The compatibility of circularity and national dietary recommendations for animal products in five European countries: a modelling analysis on nutritional feasibility, climate impact, and land use

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Summary

Background **National food-based dietary guidelines (FBDGs) are generally designed from a human health perspective and often disregard sustainability aspects. Circular food production systems are a promising solution to achieve sustainable healthy diets. In such systems, closing nutrient cycles where possible and minimising external inputs contribute to reducing environmental impacts. This change could be made by limiting livestock feed to available low-opportunity-cost biomass (LOCB). We examined the compatibility of national dietary guidelines for animal products with livestock production on the basis of the feed supplied by available LOCB.**

Methods **We investigated whether the national dietary recommendations for animal products for Bulgaria, Malta, the Netherlands, Sweden, and Switzerland could be met with domestically available LOCB. We used an optimisation model that allocates feed resources to different species of farm animals. Of the resulting scenarios, we assessed the nutritional feasibility, climate impact, and land use.**

Findings **Our results showed the environmental benefits of reducing the recommended animal products in the FBDGs, and that animal products from LOCB could provide between 22% (Netherlands) and 47% (Switzerland) of total protein contributions of the FBDGs. This range covers a substantial part of the nutritional needs of the studied populations. To fully meet these needs, consumption of plant-based food could be increased.**

Interpretation **Our results contribute to the discussion of what quantities of animal products in dietary guidelines are compatible with circular food systems. Thus, national dietary recommendations for animal products should be revised and recommended quantities lowered. This finding is consistent with recent efforts to include sustainability criteria in dietary guidelines.**

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Introduction

The production of human food affects the environment in multiple ways, including its associated resource use that alters global biomass and nutrient cycles, its effects on climate change, and biodiversity loss.[1] Unbalanced diets that are low in fruit and vegetables, and high in red and processed meat are a major risk factor for several non-communicable diseases, such as cardiovascular diseases, stroke, cancer, and diabetes.[2] In high-income countries, shifting consumption towards plant-based diets is often recommended, to decrease environmental impacts of food consumption and to improve human health benefits of diets.[3] This recommendation is due to the generally favourable environmental effects of plant-based food compared with animal products,[1] as well as the increased risk for diet-related diseases in the case of low fruit and vegetable consumption, and high red and processed meat intake.[4] Food-based dietary guidelines (FBDGs) are key references for healthier food choices. Although environmental concerns are increasingly addressed in FBDGs, for example, in the 2019 EAT–*Lancet* Commission[5] and in several national FBDGs (eg, Sweden and Germany), most national FBDGs are still primarily driven by health and nutritional criteria and often do not include sustainability aspects.[6] Compared with globally applicable guidelines, such as the EAT–*Lancet* Commission, national FBDGs take geographical and cultural circumstances into consideration,[7] and are often well embedded in education and nutrition counselling at the national level.[8]

Although the necessity to reduce the consumption and production of animal products is generally acknowledged, different solutions exist regarding how animal products could be more sustainably produced, and which animal products should be reduced and to what extent.[9,10] From a supply perspective, studies suggest that animal

Research in context

Evidence before this study

Many studies have investigated the nutritional and environmental consequences of adhering to dietary guidelines. We searched the databases Scopus and Web of Science for studies published between Jan 1, 1990, and Feb 19, 2021 in English. We used the following search terms: ("food-based dietary guideline" OR "dietary recommendation" AND "animal* food" OR meat AND "environmental impact" OR "greenhouse gas emissions" OR "resource suitab*" OR "circular*"). A study published in 2020 assessed healthiness and sustainability of 85 national dietary guidelines. Additionally, a large number of studies assessed nutritional and environmental consequences of adopting specific national dietary guidelines. None of these studies investigated the compatibility of animal-source food recommendations with circularity principles. Based on two review articles (one from 2018 and one from 2020) and their citation record, we identified 20 studies that considered the circularity principle of feeding only low-opportunity-cost biomass (LOCB) in scenarios with differing levels of animal-source foods. However, no study was found that addressed resource suitability and feed–food competition in national dietary guidelines, and investigated the potential of limiting livestock to LOCB for such guidelines.

Added value of this study

To our knowledge, this is the first study that assesses environmental consequences and nutritional contributions of national food-based dietary guidelines while considering circular food system principles. We applied our approach to five case studies in Europe (Bulgaria, Malta, the Netherlands, Sweden, and Switzerland), and thereby provide a proof of concept for contrasting situations with different geographical and cultural settings. Although we found that all national guidelines recommend more and different animal-source food than would be optimal from a resource-use and environmental perspective, we also reported substantial differences between the five case study countries. These findings stress the importance of including environmental considerations in national guidelines, and provide an estimate for potential targets for the inclusion of circular livestock in dietary guidelines as well as in current diets.

Implications of all the available evidence

Meeting the recommended amounts of animal product consumption currently stated in national dietary guidelines will not be feasible with only circular livestock systems. When limiting livestock feed to LOCB, recommended amounts of animal product cannot be reached. This amount could become feasible, and environmental impacts could be reduced, if recommendations for animal products were lowered on the basis of sustainability criteria, or when the targets are to achieve a proportion of consumption from circular systems. The composition and quantity of animal product recommendations should be revised with regard to both national resource suitability and specific nutritional requirements that animal products can provide.

production systems should be intensified, which would result in lower environmental impacts per quantity of animal products produced but would require higher concentrate feed inputs given that growth could be faster.[11] From a demand perspective, studies often recommend reducing consumption of animal products substantially or to a minimum.[1,12] In both narratives, land suitability and therefore competition between resources for feed and for food production is mostly not addressed.[13,14] Naturally, when resources are suitable to be allocated for feed and for food production, choices need to be made that have consequences for the sustainability of the food system. In circular food systems, resources are prioritised for human food first, and animal feed is allocated as a second priority.[15,16] A guiding principle for this type of system is to close nutrient cycles where possible and to minimise external inputs, such as feed and mineral fertiliser imports. Animals would then be fed with primarily domestically available low-opportunity-cost biomass (LOCB; eg, processed by-products, food waste, and grass resources), which is also known as the concept of ecological leftovers in the literature.[17] Subsequently, feed–food competition would be largely avoided and biomass could be used more effectively. Through this process, animals can contribute to recycling biomass and nutrients back into the food system, which would otherwise be lost for human food consumption.[18] Considering that recommendations in national FBDGs for most high-income countries are currently driven by health and nutritional aspects and are based on the current linear food system, the role of animal products in FBDGs from the perspective of the environment and efficient resource use is unexplored.

First, we investigated whether it would be feasible to produce the animal products recommended in national FBDGs on the basis of LOCB that would be available when the FBDGs were adhered to, meaning that domestically available plant-based food quantities would correspond to the FBDG suggestions, including imports where necessary owing to insufficient domestic production. The LOCB available for production of animal products would then be derived from these plant-based commodity quantities, their processing and waste fractions, and the domestically available grassland production. By use of a resource allocation model, which was originally developed by van Hal and colleagues[19] and adapted by van Selm and colleagues,[20] we assessed different scenarios for five European countries—namely, Bulgaria, Malta, the Netherlands, Sweden, and Switzerland. Finally, we assessed the climate impact and land use of these alternative scenarios. We explored the nutritional option space that fulfils nutritional requirements that animal products could provide without feed–food competition, and what role animal products could have in balanced diets.

Methods

Study design and system boundaries

Europe was selected as a case study region because of its stable food security situation and better quality data, where discussions on food choices mainly revolve around issues regarding overnutrition and the search for healthy and sustainable food choices.[21] Within Europe, dietary habits differ due to cultural habits and resource endowments. We identified all European countries that provide detailed dietary guidelines and selected five of them representing different regions with differing dietary habits as case studies: Bulgaria (eastern Europe), Malta (southern Europe), the Netherlands (western Europe), Sweden (northern Europe), and Switzerland (central Europe). We collected data for the food groups generally present in FBDGs (appendix pp 1–4).

Plant-based food recommendations

The collected FBDG recommendations were translated into a daily diet (g per capita per day) by disaggregating recommendations for food groups (eg, cereals) into food items (eg, wheat and products, and rye and products), based on Food Balance Sheets[22] (appendix p 1). After these transformations, we obtained an example FBDG diet per country, of which we retained only the plant-based food element for the subsequent analysis. The availability of LOCB (processed by-products, food waste, and grass resources) in each case study country was based on the recommended plant-based food intake when assuming the whole population would follow the country-specific FBDG diet (appendix pp 4–5).

Animal product scenarios

We investigated the potential contribution of animal products to a balanced diet in four different scenarios for each national FBDG. We solely focussed on animal products and therefore did not aim to provide realistic alternatives for the FBDGs used, but rather to explore the full range of options on the basis of LOCB for different nutritional foci. The scenarios all met the circular food system principle of avoiding feed–food competition, meaning that animal products only originated from animals fed on LOCB. The availability of LOCB was restricted to the production pattern resulting from the plant products of the respective national FBDGs.

In the first alternative scenario, MaxProt, LOCB was allocated to the different animal production systems such that human-digestible animal protein was maximised. Along with protein, animal products contain multiple essential nutrients for humans, such as essential fatty acids, vitamins A, D3, and B12, calcium, iron, and zinc.[23] To take the specific nutritional functions of animal products in the diet into account, we used three scenarios that put different emphasis on three main nutrient groups: omega-3 fatty acids (scenario MaxFattyAcids), minerals (scenario MaxMinerals), and vitamins (scenario MaxVitamins). In each of these scenarios, one of the respective groups of nutrients was maximised instead of protein. The scenario MaxFattyAcids maximised the sum of the omega-3 fatty acids α-linolenic acid (ALA), docosahexaenoic acid (DHA), and eicosapentaenoic acid (EPA; in g), the scenario MaxMinerals maximised the sum of the minerals calcium, iron, and zinc (in mg), and the scenario MaxVitamins maximised the sum of vitamins A and B12 (in μg). Vitamin D3 was not considered because ultraviolet B radiation from sunlight is the main source of its synthesis and only a small proportion is derived from dietary sources. We applied these three scenarios to show which nutritional functions of the original FBDGs could be met with animal products from LOCB, and which animal products are essential for which nutritional functions.

See Online for appendix

Resource allocation model

We used a resource allocation model, for which details have been published elsewhere,[19,20] to estimate potential animal products on the basis of calculated LOCB. The model contains a detailed representation of seven animal production systems (dairy cattle, beef cattle, laying hens, broiler chickens, pigs, Atlantic salmon, and Nile tilapia), and allocates feed resources to the different animal production systems while maximising different nutritional contributions (appendix p 5).

Nutritional contribution

We quantified the following nutrient contributions of the FBDG diets: protein; minerals calcium, iron, and zinc; vitamin A; vitamin B12; and omega-3 fatty acids ALA, EPA, and DHA. Nutritional contributions were calculated with food composition tables (appendix p 1). By multiplying quantities per food item of the different FBDG diets as well as the scenarios with the nutrient contents, we derived the total nutritional contribution.

Environmental impact assessment

Greenhouse gas emissions and land use of the scenario MaxProt were assessed for each case study country. For comparison with the original FBDGs, the plant-source element was added to the animal products scenario MaxProt. Further, to show the environmental impacts of comparable protein content, the MaxProt scenario with the plant-source element was scaled to the protein content of the original FBDG for each of the five countries, resulting in the scenario MaxProt (scaled FBDG), and to the protein recommendation of 60 g per capita per day from WHO,[24] resulting in the scenario MaxProt (scaled WHO).

Greenhouse gas emissions and land use were assessed by use of the biophysical mass-flow model SOLm. A detailed description of the model, including code files, is available online.[25] SOLm represents the relevant mass

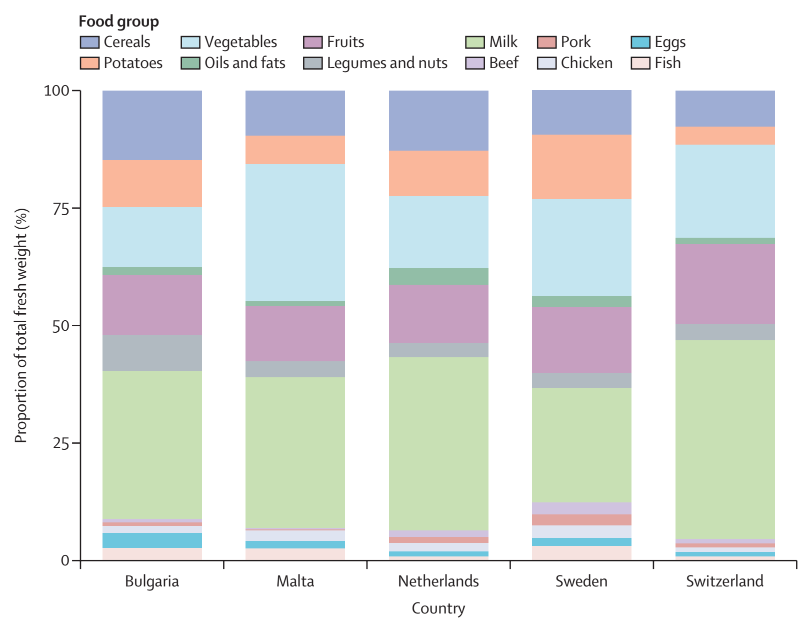

Figure 1: **Composition of the original food-based dietary guidelines (in primary product equivalents)**

	Total protein contribution (FBDG)	Animal protein contribution (FBDG)	Share animal protein / total protein FBDG
Bulgaria	93 g	44 g	0·47
Malta	60 g	34 g	0·56
Netherlands	98 g	45 g	0·46
Sweden	85 g	56 g	0·66
Switzerland	83 g	44 g	0·52

FBDG=food-based dietary guideline.

Table: **Protein contribution of FBDGs in five European countries per capita per day, by population average**

and nutrient flows of agricultural production, allowing assessment of the consequences of large-scale changes in the food system on resource use and emissions (appendix pp 5–6).

Role of the funding source

The funders of this study had no role in study design, data collection, data analysis, data interpretation, or writing of the report.

Results

The compositions of the FBDGs of the case study countries differed by agroecological and sociocultural context (figure 1). The protein contribution of the overall FBDGs of the countries investigated ranged from 60 g (Malta) to 98 g (Netherlands) per capita per day (table). All countries except Malta issued recommendations with higher protein contributions than the average daily protein requirements recommended by WHO (50–60 g),[24,26] factoring in population groups with higher-than-average protein requirements (eg, for pregnant individuals, or for older people). Moreover, the share of animal protein from total protein was remarkably high in all FBDGs assessed, ranging from 0·46 (the Netherlands) to 0·66 (Sweden).

The scenarios MaxProt, MaxFattyAcids, MaxMinerals, and MaxVitamins show the option space of different nutritional foci (figure 2). Through the optimisation process used, results were driven by relative efficiencies (ie, nutritional contribution, such as protein, in relation to feed requirements and availability). Generally, the scenarios revealed trade-offs between the different nutrients. When fatty acids were maximised, supply of minerals and vitamins (eg, calcium, iron, and vitamin A) was reduced in most countries. When maximising the three minerals calcium, iron, and zinc, mainly the fatty acids DHA and EPA showed a substantial decrease. Increased supply of vitamins came at the expense of fatty acids. Overall, these trade-offs per scenario were most pronounced for the fatty acids DHA and EPA, whereas for calcium, protein, vitamins A and B12, and zinc, the signals were less strong. These results emphasise the potential nutritional contributions of animal products, which are embedded within a balanced diet.

No alternative animal product scenario of any country was able to meet the protein contribution of the animal products recommended in the original FBDG diets (figure 2). The maximum achievable protein contribution based on LOCB (scenario MaxProt) ranged from 15·9 g protein per capita per day (Malta) to 38·9 g protein per capita per day (Switzerland). The Netherlands could provide 21·6 g protein per capita per day, Sweden reached 25·4 g, and Bulgaria reached 37·4 g.

In some scenarios and countries, ALA, calcium, zinc, vitamin A, and vitamin B12 of the animal products of the original recommendations could be met, whereas DHA and EPA were always deficient (figure 2). For Malta, no nutrient contribution at the same level as in the original FBDG could be reached. For Bulgaria, all scenarios were able to cover ALA, calcium, zinc, and vitamin A and vitamin B12 intake. For the Netherlands, only vitamin A reached the original contribution. For Sweden, ALA, calcium, and vitamin A could be fulfilled, whereas others, specifically DHA and EPA, were strongly deficient. Of all countries, Switzerland met the most animal nutrient contributions of the FBDG diets, with only slight deficiencies for protein and iron, and more pronounced deficiencies for DHA and EPA.

The differences in nutritional composition stem from changes in the composition of the animal products in the scenarios (figure 3). Compared with the MaxProt scenario, increases in fatty acids were mainly reached with increased fish, and for Bulgaria and Switzerland this outcome was shown with increased pork. When minerals were the focus, eggs were substantially increased, mainly at the expense of pork and fish.

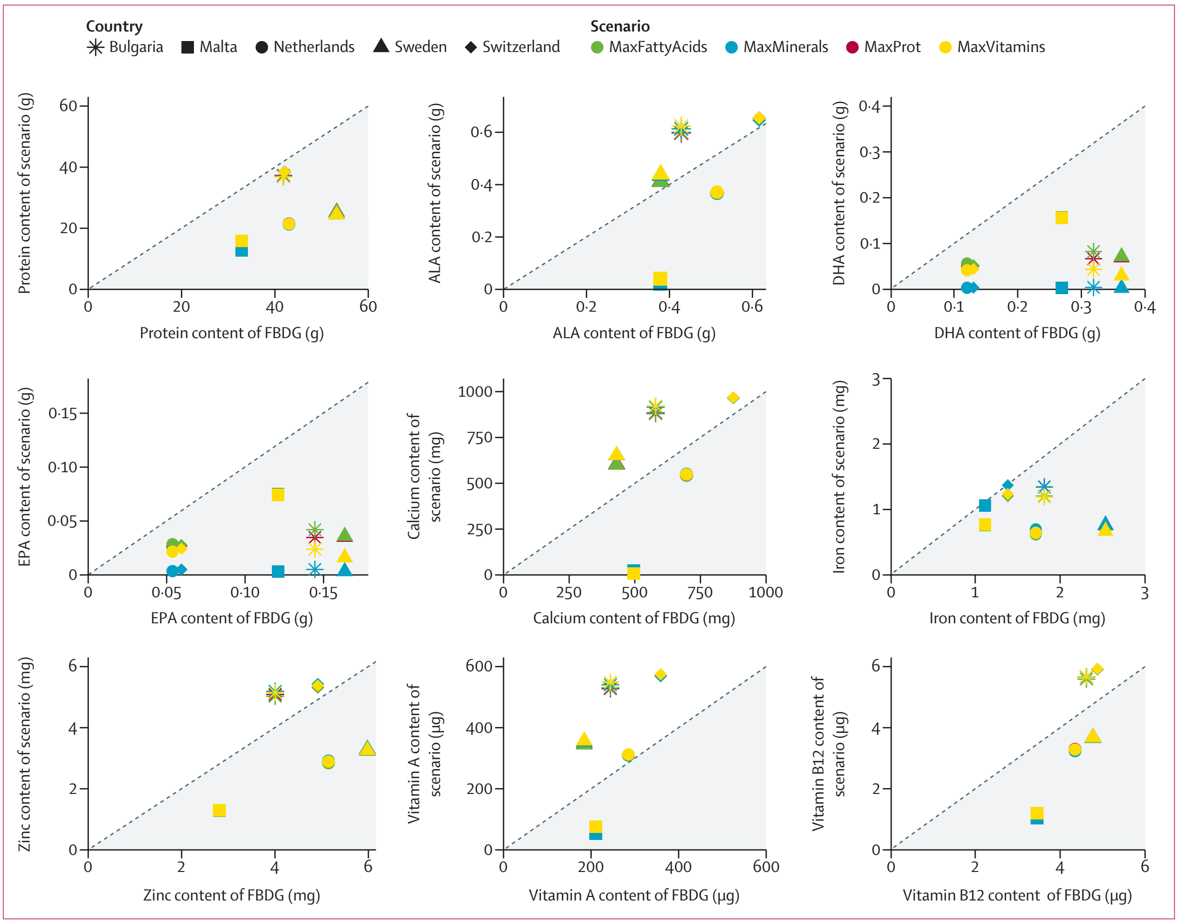

Figure 2: **Nutrients of the animal products in the original food-based dietary guidelines versus nutrients of the animal products in the scenarios and countries per capita per day**

Diagonal line indicates equal nutritional contributions in the scenarios and dietary guidelines. For values in the upper triangle, nutrient contribution of the scenarios exceeds those of the dietary guidelines, and in the lower triangle (grey shading), nutrient contribution of the scenarios is lower than those of the dietary guidelines. Horizontal differences show differences between countries and vertical differences show differences between scenarios. ALA=α-linolenic acid. DHA=docosahexaenoic acid. EPA=eicosapentaenoic acid. FBDG=food-based dietary guideline. MaxFattyAcids=maximised fatty acid scenario. MaxMinerals=maximised mineral scenario. MaxProt=maximised animal protein scenario. MaxVitamins=maximised vitamin scenario.

Moreover, focusing on vitamins A and B12 generally increased milk and the associated beef production. From a nutritional perspective, the quantity and composition of recommended animal products is incompatible with circular animal production.

Resource endowments largely drove the final composition of animal products. Milk and beef supply were mostly driven by available grass resources, which led to minimal supply of milk and beef in Malta, where grass resources are scarce. Grass resources were the main driver for milk production in Bulgaria, the Netherlands, Sweden, and Switzerland, and therefore contributed most to total protein. Thus, although milk recommendations in the original FBDGs were substantial, they were in agreement with the quantity of animal products resulting from LOCB for Bulgaria, Sweden, and Switzerland. However, chicken and fish recommendations could never be met, but pork and eggs recommendations could be met for Malta, in some scenarios.

Greenhouse gas emissions and land use were calculated for the MaxProt animal scenarios and the plant-based food of the original FBDGs, with two scaled versions. With the exception of Bulgaria (+25% for greenhouse gas emissions, +5% for land use) and Switzerland (+2% for greenhouse gas emissions), the MaxProt scenario led to a reduction in environmental impacts (figure 4). For Bulgaria and Switzerland, the high amount of milk and milk products probably contributed to the slight-to-moderate increase. The MaxProt scenario for Sweden and the Netherlands showed a notable decrease (Sweden: –12% for greenhouse gas emissions, –22% for land use; Netherlands: –24% for greenhouse gas emissions, –24% for land use). The strongest decrease was observed for Malta, for which greenhouse gas emissions were reduced by 56% and land use by 40%. When the MaxProt scenarios were scaled to the isoprotein basis of the original FBDGs, the reductions for the Netherlands and Malta were less

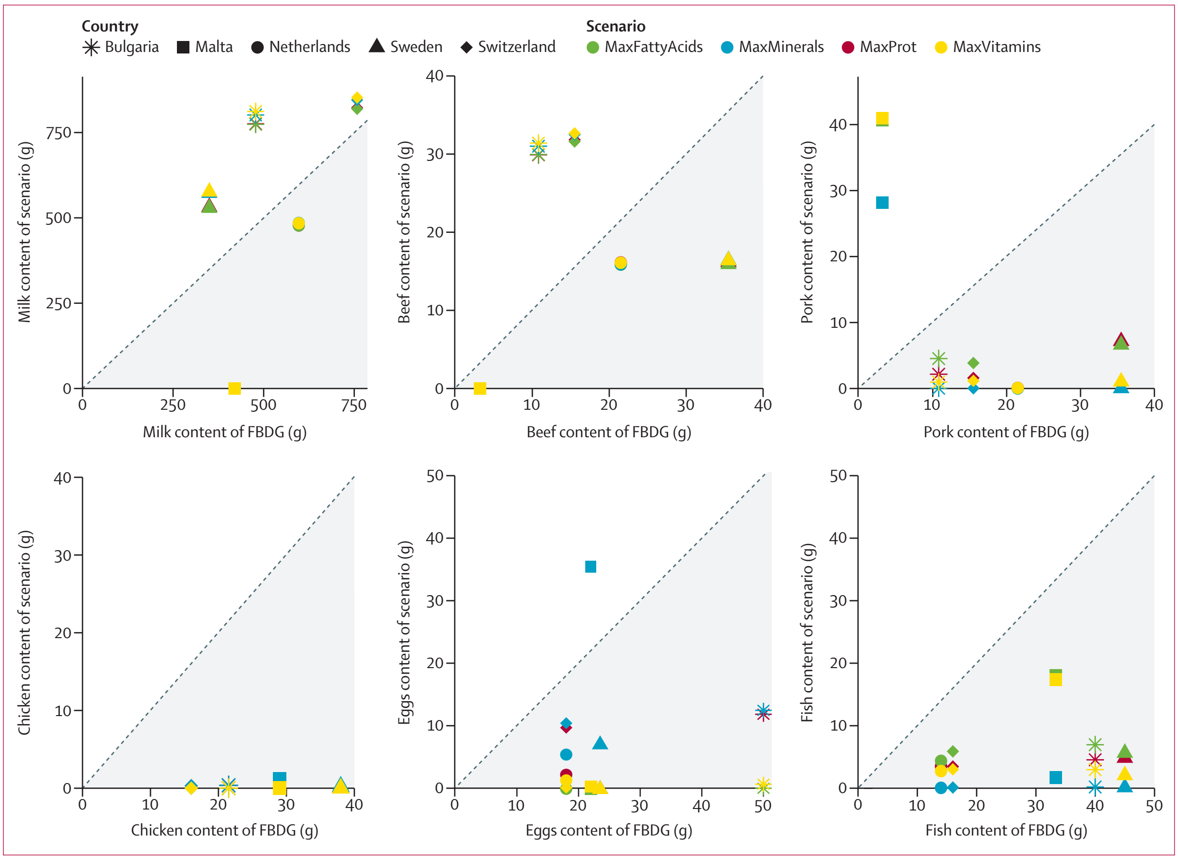

Figure 3: **Quantities of the animal products in the original food-based dietary versus quantities of the animal products in the scenarios and countries per capita per day**

Diagonal line indicates equal nutritional contributions in the scenarios and dietary guidelines. For values in the upper triangle, quantities of the scenarios exceeds those of the dietary guidelines, and in the lower triangle (grey shading), quantities of the scenarios are lower than those of the dietary guidelines. Horizontal differences show differences between countries, and vertical differences show differences between scenarios. FBDG=food-based dietary guideline. MaxFattyAcids=maximised fatty acid scenario. MaxMinerals=maximised mineral scenario. MaxProt=maximised animal protein scenario. MaxVitamins=maximised vitamin scenario.

strong, whereas for Sweden, the direction of change switched to an increase. These effects were driven by the higher protein contents of the original FBDGs. Given that the MaxProt scenarios of all countries in combination with the plant-based element of the original FBDG resulted in a higher protein content than protein requirements of 60 g protein per capita per day,[24] greenhouse gas emissions and land use decreased for all countries in the MaxProt (scaled WHO) scenario.

Discussion

Considerations for environmental impacts in national FBDGs are currently limited to side-notes and suggestions, but do not drive the actual recommended quantities. For example, multiple FBDGs in Europe recommend reducing overall consumption of animal products while increasing plant-based foods in the diet (eg, the Netherlands, Germany, Iceland, and Denmark). Four out of the five national FBDGs assessed in this study recommended amounts of animal products that exceeded what would be required to meet protein as well as other nutrient requirements in a well balanced diet.

Our results showed the benefits of reducing animal products in the FBDGs for greenhouse gas emissions and land use, and showed that animal products from LOCB could cover a substantial part of the nutritional needs of the studied populations, or all protein needs, depending on dietary shifts. With dietary shifts, the reduction in consumption of animal products would be compensated by an increase in consumption of plant-based food, which also contributes to reach nutritional requirements. Our quantitative estimates for the potential of animal products with different nutritional foci can directly contribute to discussions on recommended targets for the inclusion of animal products produced via circularity principles. Such animal products could contribute between 22% (Netherlands) and 47% (Switzerland) of total protein contributions of the original FBDGs. Using domestic availability as a proxy for the national consumption of animal products, a reduction in current animal product consumption of 24–69% in the case study countries would be required.[11] In other words, at least a third of the average daily protein needs could be provided in all countries.[24,26] Notably, the recommended protein intake could also be achieved by increasing the protein contribution from plant-based products.[27] Parallel to the indicated reduction of animal product consumption, moving towards a more circular food system would require substantial adjustments of animal production. As well as investing in breeds that are better suited to value LOCB, the guiding principle to close nutrient cycles where possible and to minimise external inputs, such as mineral fertiliser and feed imports, would result in substantial changes in trade patterns. Only by consistent transformations of food systems in this regard can the estimated environmental improvements be reached.

In line with our findings, the study by Springmann and colleagues,[28] which used similar quantities to represent diets meeting the FBDG, reported that recommendations for animal products in most FBDGs are too high from a human health and environmental impact perspective. van Zanten and colleagues[11] defined a land boundary for sustainable livestock consumption and concluded that, on a global average, 9–23 g of protein per capita—which covers around a third of the daily protein requirement[24]—could be derived from animal products solely from LOCB. However, the recommended amounts of protein from animal products in the five national FBDGs assessed in this study ranged from 34 g to 56 g. Remarkably, this amount could almost cover protein needs without considering plant-based foods. Cultural aspects can possibly explain these relatively high shares of animal products: in many countries, cattle had (and still have) an important role in converting grass resources from marginal areas into valuable animal products. Consequently, consumption of dairy—and the associated beef products and fats—proved an essential source for protein and fats for these populations. However, currently, grass resources are partly grown on land that could be used for human food consumption, and not all of this land is temporary grassland with an agronomic function in crop rotations.[13] Thus, part of these grasslands come with higher opportunity costs for alternative use in food production. These findings call for a revision of dietary guidelines assessed in this study and beyond, which would help in meeting nutrition recommendations based on LOCB-sourced animal products. Similar considerations should be made for other animal products and countries, and redesigning current food systems at a more regional level should be a priority.[27]

The four scenarios showed that, to fulfil a diverse set of nutritional requirements, diversity in animal product consumption is important. Fish and seafood substantially contribute to the dietary omega-3 fatty acid intake, and our findings support this idea. Our analysis showed that, in some countries maximising fatty acids even led to an increase in pork production, with the by-products available as feed for salmon (Bulgaria and Switzerland).[19] When focusing on minerals—specifically zinc, calcium, and iron—egg production was increased, and the

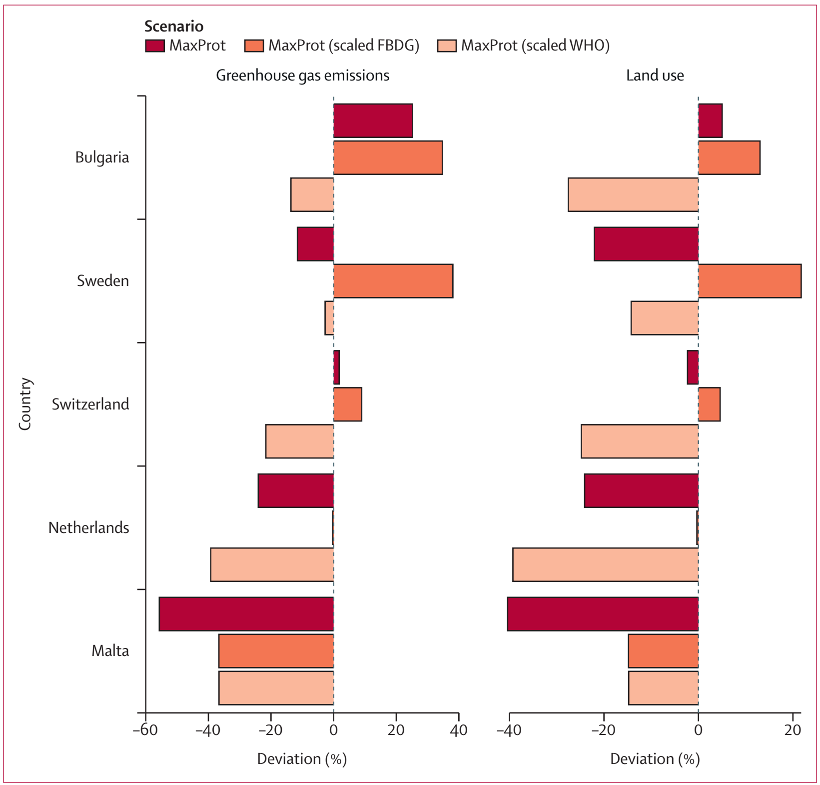

Figure 4: **Greenhouse gas emissions and land use of the scenarios MaxProt, MaxProt (scaled FBDG), and MaxProt (scaled WHO)**
Deviation is relative to the original FBDG per country. FBDG=food-based dietary guideline. MaxProt=maximised animal protein scenario. MaxProt (scaled FBDG)=maximised animal protein scenario scaled to the protein content of the original food-based dietary guideline. MaxProt (scaled WHO)=maximised animal protein scenario scaled to the protein recommendation of the WHO (60 g/capita/day).

associated meat as well. Further, when vitamins A and B12 were focussed on, milk and the associated beef showed a slight increase. In the selected FBDGs, the nutritional function of animal products beyond protein supply was rarely mentioned in the recommendations, and therefore, the reasoning behind the recommended quantities of animal products was not further clarified.

For chicken, results diverged most between our scenarios and FBDGs. Although chicken is the meat type most often recommended in FBDGs,[6] it was rarely selected in the proposed scenarios, independent of the nutritional focus. Chicken is often promoted as a relatively sustainable source of meat owing to its favourable feed conversion ratio, resulting in efficient production and low environmental impact intensities per kg of product.[12] However, the high efficiency of chicken comes with a downside—namely, the required high quality of feed that cannot be provided by standard circular feed production methods.[19] Consequently, currently widespread chicken breeds are not able to feed on lower quality feedstuffs (to which part of LOCB belong), and are therefore not competitive in scenarios with LOCB. In current production systems, feed for chicken is often of high quality, and its production competes directly or indirectly with human food production.[14] Notably, results could look different if, for example, greenhouse gas emissions would be considered in the scenario definition process, which might favour chicken over other animal production systems. Moreover, chicken features a more favourable nutritional profile than other types of meat. In several epidemiological studies, no correlation with increased risk for non-communicable diseases was found for white meat, but it was found for red and processed meat types.[29,30]

Geographical circumstances shape the availability of LOCB. Here, we used a national geographical scope, and did not allow trade of LOCB. This approach led to large imbalances between countries regarding available LOCB, and thus regarding available animal products. This imbalance was particularly pronounced for Malta, for which available LOCB was so low that a large nutritional gap resulted. Previous assessments of circular food systems took a global or regional perspective, and assumed that within these geographical contexts part of the produced LOCB can be traded freely.[19] Thus, countries with low levels of LOCB could import LOCB from other countries, based on the assumption of an equal distribution of LOCB across the geographical scope assessed. Moreover, although LOCB availability is determined by the geographical level of assessment, it is also determined by the available share of landings from fisheries. Sustainable landings from fisheries could be an important source for animal products in circular food systems. LOCB and fish landings might not be ideally allocated in the country they are produced. Therefore, it is important to investigate suitable and equitable distribution mechanisms of LOCB, animal products, and fish landings. Thus, the consequences and effects of distribution have to be weighted against the benefits that occur when resources are allocated optimally across larger scales.

There were some limitations to our study. First, we solely varied animal products in FBDGs, while keeping plant-based food constant. However, the proposed reductions in animal products would need to be compensated with increased or specifically diversified plant-based food, which would also contribute to meeting nutritional requirements. For this consideration, a land use model is needed that includes both plant-based food and animal products, while capturing resource use efficiency as well as flows between the different production systems.

For more on the **project associated with the NWO-veni grant** see www.circularfoodsystems.org

Further, we acknowledge that environmental sustainability encompasses much more than greenhouse gas emissions and land use. The production of our food affects the environment in many ways (eg, by altering the global nutrient cycles, adverse impacts on biodiversity, and fostering soil erosion). Moreover, the environment is only one dimension of total sustainability; social and economic effects of food production and human health implications of our food consumption are also important factors. Although we only considered the two environmental indicators, our proposed scenarios would probably affect many other dimensions of sustainability. For example, nitrogen surplus could be reduced substantially, resulting from the reduction in animal farming and omission of imported feed. This omission would lead to a reduction of the whole nutrient throughput in the system and, therefore, potentials for losses are smaller. Further research could, for example, focus on the implications on nutrient flows and soil health of following such scenarios, as well as economic and social consequences.

In conclusion, the proposed approach can transparently contribute to discussions on recommended targets for the inclusion of animal products produced via circularity principles. Although the animal product recommendations in the FBDGs of Bulgaria, Malta, the Netherlands, Sweden, and Switzerland are neither in their composition nor in their total nutritional value achievable with animal products from LOCB, 45–88% of the protein from animal product recommendations could be met with the proposed circularity principles. This result comes with major implications for the five national FBDGs assessed, and applies to most others in high-income countries.[28] To make the dietary guidelines of these countries compatible with principles from circular food systems as well as protein requirements, animal product recommendations would need to be substantially reduced. Such a reduction would lead to a substantial reduction in greenhouse gas emissions and land use. Clarity regarding the nutritional function of the recommended animal products in the diet could help to target the animal products composition, and to decide how to allocate LOCB resources in the optimum way.

Contributors

AF, RPMC, IJMdB, AM, CS, OvH, and HHEvZ designed the research. AF, RPMC, and BvS conducted the research. AF and RPMC analysed and verified the data. AF, RPMC, IJMdB, AM, CS, BvS, OvH, GP, SR, MH, and HHEvZ contributed to writing the paper. All authors had final responsibility for the decision to submit for publication.

Declaration of interests

We declare no competing interests.

Data sharing

Data described in the manuscript, code book, and analytic code will be made available upon request. Requests can be directed to Anita Frehner (anita.frehner@fibl.org).

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