

The compatibility of animal-sourced food and circularity in healthy European diets

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Abstract

Several dietary guidelines are developed that propose limiting the intake of animal protein to stay within planetary boundaries and improve human health. Simultaneously, circular food systems are receiving significant attention in the European Union as an option to improve the current food system. In a circular system, animals are solely fed with low-opportunity-cost-biomass (LCB), resulting in substantially fewer animals and reduced supply of animal-sourced nutrients to humans. We assessed whether this circularity principle within the EU-28 is compatible with the recommended animal-source food consumption in healthy and environmentally friendly dietary guidelines such as the EAT-LANCET dietary guidelines. Our results show that the overall quantity of animal-sourced protein in EAT-LANCET dietary guidelines can be met, but that the precise levels of inclusion of different animal-sourced foods in such a diet cannot be achieved. The EAT-LANCET guidelines recommend larger quantities of chicken meat over beef and pork while a circular food system produces mainly milk, dairy-beef, and pork. All three circularity diets outperform the EAT-LANCET diet in nutritional value while reducing GHG emissions (up-to 31%) and arable land use (up-to 42%). Careful consideration of the permissible substitutability between animal-sourced foods is urgently needed to define the role of animal products in circular human diets. In this way the consumption of animal products - based on the circularity principle of only feeding animals with LCB - benefits both human health and the environment.

Main

The global food system is responsible for about a quarter of all human-induced greenhouse gas (GHG) emissions, one third of global terrestrial acidification, the majority of global eutrophication, and is occupying 40% of the world's ice and desert-free land ^{1,2}. The global trend of a growing affluent population, thereby shifting diets towards resource-intensive foods (e.g. meat), is raising concerns that the Earth's biophysical limits will be exceeded ³. To halt this progression, numerous healthy and environmentally-friendly dietary guidelines have been proposed ⁴⁻⁶. Such dietary guidelines aim to reduce environmental impacts (e.g. GHG emissions, deforestation, eutrophication and biodiversity loss) while simultaneously reducing the risk of non-communicable diseases (e.g. cardiovascular disease, colorectal cancer and type-2 diabetes) ^{3,5}. One prominent example of a healthy and environmentally sustainable dietary guidelines is the one of the EAT-LANCET commission. Compared to conventional diets consumed in the European Union (EU-28) this EAT-LANCET dietary guidelines contain increased quantities of plant-sourced food, such as vegetables, legumes and nuts, and decreased quantities of animal-sourced food, such as meat, milk, eggs, and fish ⁴.

The foods that European societies consume, and the way they are produced, contribute substantially to destabilizing several planetary boundaries ^{7,8}. Although there is general consensus that the consumption of animal-sourced food in the EU-28 should decrease, there is no consensus about the degree of reduction of animal-sourced food to achieve healthy and environmentally sustainable diets ⁹. Some studies suggest that it would be best for the planet if we would consume plant-sourced foods only (e.g.

Poore and Nemecek, 2018), while others show that farm animals reared under a circular paradigm can play a crucial role in feeding humanity¹¹⁻¹⁵. Circular food systems aim to optimally utilise resources by prioritising arable land to produce plant biomass for human consumption, thus avoiding feed-food competition^{16,17}. Currently about 40% of our global arable land is used to produce high-quality feed for farm animals, which to a large extent is human-edible¹⁸. From a resource-efficiency point of view, farm animals, instead, could be fed low-opportunity-cost-biomass (LCB), which includes co-products from the food industry (e.g. wheat middling's or slaughter waste from farm animals), food waste, and grassland resources¹³. In this case, the resource use efficiency of the farm animals is increased which has potential to reduce the environmental impacts^{15,19}.

Our aim was to assess whether adhering to the circularity principle of feeding LCB to farm animals within the EU-28 is compatible with the recommended animal-sourced food consumption in healthy and environmentally friendly dietary guidelines. We took a reference diet derived from the EAT-LANCET dietary guidelines as an example of a future healthy diet of which the environmental impacts of the food system were kept within the safe operating space of the planetary boundaries' framework⁴. To adhere to circularity principles applied to the EU-28, animals were fed co-products and food waste resulting from the plant-sourced fraction of EAT-LANCET diet (Fig. 1). In addition, grassland resources and slaughter by-products from farm animals could be used as animal feed. A resources allocation model was used to distribute the LCB among animal production systems (dairy, beef, pigs, broilers, layers, Atlantic salmon and Nile tilapia) to maximize protein production while respecting recommended animal-sourced food intake levels of the EAT-LANCET dietary guidelines as well as land use and GHG emission boundaries. Crop and animal production systems in the EU-28 were based on current management and yields (i.e., kg per hectare or kg per animal). Nutrient adequacy of the EAT-LANCET dietary guidelines was assessed against the European Food Safety Agency (EFSA) human nutrient intake requirements²⁰. Four scenarios were investigated (Table 1), firstly an EAT-LANCET reference scenario which represented the EAT-LANCET dietary guidelines in their current form (EL Reference). Secondly, a healthier whole-grain diet with a fixed composition of animal-sourced food (EL Circular Wholegrain Fixed). Thirdly, a refined grain diet with a fixed composition of animal-sourced food (current grain consumption is dominated by refined grains and consuming wholegrains results in less by-products from cereal processing and can therefore strongly affect the role of animals when adopting circularity principles, van Hal et al., 2019a) (EL Circular Refined-grain Fixed). Lastly, a wholegrain diet with an unrestrained quantity of animal-sourced food to demonstrate the production potential of animals fed LCB (EL Circular Wholegrain Potential). Scenarios two to four provide insight into the debate about which and how many animals to keep in a circular food system and the trade-offs and synergies with health recommendations.

Table 1
Overview of scenarios employed.

| | Diet type | | Animal-sourced food composition | |
|----------------------------------|------------|---------------|---------------------------------|------|
| | Wholegrain | Refined grain | Fixed | Free |
| EL Reference | X | | X | |
| EL Circular Wholegrain Fixed | X | | X | |
| EL Circular Refined-grain Fixed | | X | X | |
| EL Circular Wholegrain Potential | X | | | X |

Results

Animal-sourced Food Supply From Circular Food Systems

Figure 1: Framework to assess the supply of animal-sourced food from animals fed LCB. Example shown represents the EL Circular Wholegrain Fixed scenario. All flows are in fresh matter except grass which is in dry matter.

Our analysis revealed that animals exclusively fed LCB were unable to provide the combination of meat, milk, eggs and fish recommended in the EAT-LANCET dietary guidelines, largely due to an insufficient quantity of high quality LCB. In total, the reference diet derived from the EAT-LANCET dietary guidelines contained 71 grams of meat and fish, 250 grams of milk and 13 grams of eggs per capita per day. It was, nevertheless, possible to fulfil these recommendations by adjusting the share of meat and fish while respecting the healthy range. The reference value for pork, for example, is 7 grams, while the healthy range is 0–14 grams of pork per capita per day.

In the **EL Circular Wholegrain Fixed** scenario, recommended quantities of milk and fish could be met while meat and eggs were 5% and 92% short of meeting the recommended intake in the EAT-LANCET dietary guidelines. In the **EL Circular Refined-grain Fixed** scenario, the recommended quantities of meat, milk, eggs and fish could be met due to the additional LCB available from the refining of grains (e.g., wheat bran). However, adjusting the shares of meat and fish was still required. Compared to the **EL Circular Wholegrain Fixed**, the **EL Circular Refined-grain Fixed** scenario could produce more poultry meat (4 vs. 2 grams of poultry meat) and meet the recommended intake of eggs in the EAT-LANCET dietary guidelines (13 eggs per capita per day). From a health externalities perspective, the consumption of poultry meat is preferred over the consumption of beef and pork⁴. Broilers and laying hens, however, were limited in their ability to upcycle *all* types of LCB and mainly required the co-products from refined grains. This creates a trade-off between consuming healthy whole grains or producing healthy white poultry meat and eggs.

The **EL Circular Wholegrain Potential** scenario showed the optimal allocation of LCB (in terms of maximising protein production) to different animals (Fig. 2). This scenario resulted in an increase in pork production (to 40 grams per capita per day) due to a pig's ability to convert low quality co-products and food waste into animal-sourced food. Milk production also increased (to 563 grams per capita per day) as dairy cattle are efficient converters of LCB (especially grassland) to protein. Increased milk production increased the supply of cull cows which produced additional beef. The increase of pork and milk was at the expense of poultry and fish production, thus showing a trade-off between optimally utilising LCB and producing the preferred white meat.

Human Nutrient Supply From Circular Food Systems

Our results showed that the **EL Circular Wholegrain Fixed**, **EL Circular Refined-grain Fixed** scenarios and the EAT-LANCET Reference did not meet zinc, calcium, vitamin B12 average nutrient requirements of the human population set out by EFSA (Fig. 3; Supplementary Material). Notably, the EAT-LANCET reference also fails to meet EPA/DHA average nutrient requirements (Fig. 3). The **EL Circular Wholegrain Potential** did meet the calcium and vitamin B12 requirements but not zinc however, largely due to an increase in milk production (250 grams vs 563 grams). For all nutrients except EPA/DHA (due to less fish), nutrient supply was greatest in the **EL Circular Wholegrain Potential** scenario. Besides calcium, all three circularity diets outperformed the EAT-LANCET diet on available nutrients.

Greenhouse gas emissions and land use impacts of circular food systems

Overall, GHG emissions were 31% and 28% lower in the **EL Circular Wholegrain Fixed** and **EL Circular Refined-grain Fixed** compared to the EAT-LANCET reference scenario. The reduction in emissions was due to the avoided emissions related to the production of animal feed (e.g., nitrous oxide (N₂O) from nitrogen fertilisation) and the **EL Circular Wholegrain Fixed** scenario requiring less grain production (i.e., more grain was destined for human consumption, due to no refining).

Figure 4 shows GHG emissions and animal-sourced food protein produced from all three EL circular scenarios and the EAT-LANCET reference diet. Higher quantities of animal-sourced food (and therefore protein) were produced in the **EL Circular Wholegrain Potential** and lower quantities in the **EL Circular Wholegrain Fixed** scenarios which influenced GHG emissions (Fig. 4). The EL circular scenarios include a default GHG emission value (according to the IPCC tier 2 approach) and a range of uncertainty to reflect the uncertainty in GHG emissions (Supplementary Material). Optimally utilising LCB (to maximise protein production from animal-sourced food) in the **EL Circular Wholegrain Potential** scenario increased default GHG emissions to 477 kg CO₂e per capita per year from 367 kg CO₂e per capita per year in the **EL Circular Refined-grain Fixed** scenario (largely due to an increase in milk and pork production, Supplementary Material). The default GHG emission values of all scenarios were within the safe operating space of the planetary boundaries' framework (511 kg CO₂e for food production per capita per year; Willett et al., 2019). In all EL circular scenarios, the upper limit to the range of uncertainty was beyond the safe operating space.

Overall, cropland use was lower in all EL circular scenarios compared to the EAT-LANCET reference diet. However, it was important to note that the EAT-LANCET reference scenario was a global land use average, while the EL circular scenarios were based on EU land use. Further, utilising cropland to produce animal feed also led to an increase in land use in the EAT-LANCET reference scenario. Cropland use was lowest in the **EL Circular Wholegrain Fixed** and **EL Circular Wholegrain Potential** scenarios due to the use of wholegrains requiring less land (i.e., less co-products from wheat results in less land required), though differences with using refined grain were marginal. Grassland use of the **EL Circular Wholegrain Fixed** and **EL Circular Refined-grain Fixed** were similar while the **EL Circular Wholegrain Potential** scenario resulted in a higher grassland use, as the use of grassland resources was increased for milk production (Fig. 3).

The milk and beef production in circular food systems was highly dependent on the availability of grassland. Variation exists in the data of quantity and quality of current grassland in the EU-28 depending on the study and definition of grassland (i.e. between managed and natural grassland) and available data sources. We compared the animal-sourced food output (e.g., milk) of the EL Circular Wholegrain Potential scenario with different areas of managed grassland resulting from three different studies/models²¹⁻²³. Milk production and beef (from dairy cattle) ranged, respectively, from 326 to 780 and 11 to 37 grams per capita per day (Supplementary Material). Including natural grasslands could further increase the output of animal-sourced food.

Discussion

Our results show that the overall quantity of animal-sourced protein in EAT-LANCET dietary guidelines can be met, but that the precise levels of inclusion of different animal-sourced foods in such a diet cannot be achieved by only feeding LCB to animals. The extent to which the recommended quantities of animal-sourced food could be met largely depended on the availability of the LCB. The EL Circular Wholegrain Fixed scenario versus the EL Circular Refined-grain Fixed scenario revealed that the role animals can play in circular food systems will be narrowed as we move towards healthier consumption of plant-sourced foods. With today's food consumption patterns, several food groups are consumed in highly processed forms, resulting in additional by-products on the one hand, but increasing the risk for non-communicable diseases on the other hand²⁴. The example employed here, wheat, results in by-products such as wheat bran and wheat germ if wheat is consumed in a refined manner. If it is however consumed as whole grain, as recommended in the EAT LANCET dietary guidelines, no by-products occur. Potatoes, vegetables, and fruits would be other examples; if potatoes for example are industrially processed, potato peels can be collected and thereafter used as animal feed.

Although dietary guidelines could not be met, it was possible to meet the nutrient recommendations when the EAT-LANCET diet restrictions were removed (i.e., the EL Circular Wholegrain Potential scenario). Comparing the two EL circular fixed scenarios with the EL Circular Wholegrain Potential scenario showed that some animal species were more efficient at upcycling LCB (e.g., dairy cattle and pigs) than others (e.g., poultry). Grass resources for example were utilised most efficiently by dairy cattle as ruminants are

well adapted to value this feed. Wet or fibrous food leftovers are used most efficiently by pigs that are known to have a high feed intake capacity. Milk, furthermore, includes relatively high amounts of calcium and beef and pork are high-quality sources of bioavailable vitamin B12 and zinc²⁵. In other words, each animal has its own unique capacity to convert LCB into specific nutrients. The nutrients provided by animals are of high bioavailability and some, such as vitamin B12 and the omega-3 fatty acids EPA and DHA are predominantly provided animal-sourced foods and are almost absent in plant-source-foods²⁵.

The circular scenarios and in particular the EL Circular Wholegrain Potential scenario showed that animals raised in a circular food system can play an essential role in providing nutrients. This is in line with earlier findings of for example Rööös et al., (2017), Van Hal et al., (2019a), Van Zanten et al., (2018). None of those studies, however, assessed the importance of the dietary recommendations. Our results made clear that although the EL Circular Wholegrain Potential scenario met all nutrient recommendations except zinc, it exceeded the intake of beef and pork. Findings from cohort studies suggest that occurrence of several noncommunicable diseases, such as cardiovascular disease, was associated with a relatively high intake of red meat, i.e., beef and pork (e.g., Etemadi et al., 2017). The higher recommended amounts of poultry as compared to beef in the EAT-Lancet reference diet was justified by the fact that poultry meat does not show associations with increased mortality, and poultry fat moreover disposes over a higher content of essential poly-unsaturated fatty acids (21% vs. 4%)⁴. The above illustrates that although it is important to optimize essential nutrients from animal-source food, following upper limits of dietary guidelines is essential to avoid dietary related diseases.

Our results furthermore showed that circularity principles were adopted, GHG emissions and land-use were reduced compared to the EAT-LANCET diet, as feed-food competition was avoided. In Willett et al. (2019), broilers perform better than e.g., cattle meat from an environmental perspective, due to their favourable feed conversion ratio. However, their assessment is based on impact intensities (e.g., GHG emissions per kg of food product) calculated for the current system. Thereby, it was not considered whether the feed for broilers would also have been suitable as food for humans, or whether the area it was grown upon would have been suitable to grow food for humans. Our analysis clearly shows that as soon as we move towards a circular food system and hence restrict the role for animals to converting LCB, broilers cannot compete with e.g., cattle anymore. This does not mean that broiler cannot play a role in circular food systems, but it demonstrates that the broilers of today are less suited to convert LCB. This stresses the importance of adapting future breeding goals and feeding strategies towards their ability of utilizing LCB. This is essential as our results showed that animals can reduce their environmental impact (and the impact of the entire food system) if they increase their efficiency in converting LCB into healthy food.

Our study and model focused on feeding LCB, including food waste to animals as a principle of circularity. The nutrient content of food waste was a weighted average based on the amount of food consumed in the human diet and the proportion wasted. By combining these products into one mix the feed value in terms of energy and protein of higher quality waste products (e.g., grains) is diluted by lower quality waste products (e.g., vegetables). Expanding the model employed to separate some streams of

food waste may increase the amount of animal-sourced food produced due to a greater availability of high quality LCB. Further expanding the optimisation model to include plant-sourced food production within the EAT-LANCET diet could offer further opportunities to reduce GHG emissions and land-use. In addition, more circularity principles could be captured, including returning nutrients in manure and crop residues to the soil. Applying alternative objective functions (e.g., minimising GHG emissions while meeting the nutrient requirements of the human diet) could also influence the animal production systems selected.

We would like to end by stressing the importance of future technologies²⁸. In our work we followed the assumptions made by Willett et al. (2019). It was for example assumed that fossil energy was replaced by renewable energy sources, causing no CO₂ emissions while crop and grass yields were based on current yields and management (obtained from the Miterra-Europe Model and Carlson et al. (2017)). In the coming decades, crop yields are expected to continue to increase due to ongoing technological developments^{30,31}. Increased crop yields would however not alter the main findings of our study, as this study focussed on the utilization choice of LCB, of which the amount is independent from crop yields. A change in crop yield would affect the environmental impacts of the remaining plant-sourced food needed to fulfil nutritional requirements. Increased crop yields may lead to less land use requirements per capita in each of the scenarios. The impacts of increased crop yields on GHG emissions are less clear. Achieving higher yields may need more nutrient inputs (especially nitrogen; Schils et al., 2018), with associated increases in GHG emissions per tonne product, but technological developments may also increase nutrient use efficiencies, playing a compensatory role.

Conclusion

We demonstrated that feeding low-opportunity-cost-biomass to animals has the potential to reduce GHG emissions and land-use. Our results showed that the quantity of animal-sourced protein in EAT-LANCET dietary guidelines could be met, but that the precise animal-sourced food composition of the EAT-LANCET dietary guidelines could not be met by only feeding LCB to animals. Dietary guidelines recommend chicken meat over beef and pork while in a circular food system mainly milk, dairy-beef, and pork are produced. Careful consideration of the permissible substitutability between animal-sourced foods is urgently needed to define the role of animal products in the human diet. In this way the consumption of animal products - based on the circularity principle of only feeding animals with LCB - benefits both human health and the environment.

Methods

In this study we extended the resource allocation model developed by van Hal, (2020) to include GHG emissions and land-use. The model of van Hal, (2020) allocates co-products and food-waste resources from the EAT-LANCET example diet derived from the EAT-LANCET dietary guidelines⁴, and grassland resources. We compared environmental impacts of the EAT-LANCET diet with three EL circular scenarios.

Each scenario varied based on the type of grain (wholegrain or refined grain) and the animal-sourced food composition. (Table 1).

Quantifying leftovers from the EAT-LANCET diet

We took the example diet developed by the EAT-LANCET Commission (derived from the EAT-LANCET dietary guidelines) as a starting point for this study. To better reflect the EU diet, some adjustments were made to grain consumption (i.e. more wheat and less rice, total quantity of grain remained unchanged) based on FAOSTAT ^{4,34}.

To calculate the amount (i.e., tonnes) and area of crop required, and co-products available, reverse calculations were made using food consumption as a starting point. Quantities of co-products (e.g. wheat bran) from crops (e.g. wheat) were calculated using so-called technical conversion factors ^{35,36}. In some scenario's grains were refined to increase the availability of co-products as animal feed and to better reflect current dietary habits (e.g., wheat bran, Table 1). Quantities of food waste were calculated using food waste fractions developed by Gustavsson et al. (2011). This process was performed for each of the EU-28 countries.

Resource allocation model

The model of van Hal, (2020) is a resource allocation model of the EU-28 developed in General Algebraic Modelling System (GAMS) version 30.3. The objective of the model is to maximise animal protein output from a given availability of animal feeds while meeting the nutritional requirements of the animals.

Animal systems include livestock (dairy, beef, pigs, broilers, and layers) and farmed fish (Atlantic Salmon and Nile Tilapia). The two fish systems are a proxy for a range of species with similar characteristics (e.g. rainbow trout for Atlantic salmon). Livestock systems include three productivity levels (high, medium and low) while farmed fish only include a high productivity level. The model included the parent stocks (e.g. sow in pig system) and reproduction stocks (e.g. heifer in a dairy system) to account for the entire lifecycle of the animal. The nutritional requirements of livestock and farmed fish can be found in Supplement Material of van Hal, (2020).

Livestock and farmed fish were exclusively fed co-products, food waste, grassland resources and animal by-products, referred to as LCB. In our model, co-products and animal by-products could be traded between EU-28 countries while food waste and grassland must be used in the country it is produced. The availability of co-products and food waste was set by the EL reference.

Thirty-five percent of the available food waste could be fed to animals as a wet feed, which is considered achievable if the feeding of food waste to animals were to be legalised ³⁸. Food waste could only be consumed by monogastric animals and fish due to food safety risks ³⁸. The availability of European grassland was based on the Miterra-Europe model ²³, and it was assumed grassland could only be consumed by ruminants. Our analysis only included managed grassland due to the uncertainty in quantity and quality of natural grasslands in Europe.

The availability of animal by-products was a fraction of the predicted live weight output of each livestock system (Supplement Material of van Hal, (2020)). Cannibalism was prevented in livestock systems, in farmed fish systems cannibalism was allowed due to the species being a proxy of a range of species. This enabled intraspecies recycling of by-products from farmed fish, meaning farmed fish can consume by-products of the same species. The nutritional value of LCB for livestock was obtained from the Dutch animal feed board; known as the CVB system ³⁹. While the nutritional value of LCB for farmed fish was obtained from the IAFFD ⁴⁰.

In addition to aquaculture, the model includes capture fisheries. Capture fisheries produced fish for human consumption and fish by-products (e.g., fish meal) which could be fed in the animal systems. Quantities of capture fisheries (i.e., harvested fish in tonnes of fresh fish) were limited to the maximum sustainable yield.

GHG emissions and land-use from animal-sourced food

The resource allocation model developed by van Hal, (2020) was extended to include GHG emissions calculations. GHG emissions were based on Intergovernmental Panel on Climate Change (IPCC) and Dutch GHG inventory methodologies ⁴¹. It was assumed that fossil energy was replaced by renewable energy sources by 2050, causing no CO₂ emissions to keep our assumptions in-line with the EAT-LANCET study ⁴. The only contribution to land-use from livestock was the grassland used as feed for ruminants. Other livestock systems were considered landless or had a very small, negligible land-use as livestock are fed exclusively LCB.

GHG emission calculations were performed using a food systems approach. A food systems approach assesses emissions from the total diet as opposed to emissions per individual products in a life cycle assessment. Emissions were limited to on-farm, including manure management, enteric fermentation and grassland production. No other animal feed emissions were considered due to the food-based allocation method ⁴².

GHG emissions from terrestrial animals (dairy, beef, pig, broiler and layer) included CH₄ and N₂O from manure management. Methane emissions from manure management were calculated by multiplying volatile solid excretion by the methane conversion factor (i.e. the conversion factor for each manure management system), B₀ (i.e. the maximum methane producing capacity for manure) and 0.67 (i.e. the conversion of methane from m³ to kg CH₄) ⁴³. Volatile solid excretion was calculated using digestibility of protein and organic matter of feed consumed by the animal species ⁴⁴. Nitrous oxide emissions from manure management included direct and in-direct emissions (the latter resulting from the volatilisation of ammonia and nitrogen (di)oxide) from nitrogen excretion in housing systems ⁴³. Nitrogen excretion was calculated by subtracting nitrogen retained in meat/milk/eggs from nitrogen intake ⁴¹.

In addition, ruminant systems included CH₄ from enteric fermentation and N₂O from grassland fertilisation. Methane emissions from enteric fermentation was calculated by multiplying gross energy

intake by Y_m (i.e. percentage of gross energy in feed converted to CH_4) and dividing by 55.65 (i.e. the gross energy content of methane)⁴³. Nitrous oxide emissions from grassland included direct and indirect emissions (the latter resulting from the volatilisation of ammonia and nitrogen (di)oxide and the leaching of nitrate) from nitrogen fertilisation and manure excretion while grazing⁴⁵. Grassland fertilisation rates were estimated by the Miterra-Europe model based on the assumption that all organic fertiliser produced by grazing animals is applied to fodder crops (e.g., grassland, fodder maize) in the same region and based on FAOSTAT data on N mineral fertilizer²³.

GHG emissions from aquatic animals (e.g., high-tropic and low-tropic aquaculture) included N_2O emissions from the aquaculture system. Nitrogen in un-consumed feed and excreta (nitrogen intake minus nitrogen retained in body tissue) was multiplied by 1.8% and converted from nitrogen to N_2O ⁴⁶.

GHG emissions were summed into carbon dioxide equivalents (CO_2e ; 100-year time horizon, 28 for biogenic CH_4 and 265 for N_2O ;⁴⁷), and summed with plant-sourced food emissions (see next section) to calculate total GHG emissions. Results were given in GHG emissions per diet per capita per year.

GHG emissions and land-use from plant-sourced food

For plant-sourced food, average national crop yields and nitrogen inputs per hectare were estimated using the Miterra-Europe model²³ with 2017 as a reference year. From national crop yields and nitrogen inputs, direct and indirect N_2O emissions were calculated using an IPCC tier 2 approach⁴⁵. A food-based allocation method was applied where all GHG emissions were allocated to the main food product (e.g. wheat flour)⁴². To calculate GHG emission intensities and crop yields at an EU level, a weighted average was applied based on harvested area in each country. Not all plant-sourced food was included in the Miterra-Europe model (Lentils, groundnuts, tree nuts, and bananas). The GHG emission intensities and crop yields per hectare were then estimated using global data, reference year circa 2000²⁹. Processing of crop into edible food products and food waste along the supply chain (see section Quantifying leftovers from the eat-lancet diet) were then considered to calculate GHG emission intensities and land-use per kg of plant-sourced food consumed.

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Figures

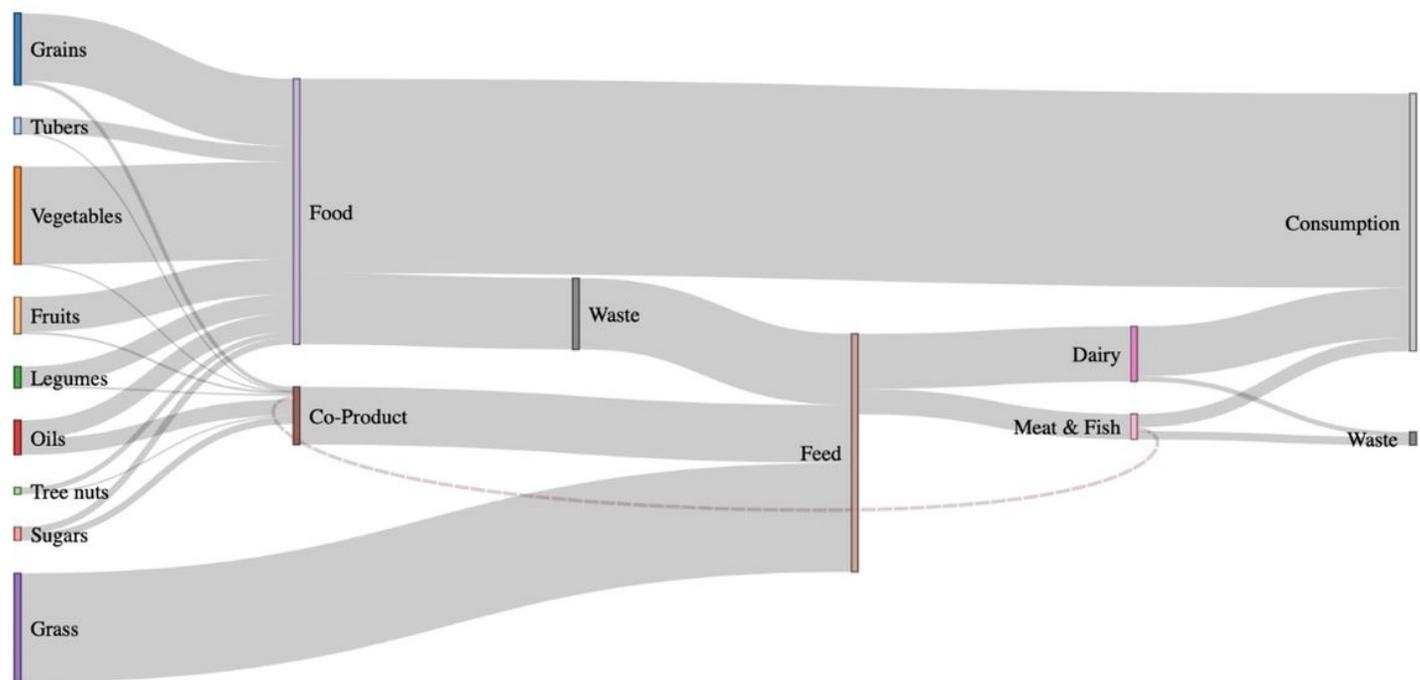


Figure 1

Framework to assess the supply of animal-sourced food from animals fed LCB. Example shown represents the EL Circular Wholegrain Fixed scenario. All flows are in fresh matter except grass which is in

dry matter.

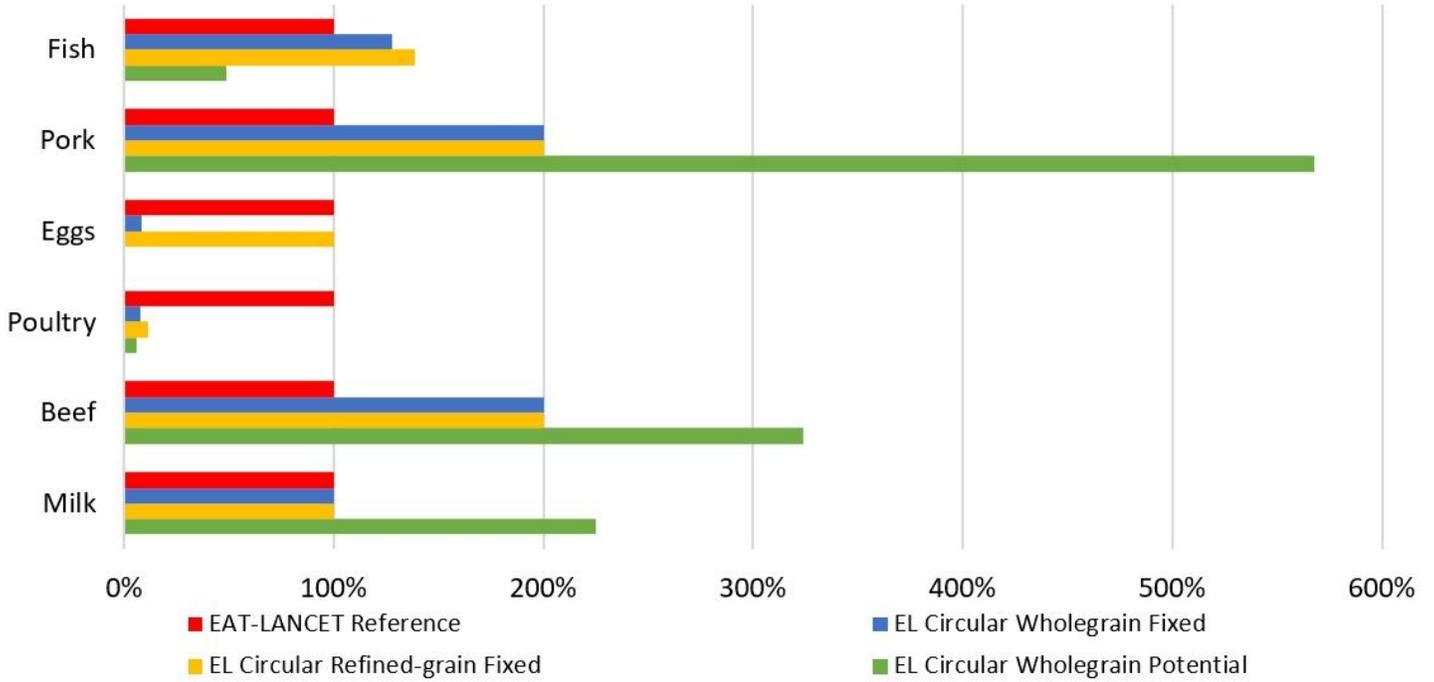


Figure 2

Animal-sourced food production from the three EL Circular scenarios. 100% is equal to the recommended intake in EAT-LANCET dietary guidelines, i.e., 28 grams of fish, 7 grams of pork, 13 grams of eggs, 29 grams of poultry meat, 7 grams of beef and 250 grams of milk

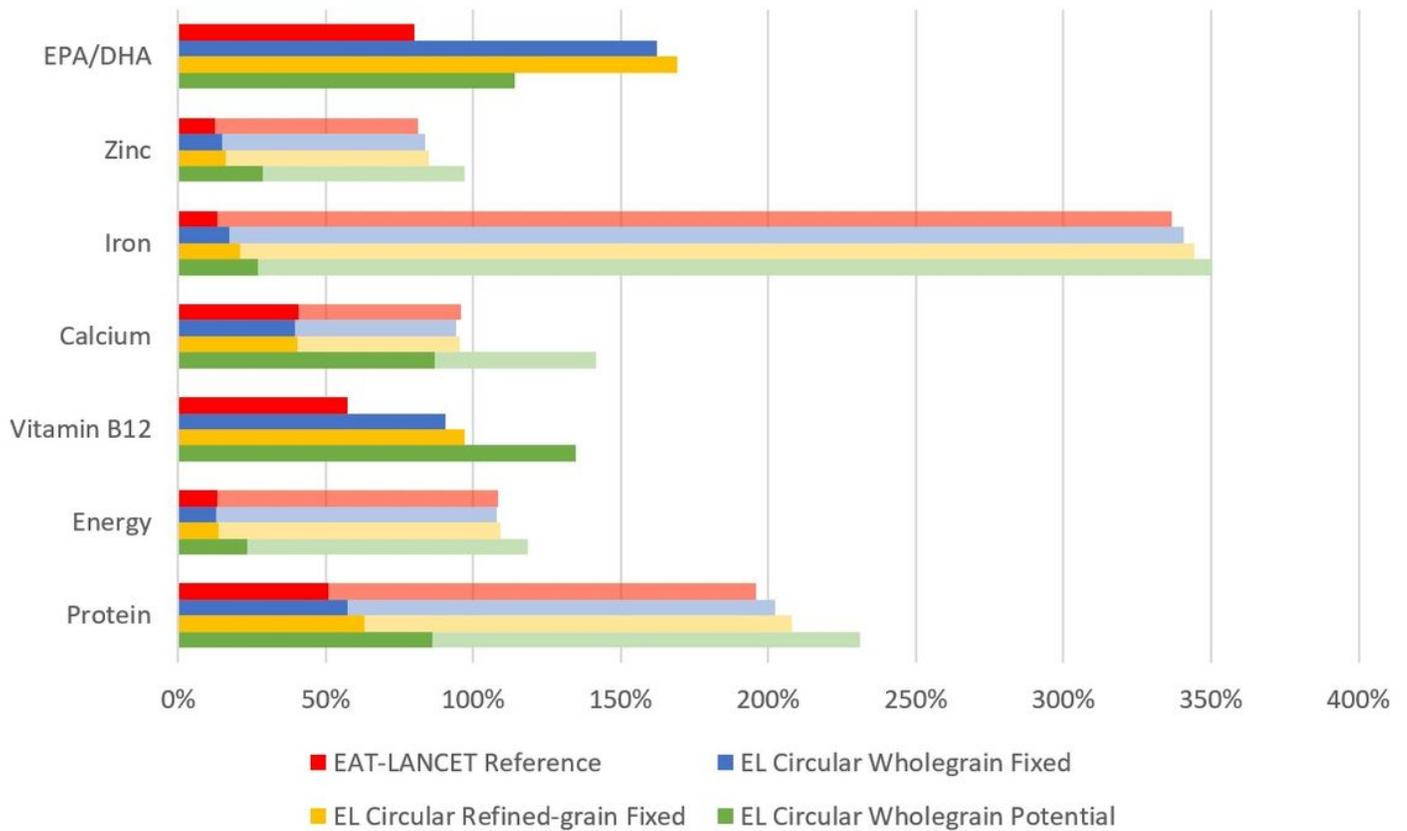


Figure 3

Nutrients available in all EL Circular scenarios and the EAT-LANCET reference diet scenario. 100% is equal to the daily average nutrient requirements outlined by EFSA (Supplementary Material). Nutrients are shown from animal-sourced food (solid fraction) and plant-sourced food (shaded fraction). Total daily dietary nutrient supply includes the solid and unshaded fractions. EPA: Eicosapentaenoic acid. DHA: Docosahexaenoic aci

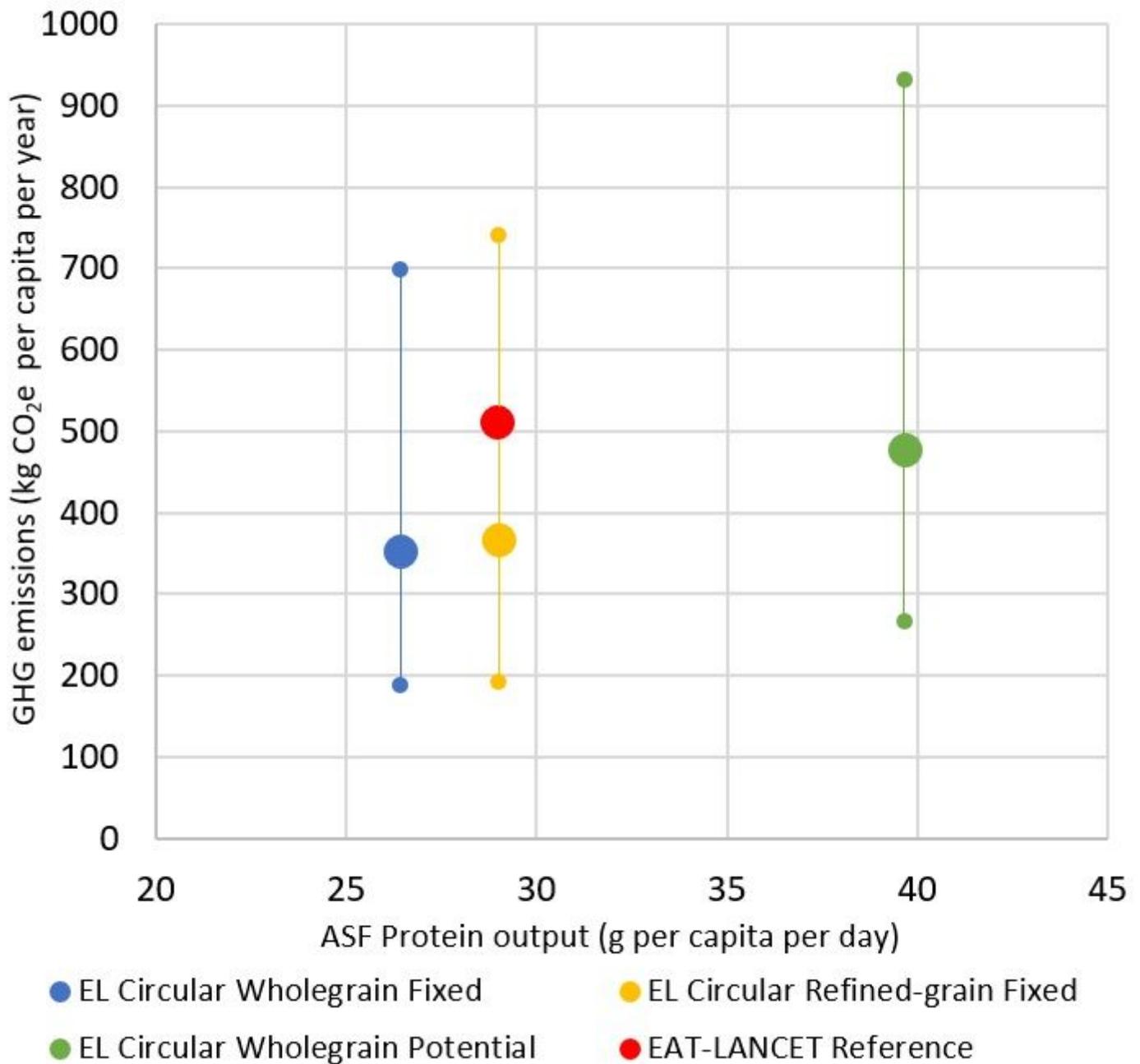


Figure 4

GHG emissions (kg CO₂e capita per year) and protein output from animal-sourced food (ASF) (g capita per day) of the EL Circular scenarios compared to the GHG emission results calculated by the EAT-LANCET commission for their reference diet (red dot). Range indicates uncertainty in GHG emissions.

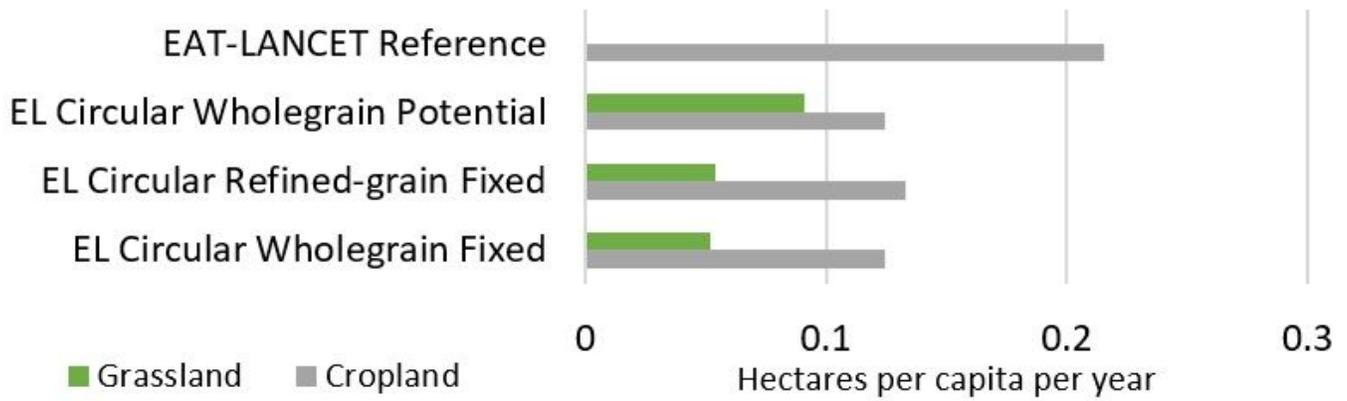


Figure 5

Cropland use (ha per capita per year) from the EAT-LANCET reference diet (which is an estimate for the entire globe, calculated by the EAT-LANCET commission) compared to cropland and grassland use in the EU-28 of the three circular scenarios.

Supplementary Files

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

- [SupplementaryMaterials.pdf](#)