and population is shifting to diets that consist of healthier foods with a lower environmental impact, compared to today's diets (Hemler and Hu, 2019; Springmann et al., 2016; Tilman and Clark, 2014). The research on the composition of such diets that benefit both planetary and human health, i.e., sustainable healthy diets, is vastly diverse and growing (Costa Leite et al., 2020; Frehner et al., 2022; Kim et al., 2020; Springmann et al., 2021). Most of this research originates from a consumption-oriented approach that separates the human diet from food production and focuses on the dietary changes that can co-benefit planetary and human health (e.g., Benton et al., 2024; Brink et al., 2019; Perignon et al., 2019; van Dooren and Aiking, 2016). However, food consumption is inherently linked to food production systems, and disruptive dietary changes – e.g., a shift from animal-rich to plant-rich diets – go hand-in-hand with changes in the agri-food system (Alexander et al., 2019; Fanzo and Davis, 2021; Godfray et al., 2010; Searchinger et al., 2019).

Contrary to isolating the human diet, approaches that aim to redesign agri-food systems can provide insights into the optimal allocation of available resources to meet food demand. Therefore, redesigning agri-food systems – e.g., based on circularity principles (Jurgilevich et al., 2016) – impacts the quantity and types of food produced, and thereby defines sustainable diets. However, as this approach is more

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https://doi.org/10.1016/j.fufo.2026.101077
Received 26 March 2026; Received in revised form 26 May 2026; Accepted 3 June 2026
Available online 4 June 2026
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production-oriented, it tends to underrepresent details on food consumption (Heerschop et al., 2024). To illustrate, a comparison between a diet optimization and an agri-food system optimization model by Heerschop et al. (2024) showed that the latter lacked a translation from commodities into food products as they are consumed, making it difficult to understand the dietary patterns.

Such a translation from commodities into food products can illustrate the diets that are associated with redesigned agri-food systems and thereby allows better assessment of how feasible these diets are. Several authors have hypothesized that a food system redesign requires radical dietary changes (Cardinaals et al., 2023; Simon et al., 2024a; Vermeulen et al., 2020), but this is difficult to substantiate without a translation into product-level diets, and the specific dietary changes that would be needed remain undefined. Redesigning agri-food systems can, for example, demonstrate a need for different crop or animal types than currently used, which would lead to food products produced from different commodities, e.g., cereal products produced from other grains than wheat (Dwivedi et al., 2017; Gazza and Nocente, 2023). Moreover, information on food product level makes it possible to assess whether such diets fit with culture-specific food choices (Carvalho et al., 2025; Hendrie et al., 2022; Sharma et al., 2020).

In addition, consistent consumption of certain food groups, foods, and nutrients can in- or decrease the risk for non-communicable diseases (NCDs) and obesity (Afshin et al., 2019). In addition, there are concerns about an overconsumption of ultra-processed foods and their link to negative health outcomes (Chen et al., 2020; Dai et al., 2024; Lane et al., 2021, 2024; Monteiro et al., 2019). For example, Lane et al. (2024) showed that higher ultra-processed food intake was associated with a 50% increased risk of cardiovascular disease-related death, a 48–53% higher risk of anxiety and common mental disorders, and a 12% greater risk of type 2 diabetes. Therefore, specifying which food products are part of sustainable diets allows for a better nutritional and health impact assessment than based on commodities.

Therefore, we propose that translating commodities into food products is needed for the following two reasons: 1) it allows for a better assessment of the gap between current diets and diets that are more sustainable and healthier, and 2) it allows for more accurate health assessments of such diets. The aim of this study was to explore how such a translation could be made by considering scenario output from an existing food systems optimization and linking this to food products that are currently consumed in different European countries. The gap between the scenario output – i.e., the combination of commodities that could be produced in a circular European agri-food systems – and quantities of food products currently consumed by the European populations was assessed. This study is therefore exploratory for the much needed link between sustainable food production and consumption, and it aims to reveal certain limitations of current practices in food systems modelling.

2. Methods

2.1. CiFoS model

The Circular Food Systems (CiFoS) model is a biophysical food systems optimization model that allows to model reconfigurations of the food system to achieve healthy diets within planetary boundaries (van Zanten et al., 2023). The CiFoS model was selected for this case study because it can be considered an agri-food systems model that includes the option to account for nutritional and dietary needs of the target population, thus allowing to derive sustainable and healthy diets, but lacks a translation from commodities into food products. The CiFoS model allows to model a wide variety of food system scenarios, depending on how the scenario settings are combined. For example, it has been employed to optimize the European and global food system based on circularity principles of feeding animals on low-opportunity biomass (Van Zanten et al., 2018b), optimizing biomass flows (van Zanten et al., 2023), avoiding nutrient overconsumption by humans (Simon et al., 2024b), and prevention or recovery of nutrient losses to optimize fertilization (Simon et al., 2024a). For this study, we used previously modelled scenarios for which the details are specified in Section 2.2.

The CiFoS model code is written in the Generic Algebraic Modeling System (GAMS), and it generally follows a linear optimization approach. The model redesigns the agri-food system by re-allocating resources, biomass and nutrients, such as land, manure or food by-products and waste, to promote circularity (Van Zanten et al., 2018b). CiFoS thereby utilizes resources, biomass and nutrients in the most environmentally favourable way by for example, applying recycling practices and optimizing crop- and livestock production based on available resources and climatic factors. This agri-food system redesign is used to fulfill one, or multiple objective function(s), e.g., to minimize greenhouse gas (GHG) emissions. Agricultural production is simulated across 51 crop production systems, 5 fertilization sources, 9 animal production systems – including farmed fish – and wild capture fisheries. The model accounts for transportation at different scales, and via processing translates crop and animal production into 154 food commodities across 14 food groups. These food commodities are included in a non- or minimally processed stage (e.g., wheat flour, milk, potatoes) and most final food products (e.g., bread, flavored dairy, potato chips) are thereby not included. From these commodities, CiFoS compiles what is available for consumption per person per day and thereby tracks the daily supply of 37 macro- and micronutrients provided by these commodities. The nutrient content of each commodity is based on USDA FoodData Central (USDA, 2018). A more detailed description of the model can be found in Van Zanten et al. (2023).

2.2. Scenarios

The CirAgri and CirHealth scenarios of Van Zanten et al. (2023) were used as input for the translation to diets (Table S1). These two scenarios were previously applied to address two different research questions of what a reconfiguration of the EU food system looks like when either current production quantities at food group level are maintained while applying circularity principles (CirAgri), or when transitioning to more nutritious and healthy diets in combination with circularity principles (CirHealth). Both scenarios applied the objective function to minimize land use. CirAgri thereby fixed current protein supply per food group based on FAO data (FAO, 2001), while applying supply-side circularity principles. CirHealth additionally introduced nutrient and food group recommendations (Table S3), that were used as model constraints such that the scenario met these recommendations. Nutrient recommendations were based on Estimated Average Requirements from the European Food Safety Authority (EFSA) (European Food Safety Authority, 2017), whereas food group recommendations were based on the EAT Lancet requirements from 2019 (Willet et al., 2019).

The output of CirAgri and CirHealth, consisting of the amount of commodities that would be available in the redesigned agri-food systems, was used to generate the diet scenarios: CirAgriDiet and CirHealthDiet (Fig. 1). In line with the concepts of the initial scenarios to maintain current production (CirAgri) or transition to healthy diets (CirHealth), we applied different objectives for CirAgriDiet and CirHealthDiet. For CirAgriDiet objective function (A) was applied to minimize the distance between what could be “produced” from the available commodities and the current diet, while adhering to the proportions at which food products were included in the current diet. For CirHealthDiet objective function (B) was applied to maximize the use of available commodities to produce currently consumed food products, without adhering to the current diet and while giving higher priority to NOVA Category 1 and lowest priority to NOVA Category 4 (Section 2.4).

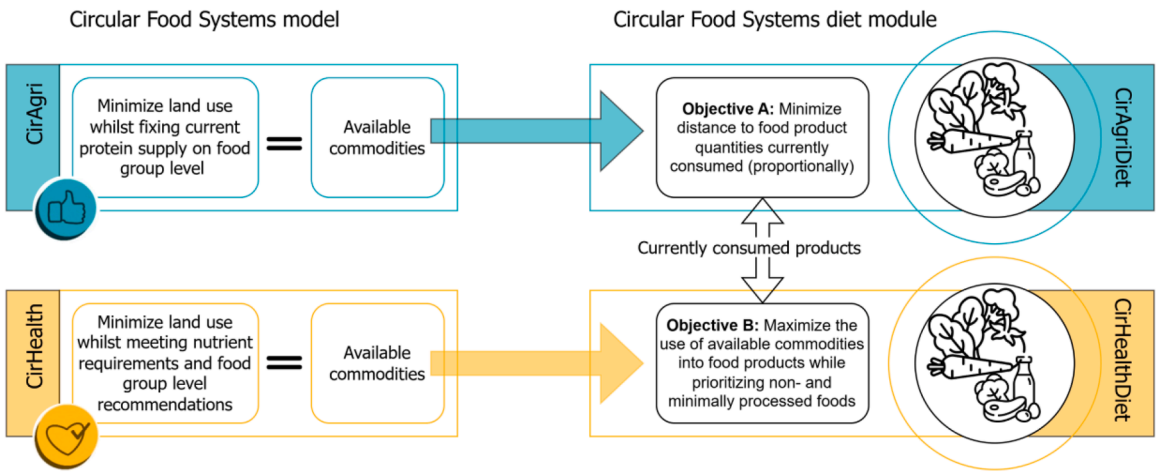


Fig. 1. Overview of diet scenarios (right-hand side, CirAgriDiet and CirHealthDiet) that are based on the output from scenarios previously modelled by the Circular Food Systems model in van Zanten et al. (2023) (left-hand side, CirAgri and CirHealth).

2.3. Current diets

Current dietary data for 22 European countries were extracted from the EFSA Comprehensive European Food Consumption Database (EFSA, 2024;Table S2). This database provides harmonized consumption data that originates from national food consumption surveys. It distinguishes between acute and chronic consumption, with the latter being representative of average food consumption across a full year (EFSA, 2011). For this study, chronic consumption data was extracted at FoodEx Level 3 product level, providing sufficient detail to distinguish among the most common food products and resulting in a list of 487 unique food products, supplemented by 115 products for which Level 4 detail was required. If multiple surveys were available for a country, either the most recent or most complete survey was considered. Because CiFoS models for an average diet for adults, only data for the population group "Adults" (≥18 years to <65 years old) was used. No demographic weighing factors were applied to adjust the data to make the survey sample more representative for the population.

2.4. Mapping between EFSA food products and CiFoS commodities

Food products were mapped to commodities, e.g., the food product "spinach" from the consumption surveys was mapped to the commodity "green vegetables" from CiFoS. When applicable, multiple commodities were combined based on a recipe to attain a food product, e.g., the food product "pancakes" consisted of a combination of the commodities "wheat flour", "eggs" and "milk". The ratios at which these commodities were combined into food products were based on common recipes obtained via Google or ChatGPT, or product labels from the largest Dutch supermarket via their website (Albert Heijn, 2020). These ratios have to be considered as approximates because product ingredients vary among consumers and brands. In some cases, multiple commodities could be used to produce a single food product, e.g., the food product "bread" may be either produced from the commodities "wheat wholemeal flour", "wheat flour", "barley flour" or "sorghum flour". In such cases, the recipe had the flexibility to select one of these commodity variants from a "commodity group" to create the food product.

2.5. Prioritization of food products

To align with the objective to translate CirHealth into a diet consisting of healthier food products, we used the assumption that diets with a higher contribution from ultra-processed foods result in negative health outcomes (Chen et al., 2020; Lane et al., 2024; Lescinsky et al., 2022; Srour and Touvier, 2021; Valicente et al., 2023). Therefore, food products were classified based on the NOVA classification system for food processing (Monteiro et al., 2019; Table S4). Although several other classification systems based on processing level exist, the NOVA system is most widely used in literature (Lawrence and Baker, 2019). The NOVA classification consists of the following categories: (1) minimally processed, (2) culinary ingredients, (3) processed, (4) ultra-processed. Each food product was individually assessed for classification based on the extensive description of each category from Monteiro et al. (2022) (Table S4) as well as applying the best practices from Martinez-Steele et al. (2023). These best practices include the following steps: (1) compiling a food list, (2) assigning food products to NOVA groups, and (3) assigning food products to alternative groups for sensitivity analysis. For step (1) and (2), ingredients were based on the recipe mapping between CiFoS and the EFSA dataset (Section 2.4). A distinction was made between single-ingredient products (e.g., raw fruit, milk or unprocessed meat, vegetable oils) that could be directly assigned to NOVA Category 1 or 2, and multi-ingredient products (e.g., bread, desserts, soups). For multi-ingredient products, these were considered NOVA Category 3 if the product was created by combining a Category 1 with one or multiple Category 2 ingredients (e.g., bread). The EFSA data did not allow to make a clear distinction between a culinary preparation and an industrially manufactured product, and it was assumed that culinary preparations would be reported as individual products (e.g., lasagna sheets, tomato sauce and cheese), whereas industrially manufactured products would be reported as composite dishes (e.g., lasagna). Thereby, all packaged food products (e.g., bars, biscuits, desserts) and all composite dishes (e.g., soups, sandwiches, prepared salads) were assigned to Category 4. In addition, pastries and confectionery bakery products were assigned to Category 4. A sensitivity analysis, as proposed in step 3 by Martinez-Steele et al. (2023), was omitted because our diet scenarios already included one version without considering NOVA Categories (CirAgriDiet), and one scenario with (CirHealthDiet), and as such, the impact from assigning food products to a Category could be assessed. A full list of all food products and their NOVA Category can be found in Table S5.

2.6. CiFoS diet module

For this study, an additional module was coded in GAMS, which was independent of the original CiFoS model. For clarity, this section lists the objective functions along with the principal equation of the GAMS optimization mode, omitting the details on the commodity variants (Section 2.4) and prioritization of NOVA categories (Section 2.5). The module uses the output from a CiFoS scenario (Table S1) as the available amount A_{kj} of commodity j per country k. A total of 22 European

countries were included in the CiFoS diet module, determined by the availability of food consumption data. In addition to the CiFoS data, input data also includes the currently consumed amount D_{ki} of food product i per country k (Section 2.3), and the "recipe mapping" R_{ij} that provides information on how much of each commodity j is required to create a product i (Section 2.4).

Per country k, the nonnegative decision variable x_{ki} represents the amount of each of the included 602 food products i that can be produced based on the availability of the required commodities A_{kj} as defined in the recipes R_{ij}. Allowing an unused surplus amount for each commodity, captured in the nonnegative decision variable s_{kj}, this condition reads

$$A_{Kj} = \sum_{i} x_{ki} R_{ij} + S_{kj} \tag{1}$$

Objective function (A) minimizes for each country the distance between the amount of products that can be produced based on the available commodities and the amount of products that are currently consumed, while adhering to the recipe mapping of commodities and products (see Equation (1)):

$$\sum_{Ki} \left| \frac{x_{ki} - D_{ki}}{D_{ki}} \right| \rightarrow \min \tag{2}$$

Objective function (B) also adheres to the recipe mapping in Equation (1) and is limited by the amount of available commodities, but additionally maximizes the use of the commodities to produce currently consumed food products, independent of the ratios at which they are included in current diets:

$$\sum_{Ki} \left| \frac{x_{ki} - D_{ki}}{D_{ki}} \right| + \sum_{Kj} S_{kj} \rightarrow \min \tag{3}$$

Due to the scaling of the first sum in Equation (3) we expect the surplus term to dominate objective function (B) so that it will effectively maximize the use of the available commodity quantity.

An additional loop was introduced, where first only products to which a priority was assigned were used in the objective function and subsequently the leftover available commodities A_{kj} entered the new solve loop of products with a lower priority. This addition allowed to assign a prioritization system to produce certain products before allowing to assign commodities to food products with lower priority (Section 2.5).

2.7. Diet scenario analyses

The results from the CiFoS diet module, i.e., the two diet scenarios, were analyzed for (1) the gap with current diets, and (2) the risk for NCDs. While the diet module operated at country level, results were aggregated for all 22 countries for the analyses using a population weighted average. The gap with current diets was quantified based on the difference between the amount of a food product included in the current diet and the amount for the same food product included in the diet scenario. In addition, indicators of the gap with current diets included the amount of food products that could not be produced at all, the amount of food products that could be produced at the same quantity as also included in the diet, and the amount of food products that deviated >25% from current consumption levels since >25% above or below a consumed portion size is considered unacceptable by consumers (Eldridge et al., 2025). It should be noted that 31% of all food products initially present in the EFSA food consumption surveys (i.e., 186 out of 602), were not mapped to any commodity because there was no matching commodity included in the CiFoS model (e.g., salt, spices or honey) and these food products were therefore excluded from the analysis. This related generally to food products consumed in low quantities, and therefore an average of 6.3% of total dietary mass that was excluded from the analysis (ranging from 1.6% in Poland to 14.8% in Austria)

As an indication for how diets relate to NCDs, the diet scenarios were compared to the GBD's TMRELs (Afshin et al., 2019). The following dietary risks were considered: high consumption of red meat, processed meat and sugar sweetened beverages, and low consumption of fruits, vegetables, legumes, whole grains, nuts and seeds, milk, calcium, omega-3 fatty acids from fish, fiber and polyunsaturated fatty acids (PUFA). The dietary risk factors of the diets in CirAgriDiet and CirHealthDiet were quantified based on nutrient content data of each commodity from the CiFoS model (calcium, omega-3 fatty acids, fiber and PUFA), and a summation of foods that could be classified as either fruits, vegetables, legumes, whole grains, nuts and seeds or milk. The latter classification was based on the definitions of dietary risks provided in the GBD cause and risk factsheets (IHME, 2025). A high consumption of sodium and trans fatty acids are also identified as risk factors by the GBD, but nutrient content data was not available for the CiFoS commodities and therefore these risks were not considered. The TMERL, which refers to the lowest level of exposure to a risk factor where there is no statistically significant increased risk of a related disease or health outcome, was used as reference level. TMERLs are also provided in the GBD cause and risk factsheets as a range for which the midpoint of this range was used to evaluate the distance between the dietary content and the TMERL.

3. Results

3.1. Catering for current diets (CirAgriDiet)

The translation from available commodities from a circular agri-food system based on current production resulted in a large proportion of commodities remaining unused, and a small share of food current diets produced (Fig. 2). From the total diet, 43% of what is currently consumed could be delivered by the available CiFoS commodities, i.e., 43% of the sum of product quantities consumed was produced from available commodities. From the food products that were included in CirAgriDiet, 43 were deviating >25% from the amount that was currently consumed. 206 food products currently consumed were not produced and included in CirAgriDiet, and 68% of the available commodities could not be used to create currently consumed food products. To provide an example, we zoom in on the share of Fruit that was effectively translated into food products – i.e., excluding the Fruit commodities that were unused – we observed that primarily whole fruits were produced, alongside a small amount of other food products like fruit spreads and desserts (Fig. 2B). However, temperate fruit were not available as commodities and the amount of fruit juice produced did not align with the amount of fruit juice consumed. On the other hand, the amount of citrus fruits consumed could be supplied by the CirAgri scenario.

Comparing the composition of the diet scenarios against the TMRELs of dietary risks showed that most of the beneficial foods (i.e., whole grains, vegetables, fruits, legumes, nuts and seeds, and milk) or nutrients (calcium, omega-3, fiber, PUFA) were available as commodities but were not utilized to produce food products due to the earlier indicated mismatch between commodities and consumed food products (Fig. 3). For example, since milk is not only consumed as milk in current diets – i.e., also as flavored dairy, yoghurts or desserts, which required other ingredients that were not sufficiently available, a large fraction of milk from CiFoS is not used to produce currently consumed food products. Subsequently, because a large share of calcium is provided by milk in the CiFoS scenarios, the available calcium is not included in CirAgriDiet.

3.2. Catering for healthy diets (CirHealthDiet)

Applying the objective to maximize the use of available commodities from a CiFoS scenario that also took health aspects into account, while also preferring un- or minimally processed food products, showed better alignment between available commodities and consumed food products

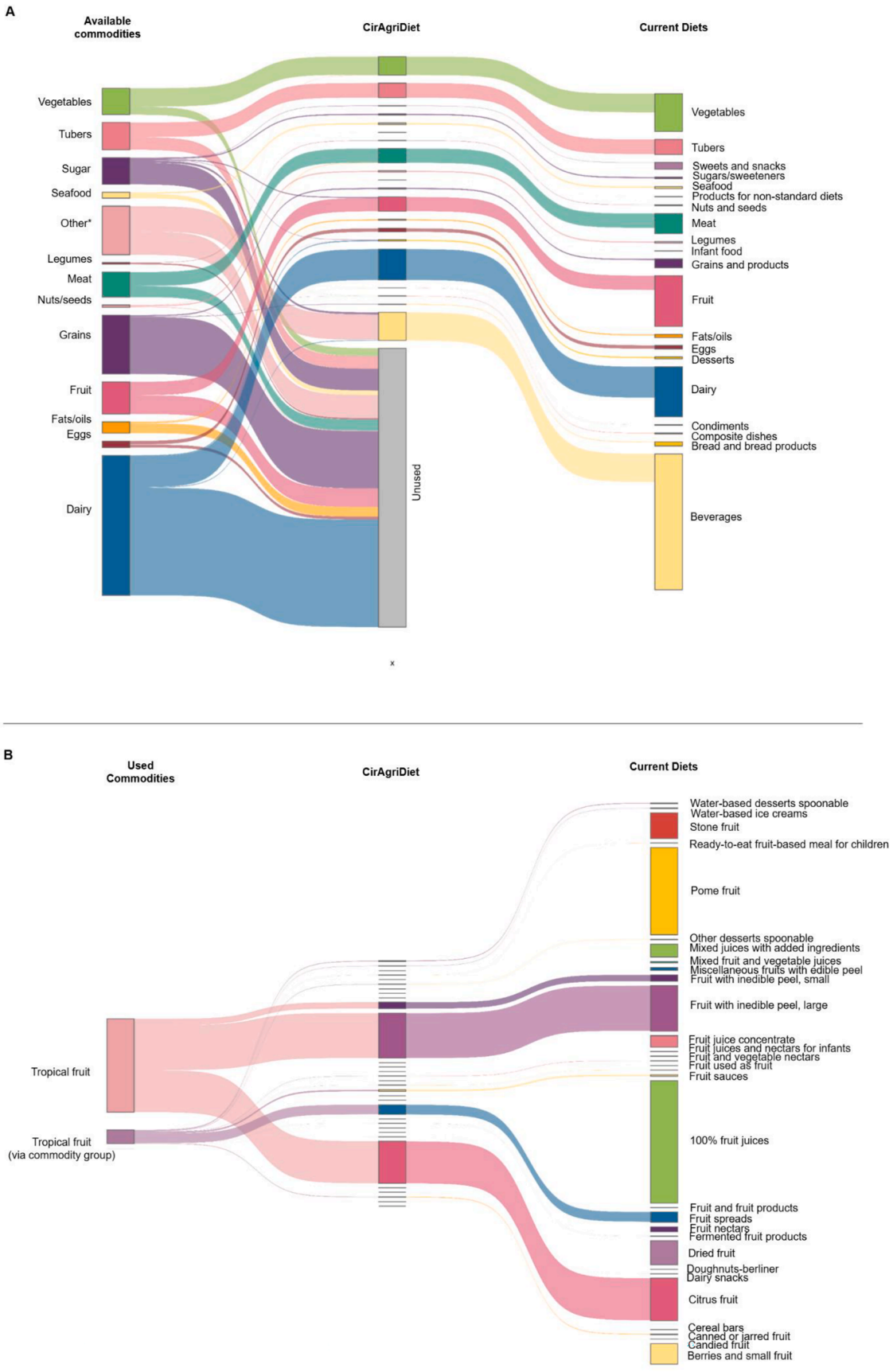


Fig. 2. The translation of available commodities in CirAgriDiet at food group level (A) and at commodity/food product level for the food group Fruit (B). Left side shows commodities, middle shows the dietary scenario and right side shows the current diet. (A) includes the share of available commodities unused, while (B) only considers the part that is effectively used.

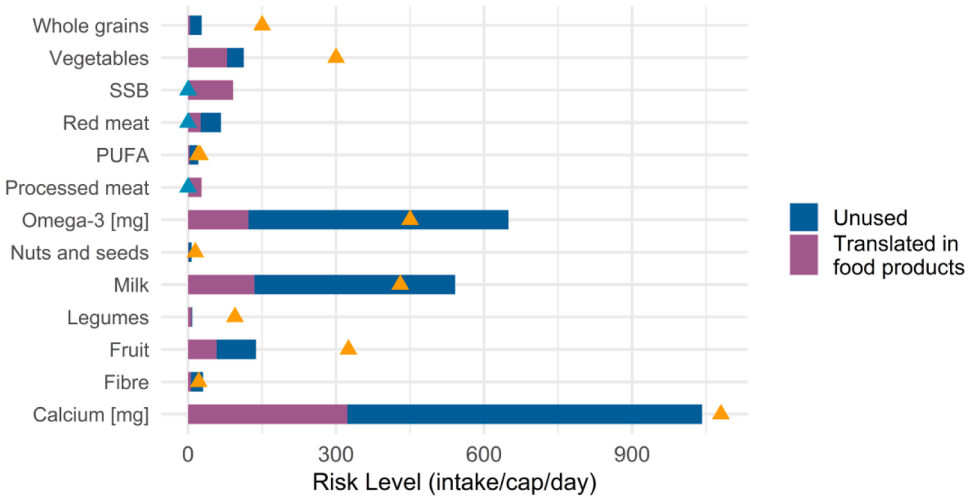


Fig. 3. Quantity of dietary risks – in grams per day except for omega-3 and calcium – included in the diet scenarios (purple), and the quantity of dietary risks that was initially available in the commodities but was not translated into food products/unused (blue). Orange and blue triangles indicate the Theoretical Minimum Exposure Level (TMREL) based on the Global Burden of Disease for beneficial and harmful dietary components, respectively (Table S6). PUFA=Polyunsaturated fatty acids; SSB=Sugar sweetened beverages.

(Fig. 4). In CirHealthDiet, 80% of what is currently consumed could be covered by the available CiFoS commodities, i.e., 80% of the sum of product quantities consumed was produced from available commodities. However, because some food products were also produced in higher quantities as currently consumed, this was not a good indicator for the gap between CirHealthDiet and current diets. To illustrate, 117 were deviating >25% from the amount that was currently consumed which was higher compared to CirAgriDiet due to those food products included at a higher quantity than currently consumed, i.e., >25% above currently consumed. 120 food products currently consumed were not produced and included in CirHealthDiet, and 9% of the available commodities could not be used to create currently consumed food products because they could not be mapped to any of these products. Zooming in on the share of Dairy that was effectively translated into food products – i.e., excluding the Dairy commodities that were unused – we observed that primarily Milk was the main food product included, at a higher quantity than currently consumed (Fig. 4B). On the other hand, a range of products (mainly desserts and confectionery bakery products) were not included in CirHealthDiet due to the preference for NOVA Category 1 products over other categories. This also indicates the difference between current diets and healthy diets.

CirHealthDiet was based on an agri-food system optimization scenario that applied constraints to include minimum and maximum amounts of certain food groups based on the EAT Lancet recommendations (Table S2). However, there was a gap between these food group recommendations and TMRELs from the GBD (Fig. 5). Although more of the beneficial dietary risk components were included in the diet due to the objective to maximize the use of available commodities, calcium, milk, and omega-3 fatty acids were less available in the commodities to start with.

4. Discussion

This study addressed the existing gap between models that are developed from a consumption perspective and focus specifically on the diet component of sustainable healthy diets, versus models that are developed from a production perspective and focus on redesigning the agri-food system and associated sustainable diets (Heerschop et al., 2024). The obtained results demonstrated that the commodities available in an agri-food system that maintained current production on food group level while being optimized based on circularity principles, could only partially be translated into current diets. However, a scenario that shifted production in favor of nutrition and health recommendations could be better translated into food products by applying an objective function to maximize the use of available commodities. None of these two diet scenarios had a composition that aligned well with a low risk for NCDs based on the minimum risk levels from the GBD. We identified that some of the driving factors for how well available commodities translated into diets, and how these diets related to TMRELs, were either due to taking a production-oriented approach in itself, or to methodological choices in this specific model, or the specific scenarios.

4.1. The implications of using a production-oriented approach for current diets

The gap between sustainable production of commodities based on circularity principles, and current diets was substantial, with less than half of the current diets covered by available commodities. Identifying the quantities of crop and livestock products that can be produced against the lowest environmental impact is fundamental to redesigning the agri-food system. While this study displayed the limitation of a strong focus on optimizing production systems, as opposed to starting from optimizing consumption, the importance of redesigning agri-food systems for sustainable healthy diets should be emphasized. That is, basing which foods should be produced where on diets that are optimized for sustainability aspects tends to maintain the status-quo of current production systems instead of revealing the environmental gains from redesigning agri-food systems. However, our results also confirm that such an approach implies a larger deviation from current diets (Cardinaals et al., 2023; Simon et al., 2024b; Vermeulen et al., 2020). Even when the original agri-food system optimization (CirAgri) adhered to current consumption at commodity food group level, only a small amount of available commodities could be used to produce current diets. To this regard, there have been concerns that acceptability of sustainable diets is not accurately considered (Biesbroek et al., 2023; Marrero et al., 2024; Perignon and Darmon, 2021) and Vieux et al. (2018) showed that diets low in GHG emissions and fulfilling nutritional requirements compromised the cultural acceptability of diets (Vieux et al., 2018). Redesigning the agri-food system can result in a change in livestock or crop types compared to current production, of which the products can be effectively used to substitute currently used ones but increasing the deviation from current diets. For example, changing from traditional wheat bread to flatbread based on legume flour, or to tortillas based on corn flour. Being able to assess such food system changes is

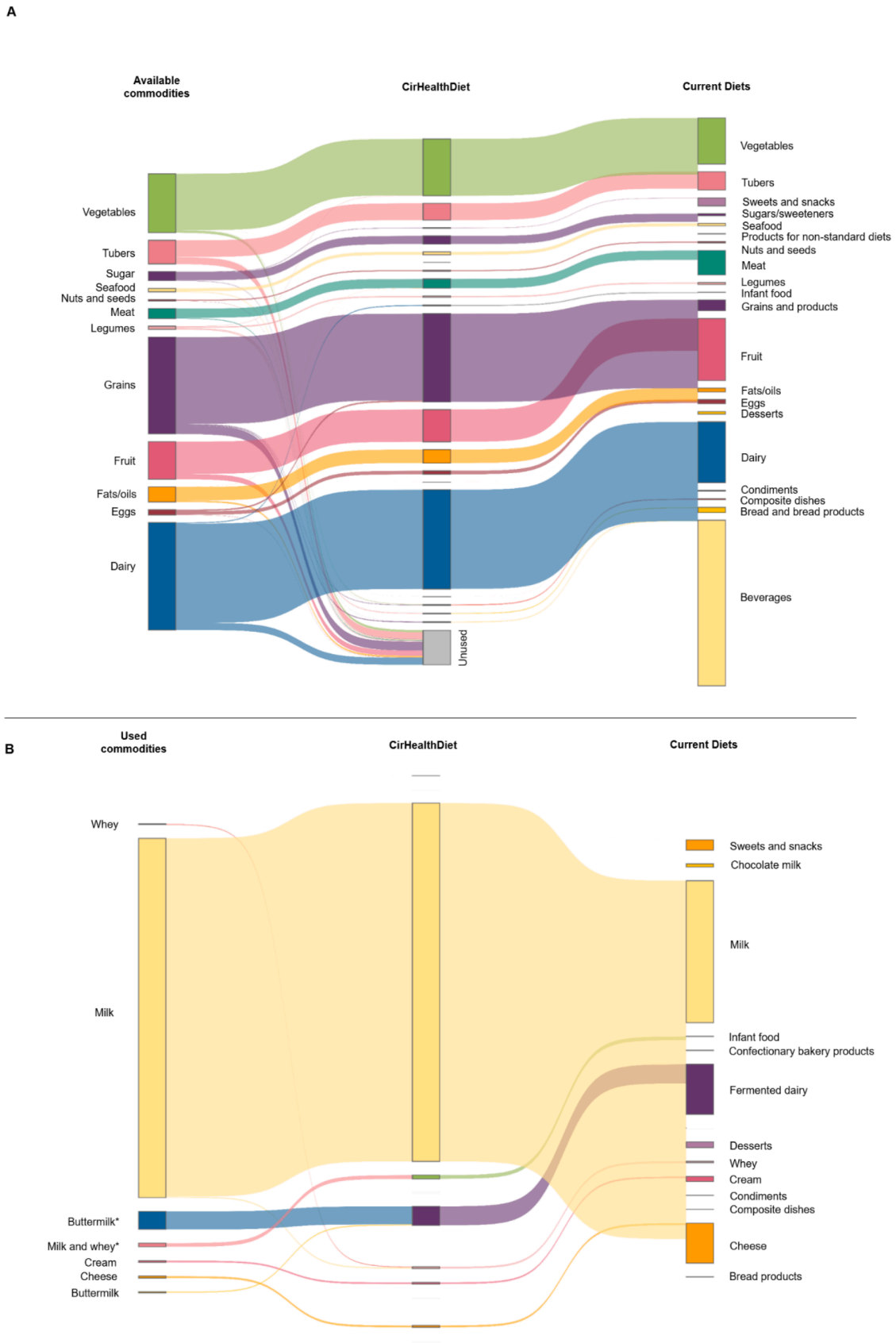


Fig. 4. The translation of available commodities in CirHealthDiet at food group level (A) and at commodity/food product level for the food group Dairy (B). Left side shows commodities, middle shows the dietary scenario and right side shows the current diet. (A) includes the share of available commodities unused, while (B) only considers the part that is effectively used.

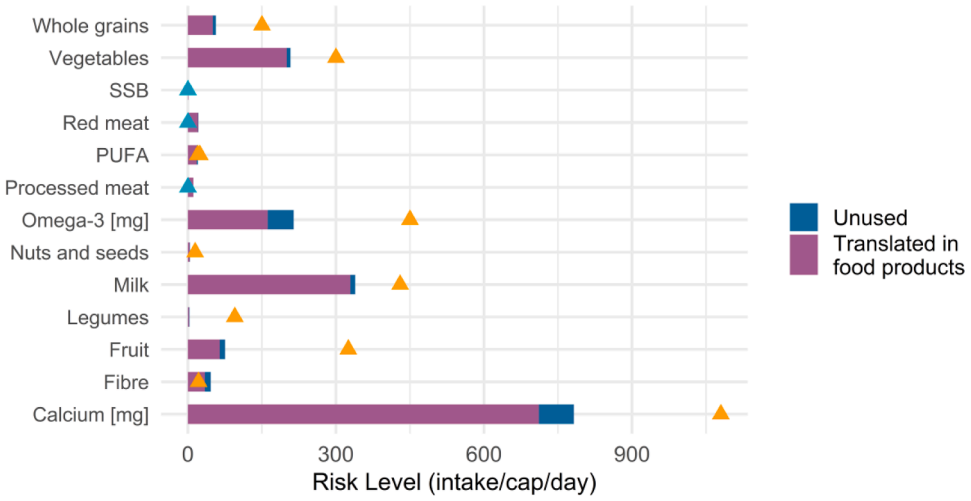


Fig. 5. Quantity of dietary risks – in grams per day except for omega-3 and calcium – included in the diet scenarios (purple), and the quantity of dietary risks that was initially available in the commodities but was not translated into food products/unused (blue). Orange and blue triangles indicate the Theoretical Minimum Exposure Level (TMREL) based on the Global Burden of Disease for beneficial and harmful dietary components, respectively (Table S6). PUFA=Polyunsaturated fatty acids; SSB=Sugar sweetened beverages.

highly relevant in the face of climate change, when needing to shift to crops that are better adapted to changing climates (Guo et al., 2024), and highlights the importance of modelling agri-food systems for sustainable diets (Fanzo et al., 2018).

4.2. Circular agri-food systems for sustainable healthy diets

Current food systems are responsible for a substantial flow of byproducts from food processing that could also be used as human food (Rao et al., 2021; Thorsen et al., 2022). Even more, some of these foods are nutrient dense (Cardinaals et al., 2023; Thorsen et al., 2022). While a large share of byproducts is currently used as animal feed, energy production or brought to landfill, reallocating them to human diets has large potential to reduce GHG emissions and land use linked to food production (van Zanten et al., 2023). Therefore, a food systems approach to improving the sustainability, is to reallocate biomass within the system to be used more efficiently for food production (Muscat et al., 2020). Closing nutrient loops, avoiding food-feed competition, and using crops adapted to climatic and soil conditions all contribute to a reduction in land use and greenhouse gas emissions (Simon et al., 2024b). Prioritizing biomass for human food includes by-products from food production that are in theory human edible, i.e., upcycled foods, but are faced with practical implications and low inclusion in current diets (Rao et al., 2021). On the other hand, there is an emerging group of sustainable consumers who, when knowing that consuming upcycled food could have environmental or health benefits, are more willing to buy these foods (Coderoni and Perito, 2020). However, the results of this study raise the questions whether including by-products for human consumption can be considered optimal use of biomass if there is no consumer market for these foods, and whether unintended waste could mean that the environmental benefits of redesigned agri-food systems are overestimated.

4.3. Food processing in relation to sustainable healthy diets

Commodities can be translated in different ways to create food products across all categories of 'food processing' in the NOVA classification. To illustrate, in CirAgriDiet dairy was used to produce ice cream, desserts and chocolate milk (NOVA classified as ultra-processed) in addition to milk (NOVA classified as minimally processed), while CirHealthDiet was optimized to produce mainly (fermented) milk, and smaller amounts of cream, cheese and whey (NOVA classified as processed). There is ongoing discussion about the role of ultra-processed foods in sustainable healthy diets (Drewnowski et al., 2022; Gustafson et al., 2022; Northcott et al., 2023; Seferidi et al., 2020), largely driven by a lack of consensus on the definition of "ultra-processed" foods (Monteiro Cordeiro de Azeredo and Monteiro Cordeiro de Azeredo, 2022). We acknowledge the weaknesses of the NOVA categorization to be used as an indicator for foods being either "healthy" or not (Black et al., 2025; Forde, 2023). Partly, because the health impact of foods is largely context dependent (i.e., consumed by who, in which quantities, in combination with which other foods). And partly, because processing is a broad term encompassing many different ways to alter food products which may result in either a positive or negative health impact. However, in this study, the NOVA system was employed as a tool to highlight the limitation of not considering the step from commodities to food products as it leaves open which specific products are included in sustainable healthy diets. More extensive research on the health impacts of food processing (Forde, 2023), as well as for its environmental impacts (Anastasiou et al., 2023), is needed to understand how processed food products should be integrated in sustainable healthy diets. Thereby, the main takeaway here is that available commodities can translate into a wide variety of products, which limits drawing conclusions for health and environment on a commodity basis.

4.4. The implications of methodological choices for sustainable healthy diets

Although the CiFoS model, and thereby a circular agri-food system, was used for this case study, the results are relevant for models that are oriented at minimizing environmental impacts by reshaping food production. More specifically, this study revealed how certain methodological choices are key to bridge the gap between an approach that optimizes the agri-food system and one that optimizes diets. Addressing the tension between what people want to eat, and what benefits their health and the environment in line with the required food system transition, requires considering diets with a higher level of detail than commodities. Although leaving a range of freedom to which specific food products are created from broader categories (e.g., "spinach" for "green vegetables"), not considering food product level, risks to redesign the agri-food system for diets that are too far removed from current diets and thereby have a lower chance to be successfully adopted by consumers. Furthermore, if redesigned agri-food systems unintentionally rely on the production of foods that will not be consumed, it could result

in unintended food waste and an overestimation of the potential to reduce environmental impacts. And finally, food product level detail allows to better quantify health impacts of diets. This need for food product level also relates to have a more accurate estimation of the environmental impact related to both the redesigned agri-food system, as well as the diet. Secondly, the definition of food groups and how a "healthy diet" or "healthy food products" are defined and quantified is a driving factor. For example, by not including a minimal amount of whole grains or making a clear distinction between whole fruits and fruit juice, there was a large gap between the outcome of CiFoS and TMRELs. On the other hand, TMERLs represent a lowest risk, while it could be argued that lower (or higher) levels of some foods or nutrients suffice or are still safe, e.g. the TMREL for calcium is 1100–1200 mg/day for females, while EFSA's estimated average requirement is 750 mg/day. Thereby, constraining a production model to the TMERLs of the GBD is unrealistic as TMRELs are not considered targets but rather optima, and it will only create diets that are far from current diets as they generally do not meet TMERLs (Forouhi and Unwin, 2019). To that regard, other guidelines may also be considered to assess how sustainable diets relate to health, e.g., HEI, AHEI, or DASH (Schwingshackl and Hoffmann, 2015). Future research would have to indicate how different levels of food constraints, and the consideration of health guidelines impact the optimization of agri-food systems for environmental impacts, e.g., wholegrain diets could decrease the availability of processing byproducts that would be used as animal feed and thereby increase the reliance on forage crop production (van Selm et al., 2022).

We stress the need to integrate production and consumption approaches for a more accurate assessment of sustainable healthy diets since these are linked to, and have an impact on, food production and not taking this into account could overlook certain trade-offs within the food system (Tuomisto, 2019). This means stepping away from an isolation of optimizing food production to determine what can be consumed, or optimizing diets to determined what should be produced.

5. Conclusion

This study revealed the research gap of defining sustainable healthy diets by optimizing agri-food production systems without a level of detail in food products that is required to understand the feasibility, acceptability and health impacts of such diets. Although the scenario outcomes from the CiFoS model were used as a case study, the finding that commodities in an optimized agri-food system may not directly translate into diets composed of currently consumed food products is highly relevant for any food systems optimization approach. Deriving sustainable healthy diets from an optimization of agri-food systems could result in unintended waste when commodities cannot be used into currently consumed products. And therefore, agri-food system optimization may overestimate the potential for reducing environmental impacts if it does not match food demand preferences. The results also showed that this translation from commodities into food products becomes more feasible when letting go of currently consumed quantities of food products, due to the redesigned food systems being more radical and divergent from current production systems. In addition, the methodological takeaway was that the definition of food groups, or the selection of included commodities, requires critical attention to align with health considerations such as the risk for non-communicable diseases. This study stressed the need to also look beyond commodities when assessing food availability from sustainable food systems, to ultimately derive at sustainable healthy diets. By making the translation from commodities into food products, the gap between sustainable diets and current diets, as well as their health impacts can be better assessed.

Data availability

Data used to define current diets in Europe is publicly available through EFSA's Comprehensive Food Consumption Database (https://www.efsa.europa.eu/en/data-report/food-consumption). Research data including the recipe mapping, quantities of food consumed in current diets, and the preference order based on the NOVA classification are stored in a Zenodo repository (https://doi.org/10.5281/zenodo.20400943). The GAMS code to translate CiFoS results into food products can be made available upon request.

Funding

This research received funding from the Topconsortium voor Kennis en Innovatie (TKI) under grant number LWV21114.

Statement for studies in humans or animals

The research presented does not involve any animal or human study.

CRediT authorship contribution statement

Renee Cardinaals: Writing – original draft, Visualization, Methodology, Formal analysis, Data curation, Conceptualization. **Thomas Maindl:** Writing – original draft, Methodology. **Thom Huppertz:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Hannah Van Zanten:** Writing – review & editing, Supervision, Methodology, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Renee Cardinaals reports financial support was provided by Top Consortia for Knowledge and Innovation (LWV21114). If there are other authors, they 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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