40:60: The optimal ratio between animal and plant-based proteins for health and environment

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Abstract

There is currently little agreement on the optimal ratio of animal-sourced (ASP) versus plant-sourced proteins (PSP) in sustainable human diets. We deployed a biophysical optimization model to find the optimal ASP:PSP ratio at current and recommended protein intake levels for the EU28 countries. Results show that the lowest environmental impact for both land use and greenhouse gas emissions is achieved at a recommended protein intake of 46 g protein/cap/day with an ASP:PSP ratio of 40:60 (18 g ASP/cap/day). At current protein intake (82 g protein/cap/day), the optimal ASP:PSP ratio for land use ranges evenly between 22:78 and 60:40 (18 and 49 g ASP/cap/day) while for greenhouse gas emissions the optimal ASP:PSP ratio is at 40:60 (18 g ASP/cap/day). Diets containing less than 18 g ASP/cap/day show micronutrient inadequacies, leading to increases in both land use and greenhouse gas emissions.

Introduction

In recent years, the European Union (EU) has shown increasing interest in the transformation of the current food system. With the European Green Deal and the embedded Farm to Fork Strategy, the EU strives to be the world's first climate-neutral trade union[1]. To achieve this ambition, production and consumption changes are needed which implies a radical food system redesign[2].

One strategy that claims to respect both human and planetary health is to reduce the share of animal sourced-foods in the human diet[3]. For instance, the scientific advisory organ of the Dutch Parliament has initiated an investigation on the optimal ratio of animal products in diets, and Germany has launched a far-reaching 'Protein Crop Strategy' ('Beans, Peas & Co') for promoting legume cultivation[4,5]. The incentive for this so-called 'protein transition' relates to the fact that the livestock sector has a large impact on the environment. The European sector contributes to 78% of terrestrial biodiversity loss, 81% of agricultural GHG emissions, and uses around 65% of total agricultural land[6] leading to feed-food competition between animals and humans[7]. Nevertheless, animals are an important source of protein – 60% of all protein are derived from animals. At the same time, the EU is facing a challenge regarding overconsumption and diet-related diseases. Today's protein intake levels are around 82 g protein/cap/day (49 g animal protein and 33 g plant protein)[8], while the European Food Safety Authority (EFSA) sets an average requirement (AR) intake of 46 g protein/cap/day[9]. Moreover, the high consumption of processed meat and red meat is associated with an increased risk of heart disease, certain types of cancer, and diabetes type 2[10–12].

Although the impact of animal products on both the environment and human health is evident, there is no consensus on the optimal dietary share of animal-sourced proteins (ASP) versus plant-sourced proteins (PSP). Some studies suggest that eating a fully plant-based diet is the most sustainable[13,14], while others report that animals still play a crucial role and provide up to 30 g ASP/cap/day if used as waste stream recyclers[15–20]. In the latter scenario, animals are only fed with products that humans cannot or do not want to eat, enabling more efficient use of resources.

The aim of this study was to assess the optimal ratio between ASP:PSP for human and planetary health under two paradigms: one in which diets shift towards healthier eating patterns while maintaining current protein intake, and a second where current protein intake is reduced to a healthy recommended protein intake within the EU context. In both paradigms we looked for the optimal ratio that would either minimize the amount of greenhouse gas emissions (GHG) emitted or total agricultural land use in the EU28 food system. Results show that the lowest impact for both land use and GHG emissions is achieved when protein intake levels are reduced to a recommended protein intake of 46 g protein/person/day with an ASP:PSP ratio of 40:60 and 18 g ASP/cap/day.

Results

Scenarios

We used the Circular Food Systems optimization model (CiFoS), a biophysical optimization model, to assess the optimal ASP:PSP ratio[21]. We assessed different scenarios to discover the optimal ASP to PSP ratios which would minimize GHG emissions and/or land use. The ASP:PSP ratios were assessed under two different paradigms: one in which diets shift towards healthier eating patterns while maintaining the current protein intake of 82 g protein/cap/day and a second representing a healthy diet based on a recommended protein intake of 46 g protein/cap/day. Healthy diets were defined by adhering to EFSA nutrient requirements[9] and recommended range of intake levels per food group derived from the EAT-Lancet guideline[22]. ASP:PSP ratios started at current levels (60:40) - the reference level - and were reduced in steps of 20% towards a fully plant-based diet while minimizing nutrient deficiencies. We assessed a total of 18 scenarios plus the reference scenario (Table 1). The reference scenario matches empirical data related to the current food system, (e.g., current crop production systems for domestic use and export with associated areas) while minimizing the difference with the current food supply[8,23,24] (objective function).

Table 1

Protein levels per protein transition scenarios. LU = land use, GHG = greenhouse gas, Cur = current intake, Rec = recommended intake, PI = protein intake, ASP = animal-sourced protein, PSP = plant-sourced protein, cap = capita.

Scenario names	Protein intake level	ASP:PSP ratio	PI (g/cap/day)	ASP intake (g/cap/day)
LU or GHG_Reference_60:40	Current protein intake	60:40	82	49
LU or GHG_CurPI_60:40	Current protein intake	60:40	82	49
LU or GHG_CurPI_40:60	Current protein intake	40:60	82	33
LU or GHG_CurPI_22:78	Current protein intake	22:78	82	18
LU or GHG_CurPI_20:80	Current protein intake	20:80	82	16
LU or GHG_CurPI_00:100	Current protein intake	00:100	82	0
LU or GHG_RecPI_60:40	Recommended protein intake	60:40	46	28
LU or GHG_RecPI_40:60	Recommended protein intake	40:60	46	18
LU or GHG_RecPI_20:80	Recommended protein intake	20:80	46	9
LU or GHG_RecPI_00:100	Recommended protein intake	00:100	46	0

The impact of ASP:PSP ratios on land use and GHG emissions

Our results show three remarkable findings. First, the largest reduction in land use (41%) and GHG emissions (61%) was achieved solely by applying circularity principles (see methods). The ASP:PSP ratio remained unchanged – 60:40 ASP:PSP (Fig. 1a,b). Secondly, applying circularity principles plus shifting the ASP:PSP towards more PSP reduces GHG emission by 80% (Fig. 1c,d) while land use is not remarkably impacted by changes in ASP:PSP ratios (Fig. 1a,b). Thirdly, a fully plant-based diet resulted in nutrient inadequacies with increased environmental impacts (Fig. 1a-d).

Finding 1: potential of applying circularity principles

Using circularity principles, land use can be reduced annually by 41% (from 172 to 101 mil ha) and GHG emissions by 61% (from 1172 to 455 kg CO2eq/cap/year) at current protein intake levels and the current 60:40 ASP:PSP ratio (paradigm 1) (Fig. 1a,c). This reduction is due to improved use of waste streams (e.g., as animal feed) and optimized plant and animal production systems. An even larger reduction of land use and GHG emissions can be achieved by applying production-side circularity principles as well as by reducing protein intake to recommended levels while maintaining the ASP:PSP at 60:40 (paradigm 2). At recommended protein intake, land use was reduced by 79% (from 172 to 36 mil ha) while GHG emissions decreased by 85% (from 1172 to 237 kgCO2eq/cap/year) (Fig. 1b,d).

Finding 2: optimal ASP:PSP ratio

Land use remains constant under different ASP:PSP ratios. The largest reduction in land use under the current protein intake paradigm, was achieved with a current ASP:PSP ratio of 60:40 (49 g ASP/cap/day): 41% reduction in land use (71 mil ha). Changing the ASP:PSP ratio to 40:60 (33 g ASP/cap/day) or 22:78 (18 g ASP/cap/day) reduced land use with 39% (67 mil ha) and 36% (63 mil ha), respectively. Thus land use only increases with 8 mil ha (5%) when shifting from 60:40 to 22:78. When transitioning towards healthy protein intakes (paradigm 2) land use was reduced by 80% to 35 mil ha. The 40:60 ratio (18 g ASP/cap/day) reveals similar results to that of the 60:40 ratio (28 g ASP/cap/day) with a reduction in land use of 79% to 36 mil ha. Changing the ASP:PSP ratio is therefore not an appropriate indicator for land use reductions. However, protein intake is; lowering protein intake from 82 to 46 g/cap/day reduces land use by 74 mil ha.

For GHG emissions the largest reduction under both paradigms (current and recommended protein intake levels) were achieved with an ASP:PSP ratio of 40:60 (33 g ASP/cap/day paradigm 1 and 18 g ASP/cap/day paradigm 2). GHG emission are reduced by 76% to 281 kgCO2eq/cap/year under the first paradigm and by 85% to 171 kgCO2eq/cap/year under the second paradigm. Reducing ASP:PSP ratios in our diets thus has a greater effect on GHG emissions than on land use due to the strong link between GHG emissions and farmed animals – especially ruminants - in the food system.

Finding 3: nutrient inadequacy and increased land use and GHG emissions in fully-plant-based diets

Nutrient inadequacy emerged consistently below a daily intake of 18g ASP/cap/day. Decreasing ASP further not only led to increased nutrient inadequacy but also to increased land use and GHG emissions. This is due to an increased demand for crops high in certain nutrients (e.g., calcium), such as legumes, vegetables, nuts and seeds, and fruits, to compensate for the absence of animal-sourced nutrients. The increased use of artificial fertilizers required for these crops and transportation of foods also results in higher GHG emissions. The main nutrients leading to inadequacies were vitamin B12, EPA and DHA (inadequately supplied below 18 g ASP/cap and day) as well as calcium, selenium, vitamin B3 and energy (at the border to nutrient inadequacy) (Fig. 3).

Food system redesigns at optimal ASP:PSP ratios

Transitioning the food system towards optimal ASP:PSP ratios requires a redesign of the food system in terms of diet, crop production systems, and animal production systems.

Dietary strategies to reduce land use and GHG emissions

Vegetables are the only food group for which consumption increased in all scenarios in order to shift to healthier diets. Their contribution to total protein intake is however limited (6–8 g/cap/day). In terms of overall supply, dairy (13 g – 19 g) and grains (8 g – 20 g) are the main protein suppliers in all scenarios. However, some notable differences were observed depending on the scenario.

At current protein intake levels (paradigm 1), the reduction in land use and GHG emissions is mainly due to a shift in protein sources. Fish consumption largely increased and therefore seems to be a strategy to reduce both land use and GHG emissions when protein intake levels remain high. The consumption of red meat (-73% to -79%), eggs (-73% to -100%) and dairy (-10% to -38%) were reduced while chicken meat increased (up to 12%) when decreasing land use and decreased (-100%) when minimizing GHG emissions. Moreover, to further minimize GHG emissions, legumes are favoured over chicken, and legumes proteins are largely increased to 29 g of protein per cap per day.

At recommended protein intake levels (paradigm 2), ASP was reduced to 18 g (ASP:PSP ratio of 40:60) when reducing land use and GHG emissions, mainly from dairy (13g) and grains (13g-16g). Lowering the overall protein intake to recommended intake levels increased the risk of nutrient inadequacies. At an ASP:PSP ratio of 40:60, calcium, vitamin B12 and energy are going towards nutrient inadequacy, driving the model to increase food sources with higher amounts of these scarce nutrients (Fig. 3). Nutritious nuts and seeds and fruits were therefore selected as nutrient sources (Table 2).

Table 2
Amount of protein sourced per food group for the optimal ASP:PSP ratio when minimizing land use and GHG emissions and the FAO reference. The percentage shows the relative increase (+) or decrease (-) when comparing the optimal scenarios to the FAO reference scenario. LU = land use, GHG = Greenhouse gas emissions, Cur = current protein intake, Rec = Recommended protein intake, cap = capita.

Food group	FAO Reference (g/cap/day)	LU_Cur_60:40	LU_Rec_40:60	GHG_Cur_40:60	GHG_Rec_40:60
Red meat	19	5 (-73%)	4 (-79%)	4 (-79%)	4 (-79%)
Chicken	11	12 (12%)	0 (-100%)	0 (-100%)	0 (-100%)
Fish	6	14 (136%)	1 (-83%)	9 (52%)	1 (-83%)
Dairy	21	17 (-20%)	13 (-38%)	19 (-10%)	13 (-38%)
Eggs	4	1 (-73%)	0 (-100%)	1 (-73%)	0 (-100%)
Oil Fat	1	0 (-100%)	0 (-100%)	0 (-100%)	0 (-100%)
Legumes	4	4 (14%)	0 (-100%)	29 (725%)	4 (14%)
Nuts seeds	2	0 (-100%)	3 (97%)	3 (97%)	2 (31%)
Vegetables	4	6 (67%)	6 (67%)	8 (123%)	6 (67%)
Fruits	1	1 (-30%)	2 (39%)	1 (-30%)	1 (-30%)
Tubers	3	2 (-29%)	1 (-65%)	1 (-65%)	2 (-29%)
Grains	29	20 (-32%)	16 (-46%)	8 (-73%)	13 (-56%)
Sugars	0	0 (-100%)	0 (-100%)	0 (-100%)	0 (-100%)

Strategies for reducing land use and GHG emissions by changing crop production systems

One key factor to reduce land use and GHG emissions in all scenarios was to increase the production of legumes, especially soybeans. This is due to their high protein content (up to 20 g protein/100g and 36 g protein/100g for soybeans), their favourable amino acid profile (especially for soybeans), and the ability of legume crops to fix atmospheric nitrogen, thereby reducing the amount of artificial fertilizer required and associated GHG emissions. At current protein intake levels (paradigm 1) the relative land share of legumes to all other crops increased by a factor of 13 (to 40 mil ha of the 101 mil ha), to cover almost half of the arable land when reducing land use and a factor of 16 (to 59 mil ha of the 122 mil ha) when reducing GHG emissions (Fig. 2 and S1). Although at recommended protein intake level (paradigm 2), cereals were favoured over legumes, the production of legumes still increased 5 times (to 40 mil ha of the 36 mil ha) when reducing land use, and 11 times (to 59 mil ha of the 122 mil ha) when reducing GHG emissions. In addition to the increase in legumes, vegetable and oil crops also increased considerably under both paradigms, while forage crops and permanent grassland decreased in land share.

Strategies for reducing land use and GHG emissions by changing animal production systems

Overall animal numbers are largely reduced. Nevertheless, the reduction in animal numbers is larger when reducing GHG emissions compared to land use. Fish is the only animal production system where numbers increased; this can be explained by three factors: first, fatty fish are the most important provider of omega-3 fatty acids (i.e., alpha-linolenic acid (ALA), eicosapentaenoic acid (EPA), docosahexaenoic acid (DHA)), a nutrient causing nutrient inadequacy. Second, fish have an efficient protein conversion ratio; compared to other animal production systems, they need less nutrients to produce proteins for human consumption[25]. Last, fish production - especially offshore salmon – does not require agricultural land as long as no additional feed has to be grown, making it the most land efficient animal type when minimizing land use. In addition to an increase in fish in paradigm 1, broiler meat also increased (current protein intake) while land use was reduced. Similar to fish, broilers have an efficient protein conversion factor. In this scenario, broilers were mainly fed with food system leftovers thereby reducing land use. All other animal production systems were largely reduced: beef (-3% to -100%), pigs (-69% to -100%), layers (-66% to -100%) and dairy (-66% to -100%) compared to the reference scenario (Figure S2). Although dairy numbers decreased, dairy in general is clearly favoured over other animal production systems as it provides highly nutritious food (i.e., milk and meat) while at the same time upcycling human-inedible biomass like grass.

Transportation strategies to reduce emissions

Our results show that a highly effective strategy to reduce GHG emissions is cutting down on transportation. In the optimal GHG minimizing scenarios, the share of transportation to the whole GHG emissions was only 10%, compared to 29% in the reference scenario. However, transitioning towards a fully plant-based diet in the food system leads to an accompanying increase in transportation emissions, since the acquisition of location-specific and nutrient-rich crops exclusively cultivated in certain areas of the EU28 necessitates sourcing food items from more distant regions. This shows the clear trade-off between reducing land use and greenhouse gas (GHG) emissions regarding transportation emissions (Figure S3).

Discussion

The optimal ASP:PSP ratio: 40:60

Transitioning towards healthy diets with recommended protein intake levels results in the lowest land use (80% reduction) and GHG emission (85% reduction) with an ASP:PSP ratio of 40:60. When shifting towards healthier diets while maintaining current protein intake, the optimal ASP:PSP ratio for land use ranges between 22:78 and 60:40 (36% – 41% reduction), while for greenhouse gas emissions the optimal ASP:PSP ratio is 40:60 (76% reduction).

Overconsumption of proteins therefore has a large environmental impact, especially on land use. We found a difference of 66 mil ha between the optimal land use scenarios of current vs recommended protein intake. This finding aligns with previous studies showing the impact of overconsumption on the environment[26]. It should however be noted that our results show that a reduction of protein towards recommended protein intake levels increases the probability for nutritional inadequacies, as more nutrients move towards the lower end of requirements. Moreover, although requirements for individual amino acids had to be met, we did not consider protein quality and digestibility. Including these aspects may affect the results as the fraction of total protein taken up by the body will be lower in plant-based diets. This may imply that the protein recommendation should be higher than used in this study. Nevertheless, the EFSA protein recommendations are based on a mixed EU diet and therefore already assume a certain share of protein from plant-sources[9]. Careful planning is needed to ensure the intake of both macronutrients and micronutrients remains adequate. From that perspective, a protein intake above the average requirement can help avoid nutrient inadequacies if the share of PSP in EU diets is increased.

The potential of applying circularity principles

Although an ASP:PSP ratio of 40:60 results in the lowest land use and GHG emissions, our results show that a large reduction can be achieved when solely applying circularity principles and without changing the ASP:PSP ratio. Land use can be reduced by 41% and GHG emissions by 61% without changing total protein intake or share of animal-sourced protein. The circularity principles were i) feeding animals with products human cannot or do not want to eat[17], ii) increasing the edible ratio of animals, i.e., all edible parts of farmed animals are consumed by humans and, iii) improving nutrient re-cycling by fostering circular fertilization using leguminous crops in crop rotation, compost from organic waste streams, manure, and crop residues. Our findings support recent studies showing that agricultural land can largely be spared for other purposes when feeding farmed animals with human-inedible products, and reducing animal numbers accordingly[28]. This spared land could then be used for other purposes, for example to sequester carbon through forests, increase biodiversity or to produce biofuels[29].

Eliminating nutritional inadequacy in plant-based diets

We show that, when shifting towards plant-based diets, we need to balance both micronutrients and macronutrients to ensure nutritionally adequate diets. When transitioning to a plant-based diet, a suite of (predominantly animal-sourced) micronutrients such as vitamin B12, calcium, EPA and DHA drive GHG emissions and land use[30,31]. It is therefore relevant to understand whether these nutrient inadequacies can be mitigated with future foods or fortified food products like seaweeds, insects and cultured meat to substitute animal-sourced micronutrients in plant-based diets[32–35] while providing an environmentally friendly solution[36,37]. Other studies report that future food diets in the EU can reduce land use (-87%) and GHG emissions (-83%) compared to current production systems[36,38].[37] found that food-based strategies like fortification, biofortification and dietary diversification can improve micronutrient intake. Thus, adding future foods and food fortification to our suite of dietary options can have a beneficial effect on land use and GHG emissions when transitioning towards more plant-based diets, yet these were not included in this study[39,40].

No regret solutions

Food system redesigns are complex and, as our results reveal, both trade-offs and synergies occur between minimizing land use and GHG emissions. So-called no regret solutions (synergies) to reduce both land use and GHG emissions were: i) reduce the amount of ASP in diets by at least 20% to a ratio of 40:60 ASP:PSP, ii) increasing the cultivation of legumes to at least 40% of agricultural land, iii) increasing cultivation of vegetables, increasing fish production and to largely reducing livestock numbers.

An example of a trade-off is the cultivation of legumes (> 40% of agricultural land) to reduce GHG emissions. Legumes require more land for the same amount of protein compared to cereals but decrease GHG emissions. This trade-off could be reduced by increasing legume competitiveness with novel breeding strategies. Our results also reveal a trade-off related to transportation (land use increases with local production due to decreased yields) which could be overcome when transitioning towards more sustainable energy sources.

ASP:PSP ratio in food-based dietary guidelines (FBDGs)

We show that optimal ASP:PSP ratios depend on the total protein intake level. In high income-countries with high protein intake, lower ASP:PSP ratios have large environmental and, in combination with a balanced diet, human nutritional benefits. National food-based dietary guidelines (FBDGs) in general do not consider environmental sustainability in their recommendations[41], however this is changing. Although, most European FBDG recommendations advice to eat less red and processed meat and to replace it with legumes, white meat, and fish[42], still recommendations with regards to overall protein intake levels are high. For example the Netherlands advices in its FBDG a protein intake of 98 g cap/day (45 g ASP cap/day) and Sweden 85 g cap/day (56 g ASP cap/day)[43]. This clearly shows the potential for improvement towards achieving the optimal ratios we present in this study. Therefore, we strongly recommend further reducing the consumption of ASP and increasing the consumption of legumes to redesign European FBDGs towards improving both human and planetary health.

Online methods

Circular food system model

This study is based on the Circular Food Systems model (CiFoS)[28]. CiFoS is a bio-physical data- driven food system linear programming optimization model coded in GAMS[44]. The model was developed to represent a circular food system with all its subsystems such as human nutrition, animal and plant-production, capture and fisheries, and waste streams.

Human nutrition

In CiFoS, the daily recommended nutrient requirements advised by the European Food Safety Agency (EFSA) for the EU28 are met to ensure a nutritious diet. The model covers 37 nutritional indicators including macro and micronutrients, vitamins, amino acids, fatty acids and energy content. Vitamin D and iodine recommendations were excluded as a nutritional requirement due to mandatory salt fortification for iodine in the EU and implicit limitations in obtaining enough vitamin D from diets alone. Nutritional content of the CiFoS products is based on the FoodData Central Data from USDA[45]. In addition to nutrient requirements, food intake constraints per product and/or food family were included based on the reference range of the EAT-Lancet dietary guidelines[22]. All scenarios apart from the reference scenarios complied with the nutrient requirements and the EAT-Lancet diet[22].

Land availability

The total area of agricultural land available in the EU28 is 172 mil ha.[24] This land is divided in three distinct land use types: arable land, marginal grassland, and rangelands. On arable land, temporary grassland is a nested land use type that can be selected in crop rotations as any other crop. Land cover maps for grassland were taken from the History Database of the Global Environment (HYDE)[46] and represent the year 2010, while the cropland was taken from IIASA-IFPRI[47]. Grassland was classified as temporary when cropland and grassland land cover maps overlapped.

Plant production

CiFoS includes 43 food crops and 8 fodder crops including 3 different grass types. Production data of the 43 food crops are based on the Global Spatially-Disaggregated Crop Production Statistics Data for 2010 (Version 2.0) further referred to as SPAM[48,49]. Production data for the fodder crops were sourced from the EARTHSTAT dataset “Harvested Area and Yield for 175 Crops”[50]. Yields and area data were spatially extracted for climate-soil zones. These zones were created based on the intersection of the Global Agro-ecological Zones[51] and the IPCC default soil classes derived from the Harmonized World Soil Data Base[52]. The Crop rotations were represented as fractions of areas based on the rotation break data[53]. Fertilization is assumed to be balanced, meaning that we only fertilize as much as the nutrient uptake of the plants plus the losses. The losses for nitrogen were calculated based on the IPCC[54], while field losses for phosphorus were assumed to be 12.5% of application[55].

Animal production

The animal system includes livestock (dairy, beef, pigs, broilers, layers) and farmed fish (Atlantic Salmon and Nile Tilapia)[56]. The two farmed fish species function as proxies for salt and freshwater species. The animal type determines the nutrient requirements and other characteristics such as the feed intake capacity. Furthermore, the model includes the whole herd structure with parent stocks (e.g., sow in pig system) and reproduction stocks (e.g., heifer in a dairy system) to account for the animal’s entire lifecycle. The final feed ration is a model outcome. To meet these requirements, the model can select different feed ingredients ranging from co-products, food waste, grass resources, animal by-products, and high quality biomass such as grains, which humans can also consume.

Fisheries

The model further includes capture fisheries as food and feed. Capture fisheries provide fish for human consumption and fish by-products which can be fed to animals. Landings of capture fisheries are based on a combined database of the RAM Legacy Stock Assessment[57] and FAO marine capture data[58]. Landings were assumed to be limited to the maximum sustainable yield (MSY) implemented in EU legislation. This MSY represents the highest achievable landings without long-term negative impacts on the population. A distinction was made between the edible yield fraction of all landed food-grade fish and their non-edible by-products to account for feed-food competition.

Residual streams

The model represents different residual streams such as crop residues, by-products, food losses and waste, manure, compost, and human excreta. Depending on the type and suitability, these streams can be used as feed, fertilizer, or food. A more detailed description can be food in[28] .

Greenhouse gas emissions

Greenhouse gas emissions arise from cropping and animal production systems and transportation. GHG emissions from cropping systems are based on the direct and indirect emissions from N2O in relation to soil and climate and fertilizer type[59]. For animal GHG emissions, we used the tier2 approach from the IPCC methodology[60]. The precise way to calculate animal-based GHG emissions is described in [28]. The transportation of crops, animals and by-products is allowed between EU28 countries. These GHG emissions are the result of transportation fossil fuel use. The emissions were calculated using the distance between countries, the lorry size, and the emission factor per kilometre from evo-invent[61]. Compost emissions were further accounted for by converting the N losses and the CH4 losses to CO2. All emissions were converted to CO2 equivalents and summed to calculate the total amount of GHG emission per food system.

Circular principles

Circularity was modelled following three major principles. First, animals can only be fed by low-cost biomass that humans cannot or do not want to eat[17]. Farmed animals are then fed by all the supply chain losses and co-products from food processing. Second, the edible ratio of animals is increased, meaning that all edible parts of the farmed animals (i.e. offal) are consumed by humans. Third, nutrient re-cycling is improved by preventing over-fertilization and fostering circular fertilization. Circular fertilization makes use of leguminous crops in crop rotation, compost from organic waste streams and crop residues to reduce artificial fertilizer inputs.

Scenario description

Reference scenario

The reference scenario fixes the current agricultural land from FAOSTAT and minimizes the difference to the FAO protein supply per food group[8]. Trade was only allowed between countries but not outside the study boundaries. The reference is therefore a self-sufficient production and consumption scenario for the EU28 countries. The agricultural land is based on the MAPSPAM data[48] and was scaled to the total FAOSTAT areas per land use[23,24]. The current protein supply was derived from Food Balance Sheet (FBS) element: "protein supply quantity (g/cap/day)")[8].

Protein intake scenarios

Two protein intake levels were defined to assess the effect of these levels on land use and GHG emissions at a food system level. Current protein intake was calculated by subtracting consumption losses from the protein food supply based on food groups (FAO-FBS element: "protein supply quantity (g/cap/day)")[8,62]. The current EU28 protein intake resulted in 82 g protein/cap/day. Recommended protein intake was calculated by combining the EFSA average requirement (AR) of 0.66 g protein/kg body weight with a 70 kg reference body weight[9]. This resulted in a recommended protein intake of 46 g protein/cap/day, thus the difference between current and recommended protein intake is 36 g protein/cap/day. The current ratio of around 60:40 between animal and plant sourced proteins was calculated from the FBS[8]. To derive the amount of animal protein intake, current and recommended protein intake were multiplied by 0.6 to result in an ASP intake of 49 and 28 g/cap/day, respectively (Fig. 4).

Protein transition scenarios

The protein transition from the current to a plant-based food system is modelled as a stepwise reduction of ASP in the diet. The transition is modelled in four steps going from an ASP:PSP ratio of 60:40, 40:60, 20:80 to 00:100% (plant-based). For current total protein intake levels, an additional ASP:PSP ratio of 22:78 was added because the 20:80 ratio was nutrient inadequate (< 18 g ASP/cap/day), which led to difficulties in comparison with the other ratios.

Objective function and final scenario definitions

We expanded the initial food systems model developed by [28] to quantify the effect of the protein transition in EU28 on land use and GHG emissions. The adjusted model included a double optimization option: first the human nutrition gap was minimized, followed by minimizing either land use or GHG emissions. In this manner, we ensured that model outcomes closely met the nutritional requirements for macro and micronutrients (Fig. 4). To model all the scenarios, we use four different objective functions combined in three optimization scenario options (see 'Objective function equations' in Supplementary information):

1. Minimizing the positive and negative deviation to the FBS protein supply while fixing the current total agricultural land.

2. Minimizing the human nutrient gap + Minimizing the land use

3. Minimizing the human nutrient gap + Minimizing GHG emissions

By using one reference scenario, two different optimization approaches, with two protein intake scenario levels and four protein transition step scenarios and the two ‘22:78’ scenarios, we generated a total of 19 scenarios. The basis of the scenarios is shown in Table 3:

Table 3
Scenario parameters and associated assumptions for the modelling procedure.

Scenario	Parameter	Description/Assumption
All protein transition scenarios	Use of Low-cost biomass	Low-cost biomass can be used as feed or fertilizer. Offal can be used as food. All animal products have to be used either as food or as feed and are not allowed as fertilizers. This is an important premise of a circular food system[17,27].
All	Import, Export	No import or export from outside EU28. Trade between all countries is allowed. Emissions through transport are considered.
All	Animal numbers	Animal numbers are variable. Animals can have different intensity levels, which is reflected in their feed demand and related impact.
Reference	Minimize difference to protein supply	Minimizing the deviation to the protein supply by food group of the FBS[8].
Reference	Fixing agricultural land	Fixing the current agricultural land to the baseline so it serves as a land reference scenario per land type (arable land, grassland on arable land, marginal grassland and rangeland) and crop group (e.g., cereals, legumes, vegetables).
Protein transition (PT)	Meet human nutrient requirements	Human nutrition requirements have to be met as much as possible. We included all macro (energy, fat, protein) and micro nutrients (minerals, vitamins, fatty acids and amino acids).
Protein transition (PT)	Total protein intake	Total protein intake was either 82 (current) to 46 (recommended) g protein/cap/day.
Protein transition (PT)	Animal protein intake	The current animal protein intake is derived by the ratio of 60:40 between animal and plant proteins (Table 1).
Protein transition (PT)	Share of animal protein intake	The ratio of ASP: PSP ranged between 60:40 to 0:100 for both protein intake levels (Table 1).

Software and data analysis

All data transformation, analysis and visualization were performed using R (version 4.2.2)[63]. The optimization modelling was performed using the General Algebraic Modeling System (GAMS)[21].

Declarations

Data availability

The raw data have been deposited in a GIT repository and are available on request under a licence similar to Creative Commons Attribution-Non Commercial-Share A like 4.0 International Public License.

Code availability

The model code has been deposited in a GIT repository and is available on request under a licence similar to Creative Commons Attribution-Non Commercial-Share A like 4.0 International Public License.

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References

1. EU. *Farm to fork strategy - for a fair, healthy and environmentally-friendly food system*. https://food.ec.europa.eu/system/files/2020-05/f2f_action-plan_2020_strategy-info_en.pdf (2020).
2. EC. *The european green deal*. https://eur-lex.europa.eu/resource.html?uri=cellar:b828d165-1c22-11ea-8c1f-01aa75ed71a1.0002.02/DOC_1&format=PDF (2019).
3. Springmann, M. *et al.* Options for keeping the food system within environmental limits. *Nature* **562**, 519–525 (2018).
4. Centre, N. N. White paper: Towards a more plant-based diet. *Ministry of Agriculture, Nature and Food Quality* (2023).
5. BMEL. Beans, peas & co. *Federal Ministry of Food and Agriculture* (2020).
6. Leip, A. *et al.* Impacts of european livestock production: Nitrogen, sulphur, phosphorus and greenhouse gas emissions, land-use, water eutrophication and biodiversity. *Environmental Research Letters* **10**, 115004 (2015).
7. EC. *Cereals, oilseeds, protein crops and rice*. https://agriculture.ec.europa.eu/farming/crop-productions-and-plant-based-products/cereals_en#studies (2022).
8. FAO. *Food balances (2010-) (FBS)*. https://www.fao.org/faostat/en/#data/FBS (2022).

9. EFSA Panel on Dietetic Products, N. & Allergies. Scientific opinion on dietary reference values for protein. *EFSA Journal* **10**, 2557 (2012).
10. Wolk, A. Potential health hazards of eating red meat. *J Intern Med* **281**, 106–122 (2017).
11. Domingo, J. L. & Nadal, M. Carcinogenicity of consumption of red meat and processed meat: A review of scientific news since the IARC decision. *Food and Chemical Toxicology* **105**, 256–261 (2017).
12. Bouvard, V. *et al.* Carcinogenicity of consumption of red and processed meat. *Lancet Oncol* **16**, 1599–600 (2015).
13. Xu, X. *et al.* Global greenhouse gas emissions from animal-based foods are twice those of plant-based foods. *Nature Food* **2**, 724–732 (2021).
14. Poore, J. & Nemecek, T. Reducing food's environmental impacts through producers and consumers. *Science* **360**, 987 (2018).
15. Schader, C. *et al.* Impacts of feeding less food-competing feedstuffs to livestock on global food system sustainability. *Journal of The Royal Society Interface* **12**, 20150891 (2015).
16. Smil, V. Eating meat: Constants and changes. *Global Food Security* **3**, 67–71 (2014).
17. Zanten, H. H. E. van, Meerburg, B. G., Bikker, P., Herrero, M. & Boer, I. J. M. de. Opinion paper: The role of livestock in a sustainable diet: A land-use perspective. *animal* **10**, 547–549 (2016).
18. Röös, E. *et al.* Greedy or needy? Land use and climate impacts of food in 2050 under different livestock futures. *Global Environmental Change* **47**, 1–12 (2017).
19. Elferink, E. V., Nonhebel, S. & Moll, H. C. Feeding livestock food residue and the consequences for the environmental impact of meat. *Journal of Cleaner Production* **16**, 1227–1233 (2008).
20. Röös, E., Patel, M., Spångberg, J., Carlsson, G. & Rydhmer, L. Limiting livestock production to pasture and by-products in a search for sustainable diets. *Food Policy* **58**, 1–13 (2016).
21. Corporation, G. D. *General algebraic modeling system (GAMS).* vols Release 41.5.0 (2021).
22. Willett, W. *et al.* Food in the anthropocene: The EATLancet commission on healthy diets from sustainable food systems. *The Lancet* **393**, 447–492 (2019).
23. FAO. *Land use (RL).* https://www.fao.org/faostat/en/#data/RL (2022).
24. FAO. *Crops and livestock products (QCL).* https://www.fao.org/faostat/en/#data/QCL (2022).
25. Fry, J. P., Mailloux, N. A., Love, D. C., Milli, M. C. & Cao, L. Feed conversion efficiency in aquaculture: Do we measure it correctly? *Environmental Research Letters* **13**, 024017 (2018).
26. Ranganathan, J. *et al.* Shifting diets: Toward a sustainable food future. (2016).
27. Van Zanten, H. H. E. *et al.* Defining a land boundary for sustainable livestock consumption. *Global Change Biology* **24**, 4185–4194 (2018).
28. Zanten, H. H. E. van *et al.* Circularity in europe strengthens the sustainability of the global food system. *Nature Food* (2023) doi:10.1038/s43016-023-00734-9.
29. Röös, E. *et al.* Protein futures for western europe: Potential land use and climate impacts in 2050. *Regional Environmental Change* **17**, 367–377 (2017).

30. Vieux, F., Darmon, N., Touazi, D. & Soler, L. G. Greenhouse gas emissions of self-selected individual diets in france: Changing the diet structure or consuming less? *Ecological economics* **75**, 91–101 (2012).
31. Scarborough, P. *et al.* Dietary greenhouse gas emissions of meat-eaters, fish-eaters, vegetarians and vegans in the UK. *Climatic change* **125**, 179–192 (2014).
32. Bak, U. G. Seaweed cultivation in the faroe islands: An investigation of the biochemical composition of selected macroalgal species, optimised seeding technics, and open-ocean cultivation methods from a commercial perspective. (2019).
33. Croft, M. T., Lawrence, A. D., Raux-Deery, E., Warren, M. J. & Smith, A. G. Algae acquire vitamin B12 through a symbiotic relationship with bacteria. *Nature* **438**, 90–93 (2005).
34. Kanazawa, A. VITAMINS IN ALGAE. *NIPPON SUISAN GAKKAISHI* **29**, 713–731 (1963).
35. Mišurcová, L., Ambrožová, J. & Samek, D. Chapter 27 - seaweed lipids as nutraceuticals. in *Advances in food and nutrition research* (ed. Kim, S.-K.) vol. 64 339–355 (Academic Press, 2011).
36. Tzachor, A. Novel foods for human and planetary health. *Nature Food* **3**, 247–248 (2022).
37. Parodi, A. *et al.* The potential of future foods for sustainable and healthy diets. *Nature Sustainability* **1**, 782–789 (2018).
38. Mazac, R. *et al.* Incorporation of novel foods in european diets can reduce global warming potential, water use and land use by over 80. *Nature Food* **3**, 286–293 (2022).
39. Eustachio Colombo, P., Elinder, L. S., Lindroos, A. K. & Parlesak, A. Designing nutritionally adequate and climate-friendly diets for omnivorous, pescatarian, vegetarian and vegan adolescents in sweden using linear optimization. *Nutrients* **13**, (2021).
40. Gazan, R. *et al.* Individual diet optimization in french adults shows that plant-based 'dairy-like' products may complement dairy in sustainable diets. *Sustainability* **14**, 2817 (2022).
41. James-Martin, G. *et al.* Environmental sustainability in national food-based dietary guidelines: A global review. *The Lancet Planetary Health* **6**, e977–e986 (2022).
42. EC. Food-based dietary guidelines in europe. *Health Promotion and Disease Prevention Knowledge Gateway* **Table 1 - 22**, (2021).
43. Frehner, A. *et al.* 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. *The Lancet Planetary Health* **6**, e475–e483 (2022).
44. GAMS - a user's guide, GAMS release 24.2.1. (2013).
45. (2019).
46. Goldewijk, K. K., Beusen, A., Drecht, G. van & Vos, M. de. The HYDE 3.1 spatially explicit database of human-induced global land-use change over the past 12,000 yearsgeb_587. (2010).
47. Fritz, S. *et al.* Mapping global cropland and field size. *Global Change Biology* **21**, 1980–1992 (2015).
48. Yu, Q. *et al.* A cultivated planet in 2010 – part 2: The global gridded agricultural-production maps. *Earth Syst. Sci. Data* **12**, 3545–3572 (2020).

49. Wood-Sichra, U., Joglekar, A. & You, L. Spatial production allocation model (SPAM) 2005:technical documentation. (2016).
50. Monfreda, C., Ramankutty, N. & Foley, J. A. Farming the planet: 2. Geographic distribution of crop areas, yields, physiological types, and net primary production in the year 2000. *Global Biogeochemical Cycles* **22**, n/a–n/a (2008).
51. Fischer, G. *et al.* Global agro-ecological zones (GAEZ v4)-model documentation. (2021).
52. Batjes, N. *IPCC default soil classes derived from the harmonized world soil data base (ver. 1.0), carbon benefits project (CBP) and ISRIC-world soil information*. (2009).
53. (2019).
54. Eggleston, S., Buendia, L., Miwa, K., Ngara, T. & Tanabe, K. *2019 refinement to the 2006 IPCC guidelines for national greenhouse gas inventories*. (2019).
55. Lun, F. *et al.* Global and regional phosphorus budgets in agricultural systems and their implications for phosphorus-use efficiency. *Earth System Science Data* **10**, 1–18 (2018).
56. Hal, O. van *et al.* Upcycling food leftovers and grass resources through livestock: Impact of livestock system and productivity. *Journal of Cleaner Production* **219**, 485–496 (2019).
57. Ricard, D., Minto, C., Jensen, O. P. & Baum, J. K. Examining the knowledge base and status of commercially exploited marine species with the RAM legacy stock assessment database. *Fish and fisheries* **13**, 380–398 (2012).
58. Department, F. S., Fisheries, I. S. of the & Agriculture. FAO statistics and information service of the fisheries and agriculture department. *Food and Agriculture Organization of the United Nations* (2014).
59. Hergoualch, K. *et al.* N2O emissions from managed soils, and CO2 emissions from lime and urea application. (2019).
60. Gavrilova, O. *et al.* Emmisions from livestock and manure management. (2019).
61. Wernet, G. *et al.* The ecoinvent database version 3 (part i): Overview and methodology. *The International Journal of Life Cycle Assessment* **21**, 1218–1230 (2016).
62. Gustavsson, J., Cederberg, C., Sonesson, U., Van Otterdijk, R. & Meybeck, A. *Global food losses and food waste*. (FAO Rome, 2011).
63. Team, R. C. *R: A language and environment for statistical computing*. (2022).

Figures

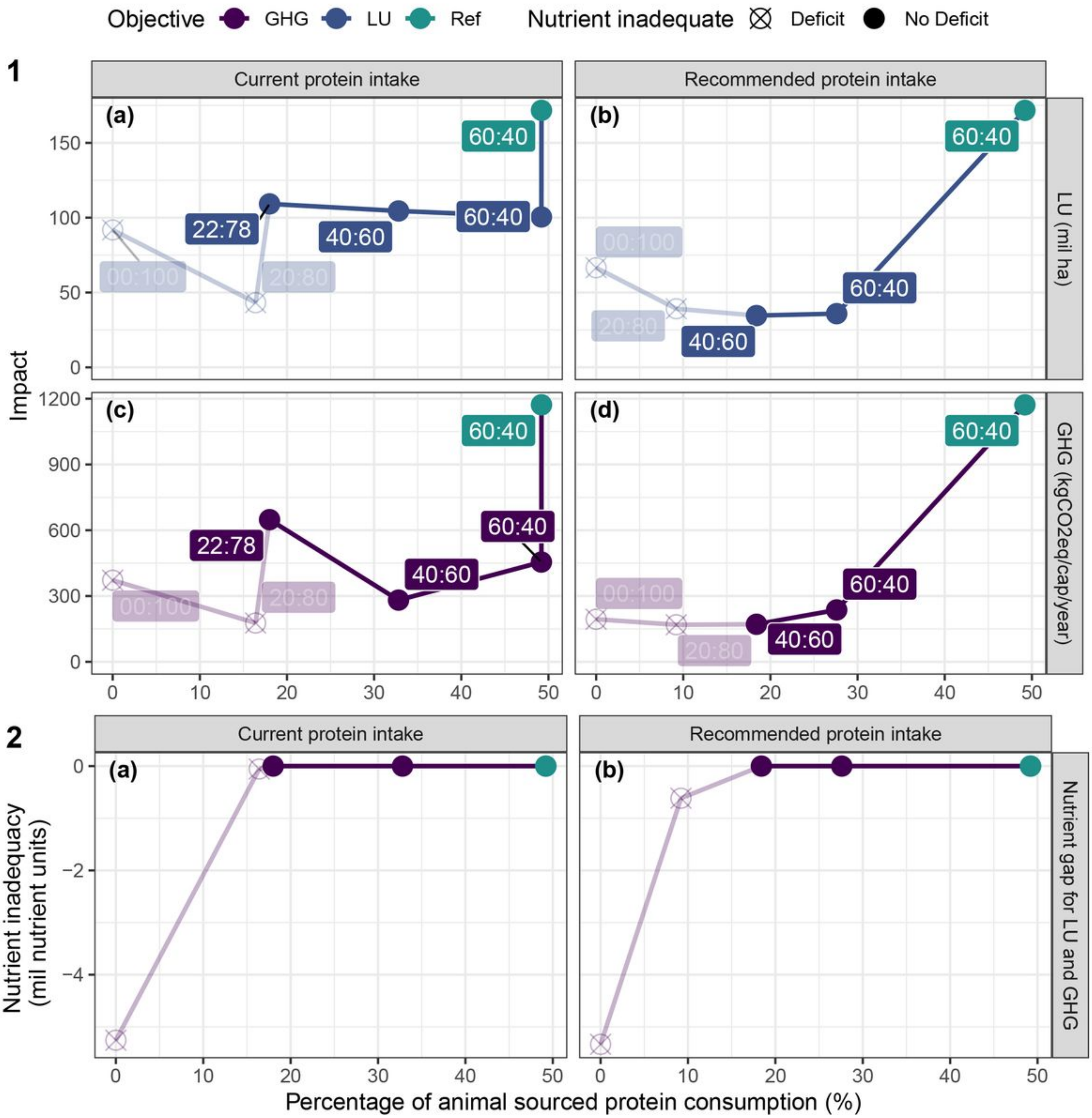

Figure 1

Step-wise reduction of animal source protein in different protein intake scenarios together with a total representation of the nutrient gap for each protein transition step. (1) redesigning the food system under circular principles at current ASP:PSP ratios. (2) Redesigning the food system based on the recommended ASP:PSP ratio. (3) Redesigning a plant-based food system allowing for nutrient deficiencies. Ref = Reference scenario, LU = Land use, GHG = Greenhouse gas emissions, cap = capita, ha = hectare.

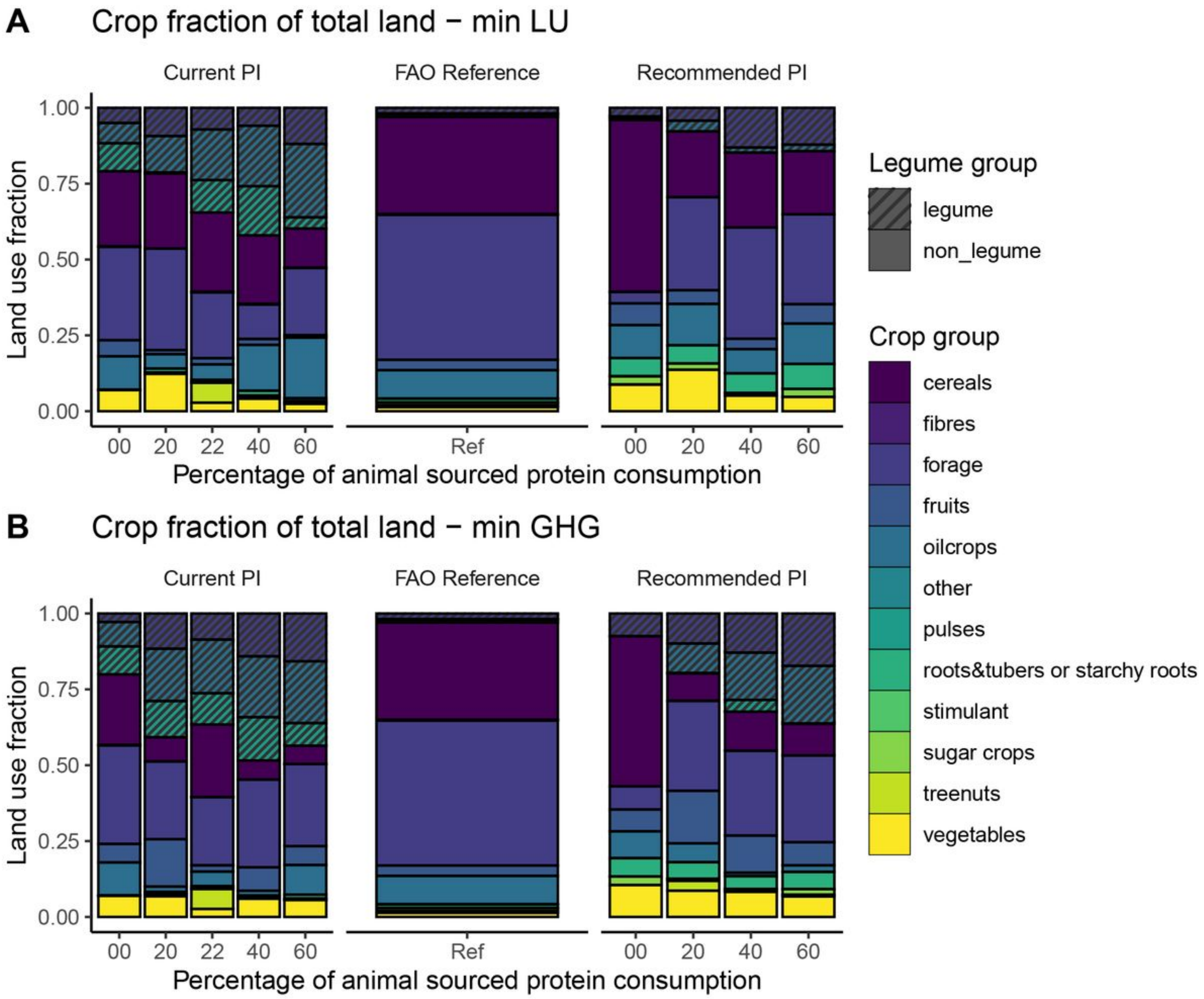

Figure 2

Relative crop shares of agricultural land per crop group, protein intake level and environmental impact category. Min LU / Min GHG = Minimizing land use / greenhouse gas emissions. PI = Protein intake, Ref = FAO Reference scenario.

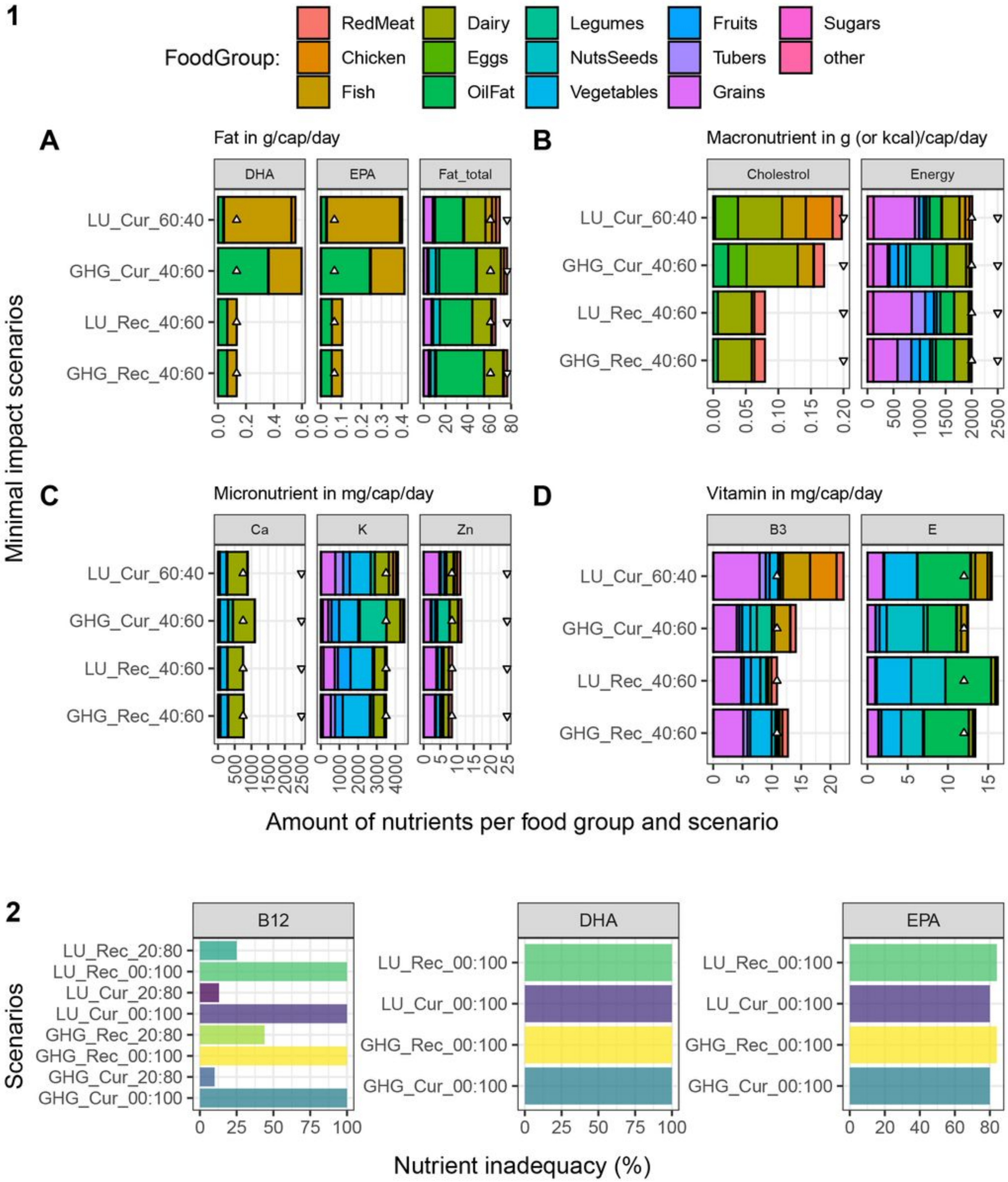

Figure 3

Selection of nutrients moving towards inadequacy per optimal scenarios. Nutrient units can be derived from the facet labels in section (1). Abbreviations: B12 = Vitamin B12, EPA = eicosapentaenoic acid, DHA = docosahexaenoic acid. 1A: Different fats, 1B: Macronutrients and Energy, 1C: Micronutrients, 1D: Vitamins. Section (2) shows the nutrient inadequacy in % per inadequate nutrient and scenario (scenarios with <18 gASP/cap/day).

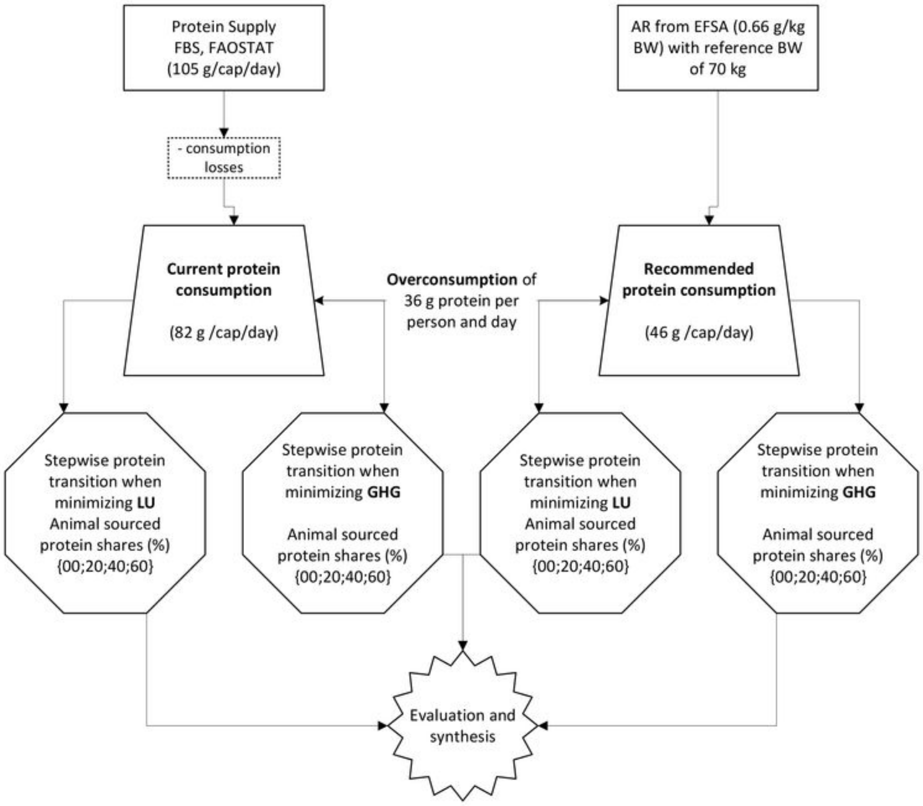

Figure 4

Modelling workflow and main data source for defining current and recommended protein intake levels (PIL). EFSA = European Food Safety Authority; FBS = Food Balance Sheet; PRI = Population reference intake; BW = Body weight; LU = Land use; GHG = Greenhouse gas emissions.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- SupplementaryInformationOptimalRatioNatureFood.docx
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