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Circularity in animal production requires a change in the EAT-Lancet diet in Europe

Benjamin van Selm [1,2] ✉, Anita Frehner [1,3], Imke J. M. de Boer [1], Ollie van Hal [1], Renske Hijbeek [2], Martin K. van Ittersum [2], Elise F. Talsma [4], Jan Peter Lesschen [5], Chantal M. J. Hendriks [5], Mario Herrero [6] and Hannah H. E. van Zanten [7]

It is not known whether dietary guidelines proposing a limited intake of animal protein are compatible with the adoption of circular food systems. Using a resource-allocation model, we compared the effects of circularity on the supply of animal-source nutrients in Europe with the nutritional requirements of the EAT-Lancet reference diet. We found the two to be compatible in terms of total animal-source proteins but not specific animal-source foods; in particular, the EAT-Lancet guidelines recommend larger quantities of poultry meat over beef and pork, while a circular food system produces mainly milk, dairy-beef and pork. Compared with the EAT-Lancet reference diet, greenhouse gas emissions were reduced by up to 31% and arable land use reduced by up to 42%. Careful consideration of the feasible substitutability between animal-source foods is needed to define potential roles of animal products in circular human diets.

The global food system is responsible for about a quarter of all human-induced greenhouse gas (GHG) emissions, one-third of global terrestrial acidification and 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 (for example, 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[4–7]. Such dietary guidelines aim to improve health outcomes by reducing the risk of non-communicable diseases (for example, cardiovascular disease, colorectal cancer and type 2 diabetes), while simultaneously reducing environmental impacts (for example, GHG emissions, deforestation, eutrophication and biodiversity loss)[3,5,8]. One prominent example of healthy and environmentally sustainable dietary guidelines is the one proposed by the EAT-Lancet Commission. Compared with conventional diets consumed in the European Union and the United Kingdom (EU-27 + UK) the EAT-Lancet dietary guidelines contain increased quantities of plant-source food, such as vegetables, legumes and nuts, and decreased quantities of animal-source food, such as meat, milk, eggs and fish[4].

The foods that European societies consume, and the way in which these foods are produced, contribute substantially to destabilizing several planetary boundaries[9,10]. Although there is a general consensus that the consumption of animal-source food in the EU-27 + UK should decrease, there is no consensus about the degree of reduction of animal-source food to achieve environmentally sustainable diets[11]. Some studies suggest that it would be best for the planet if we were to consume only plant-source foods (for example, ref. [12]), while others show that farm animals reared under a circular paradigm can play a crucial role in feeding humanity[13–17].

Circular food systems aim to optimally utilize resources by prioritizing arable land to produce plant biomass for human consumption, thus avoiding feed–food competition[18,19]. Currently about 40% of our global arable land area is used to produce high-quality feed for farm animals, which to a large extent is human-edible[20]. From a resource-efficiency point of view farm animals could instead be fed what is currently considered low-opportunity-cost biomass (LCB). LCB includes co-products from the food industry (for example, wheat middlings or slaughter waste from farm animals which is currently prohibited), food waste and grassland resources[15]. In the current food system, humans cannot or do not want to consume these resources; instead, LCB can be fed to farm animals to increase their resource-use efficiency and potentially reduce the environmental impact of animal-source food[17,21].

Our aim was to assess whether adhering to the circularity principle of feeding LCB to farm animals within the EU-27 + UK is compatible with the recommended animal-source food consumption in healthy and environmentally friendly dietary guidelines. We took a reference diet derived from the EAT-Lancet guidelines as an example of a future healthy diet that was the product of a food system with environmental impacts that remained within planetary boundaries[4]. To adhere to circularity principles applied to the EU-27 + UK, animals were fed co-products and food waste resulting from the plant-source fraction of the EAT-Lancet dietary guidelines (Fig. 1). In addition, grassland resources and slaughter by-products from farm animals could be used as animal feed. A resource-allocation model was used to distribute the LCB among animal production systems (dairy, beef, pigs, broilers, laying hens, Atlantic salmon and Nile tilapia) to maximize protein production while respecting recommended animal-source food intake levels of the EAT-Lancet dietary guidelines and to calculate land use and GHG emissions.

[1]Animal Production Systems Group, Wageningen University & Research, Wageningen, Netherlands. [2]Plant Production Systems Group, Wageningen University & Research, Wageningen, Netherlands. [3]Department of Socioeconomics, Research Institute of Organic Agriculture FiBL, Frick, Switzerland. [4]Division of Human Nutrition and Health, Wageningen University & Research, Wageningen, Netherlands. [5]Wageningen Environmental Research, Wageningen University & Research, Wageningen, Netherlands. [6]Department of Global Development, College of Agriculture and Life Sciences and Cornell Atkinson Center for Sustainability, Cornell University, Ithaca, NY, USA. [7]Farming Systems Ecology Group, Wageningen University & Research, Wageningen, Netherlands. ✉e-mail: ben.vanselm@wur.nl
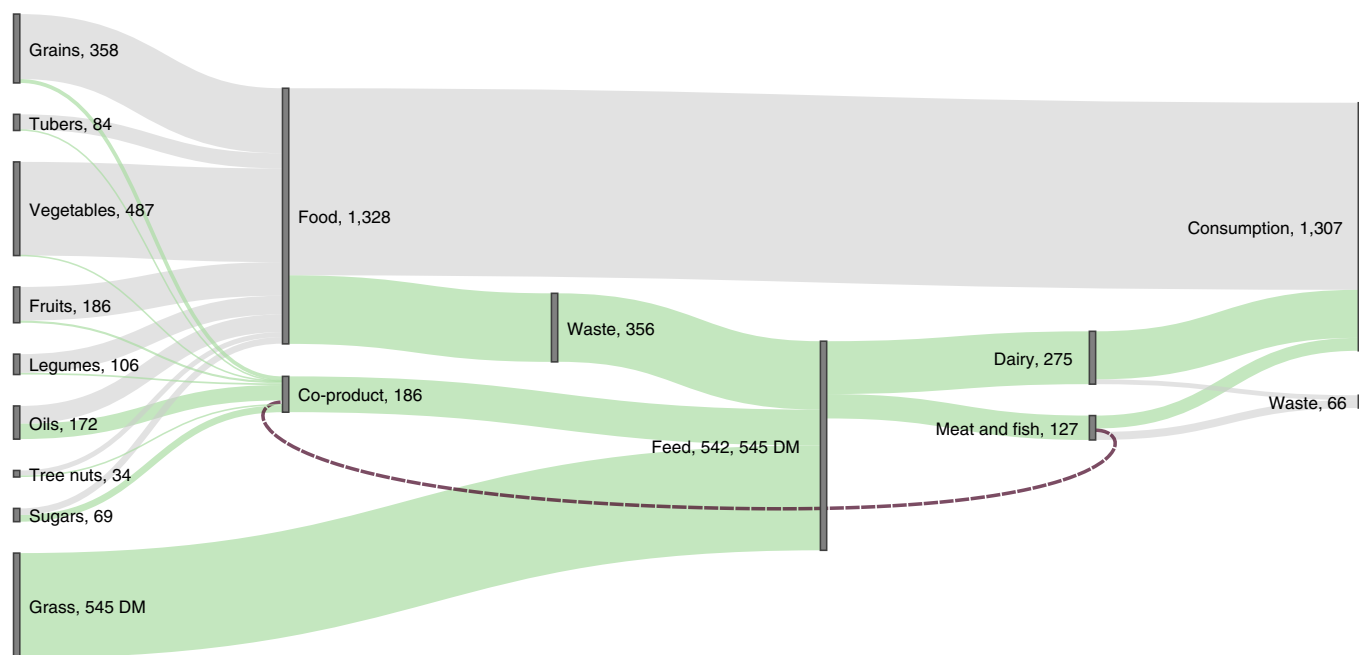
Fig. 1 | Framework to assess the supply of animal-source food from animals fed LCB. Example shown represents the EL Circular Wholegrain Fixed scenario. All flows are in grams fresh matter per human capita per day except grass which is in grams dry matter (DM) per human capita per day. Green flows indicate modelled flows. Dashed line indicates flow of slaughter waste back to co-product.

Table 1 | Overview of scenarios employed

	Diet type		Animal-source food composition	
	Wholegrain	**Refined grain**	**Fixed**	**Free**
EL Reference	×		×	
EL Circular Wholegrain Fixed	×		×	
EL Circular Refined-grain Fixed		×	×	
EL Circular Wholegrain Potential	×			×

Three different diet scenarios and a reference scenario were included with varying consumption of grains and animal-source food composition.

We did not consider the economic consequences of feeding LCB to livestock. Crop and animal production systems in the EU-27 + UK were based on current management and yields (that is, kg per hectare or kg per animal). The nutrient adequacy of any changes to the EAT-Lancet dietary guidelines was assessed against the European Food Safety Agency (EFSA) human nutrient intake requirements[22]. Four explorative theoretical scenarios were investigated (Table 1), which assess the impacts of changing diets on land use and GHG emissions (although we remain aware that agricultural practices are driven by a larger array of factors): (1) an EAT-Lancet reference scenario which represented the EAT-Lancet dietary guidelines in their current form (EL Reference); (2) a healthier wholegrain diet with a fixed composition of animal-source food (EL Circular Wholegrain Fixed); (3) a refined grain diet with a fixed composition of animal-source food (EL Circular Refined-grain Fixed); (4) a wholegrain diet with an unrestrained quantity of animal-source food to demonstrate the production potential of animals fed LCB

(EL Circular Wholegrain Potential). The EL Circular Wholegrain Fixed and EL Circular Refined-grain Fixed scenarios offer insights into how grain consumption can influence the role of animals when adopting circularity principles. Consuming wholegrains is preferred from a health perspective; however, consuming refined grains results in additional by-products for animal feed derived from cereal processing[15,23]. This is meant as an example because processing often impacts the potential production of animals fed LCB and health, for example, rice or potatoes with or without peels. The EL Circular Wholegrain Fixed and EL Circular Wholegrain Potential Scenarios 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.

Results

Supply of animal-source foods. 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 g of meat and fish, 250 g of milk and 13 g of eggs per capita per day. It was, nevertheless, possible to fulfil the 'total' recommendations by adjusting the share of meat and fish while respecting the healthy range. The reference value for pork, for example, is 7 g, while the healthy range is 0–14 g pork per capita per day.

In the EL Circular Wholegrain Fixed scenario, the recommended quantities of milk and fish could be met while meat was only 1% short; eggs were 100% short of meeting the recommended intake in the EAT-Lancet dietary guidelines. No eggs were produced in the EL Circular Wholegrain Fixed scenario. In the EL Circular Refined-grain Fixed scenario, the recommended quantities of meat, milk, eggs and fish could be met and exceeded (meat and fish, 12%) due to the additional LCB available from the refining of grains (for example, 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
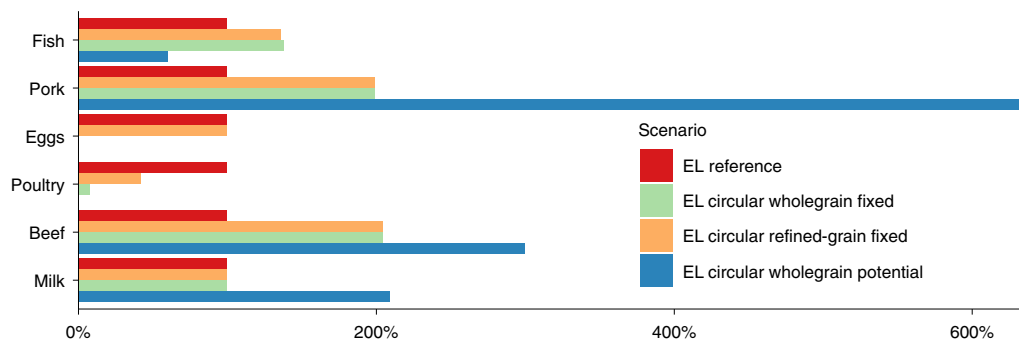
Fig. 2 | Animal-source food production from all EL Circular scenarios and the EL Reference diet. On this graph '100%' is equal to the recommended daily intake in the EAT-Lancet dietary guidelines, that is, 28 g of fish, 7 g of pork, 13 g of eggs, 29 g of poultry meat, 7 g of beef and 250 g of milk.

more poultry meat (12 g versus 2 g 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 perspective, the consumption of poultry meat is preferred over the consumption of beef and pork[4]. 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 wholegrains or producing healthy white poultry meat and eggs.

The EL Circular Wholegrain Potential scenario showed the optimal allocation of LCB (in terms of maximizing protein production) to different animals (Fig. 2). This scenario resulted in an increase in pork production (to 44 g per capita per day) due to the ability of pigs to convert low-quality co-products and food waste into animal-source food. Milk production also increased (to 523 g 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 utilizing LCB and producing the preferred white meat.

Nutrient supply for human consumption. Our results showed that all EL Circular scenarios increased the supply of eicosapentaenoic acid (EPA)/docosahexaenoic acid (DHA), zinc, iron, vitamin B12 and protein compared to the EL Reference. The supply of calcium and energy was only increased compared to the EL Reference in the EL Circular Wholegrain Potential scenario.

Compared to the EFSA dietary nutrient requirements, the EL Circular Wholegrain Fixed, EL Circular Refined-grain Fixed scenarios and the EL Reference did not meet zinc, calcium and vitamin B12 requirements (Fig. 3 and Supplementary Information). Notably, the EL 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 g versus 523 g). For all nutrients except EPA/DHA (due to less fish), nutrient supply was greatest in the EL Circular Wholegrain Potential scenario. Besides calcium and fat, all three circularity diets outperformed the EAT-Lancet diet on available nutrients.

GHG and land use impacts. Overall, GHG emissions were 31% and 23% lower in the EL Circular Wholegrain Fixed and EL Circular Refined-grain Fixed scenario compared with the EL Reference diet. The reduction in emissions was due to the avoided emissions related to the production of animal feed (for example, nitrous oxide (N_2O) from nitrogen fertilization) and the EL Circular Wholegrain Fixed scenario requiring less grain production (that is, more grain was destined for human consumption, due to no refining). Figure 4 shows

GHG emissions and animal-source food protein produced from all three EL Circular scenarios and the EL Reference diet. Higher quantities of animal-source 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 Intergovernmental Panel on Climate Change (IPCC) tier 2 approach) and a range of uncertainty to reflect the uncertainty in GHG emissions. Optimally utilizing LCB (to maximize protein production from animal-source food) in the EL Circular Wholegrain Potential scenario increased default GHG emissions to 483 kg CO_2e per capita per year from 390 kg CO_2e per capita per year in the EL Circular Refined-grain Fixed scenario (largely due to an increase in milk and pork production, Supplementary Information). The types of animal-source food produced impacted the ratio of GHG emissions; in the EL Circular Wholegrain Potential scenario additional dairy increased the contribution of methane (CH_4) to total GHG emissions (Figs. 2 and 4). The default GHG emission values of all scenarios were within the safe operating space of the planetary boundaries' framework (511 kg CO_2e for food production per capita per year[4]). In all EL Circular scenarios, the upper limit to the range of uncertainty was beyond the safe operating space (Fig. 4).

Overall, cropland use was lower in all EL Circular scenarios than in the EL Reference diet (Fig. 5). However, it is important to note that cropland use for the EAT-Lancet reference scenario was based on a global cropland use average and could overestimate EU cropland use per capita; all EL Circular scenarios were based on EU cropland-use data specific for the EU. Further, utilizing 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 (that is, lower amounts of co-products from wheat result in less land required), although 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 higher grassland use because the use of grassland resources was increased for milk production (Fig. 3).

The production of milk and beef in circular food systems is highly dependent on the availability of grassland. Variation exists in the data on the quantity and quality of current grassland in the EU-27 + UK depending on the study and definition of grassland (that is, between managed and natural grassland) and available data sources. We compared the animal-source food output (for example, milk) of the EL Circular Wholegrain Potential scenario with different areas of managed grassland resulting from three different studies/models[24–26]. Milk production and beef (from dairy cattle)
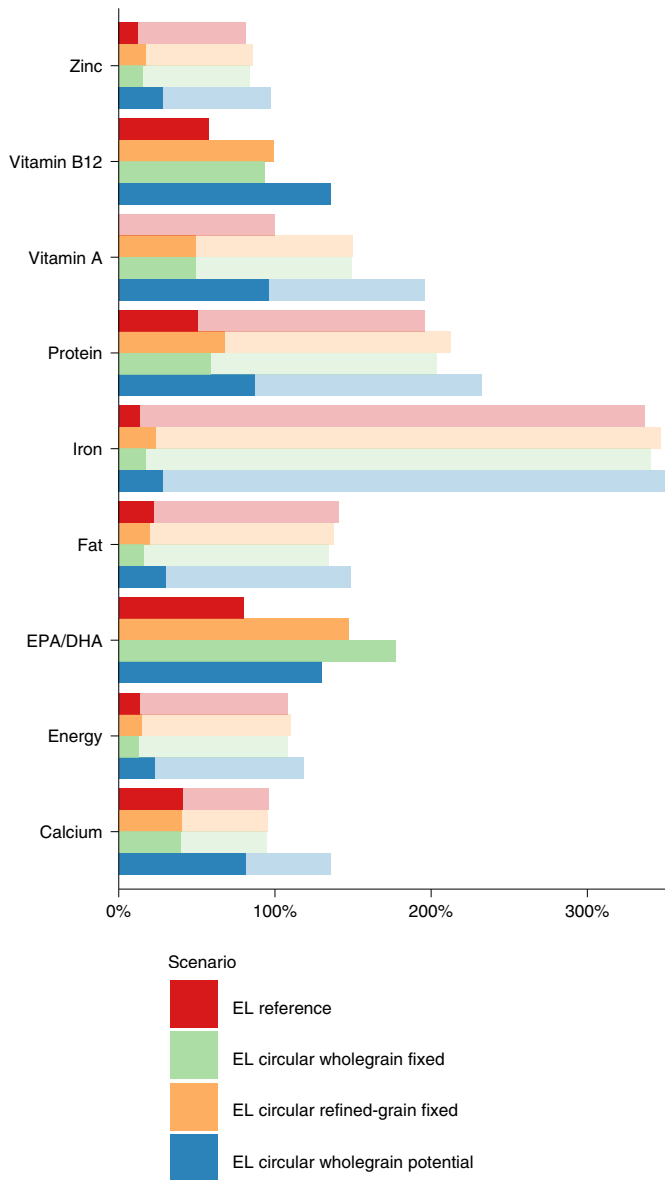
Fig. 3 | Nutrients available in all EL Circular scenarios and the EL Reference diet. On this graph '100%' refers to the daily average nutrient requirements outlined by EFSA (see Supplementary Information). Nutrients are shown from animal-source food (solid fraction) and plant-source food (shaded fraction). Total daily dietary nutrient supply includes the solid and unshaded fractions.

ranged, respectively, from 291 to 748 and 11 to 32 g per capita per day (Supplementary Information). Including natural grasslands could further increase the output of animal-source food.

Discussion

Our results show that the overall quantity of animal-source protein in the EAT-Lancet dietary guidelines can be met, but that the precise levels of inclusion of different animal-source foods in such a diet cannot be achieved by only feeding LCB to animals. The extent to which the recommended quantities of animal-source food could be met largely depended on the availability of 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-source foods. With today's food consumption patterns, several food groups are consumed in highly processed
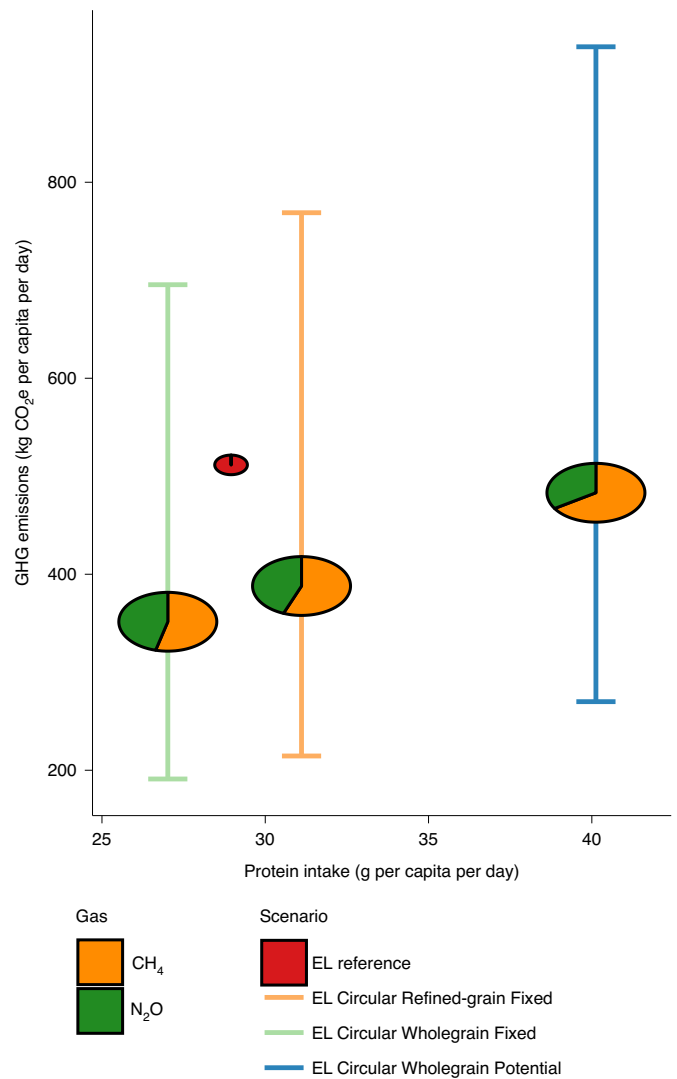

Fig. 4 | GHG impacts from all EL Circular scenarios and the EL Reference diet. GHG emissions (kg CO_2e capita per year) and protein intake from animal-source food (g per capita per day) of the EL Circular scenarios compared to the GHG emission results calculated by the EAT-Lancet Commission for its reference diet (red dot). Range indicates uncertainty in GHG emissions. Pie charts indicate midpoint (default) GHG emissions and contribution of each GHG (N_2O and CH_4).

forms, resulting in additional by-products on the one hand, but increasing the risk for non-communicable diseases on the other hand[27]. 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 wholegrain, 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, their peel can be collected and 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 (that is, 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 (for example, dairy cattle and pigs) than others (for example, poultry). Grass resources, for example, were utilized most efficiently by dairy cattle because ruminants are well adapted to value this feed.
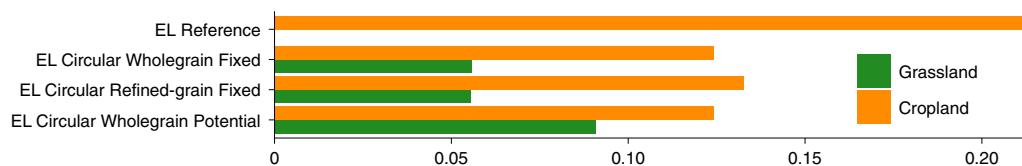
Fig. 5 | Land-use impacts from all EL Circular scenarios and the EL Reference diet. Cropland use (hectares per capita per year) from the EL Reference diet (which is an estimate for the entire globe, calculated by the EAT-Lancet Commission) compared to cropland and grassland use in the EU-27 + UK for the three EL Circular scenarios.

Wet or fibrous food leftovers are used most efficiently by pigs, which 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 zinc[28]. 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 by animal-source foods and are almost absent in plant-source foods[28].

The EL 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, Röös et al.[29], van Hal et al.[15] and van Zanten et al.[14]. None of those studies, however, assessed the importance of the dietary recommendations. Our results clearly show that although the EL Circular Wholegrain Potential scenario met all the nutrient recommendations except that of zinc, it exceeded the intake of beef and pork. Evidently, a healthy diet is not only defined by the sum of its nutrients. In fact, since the majority of the EL Reference diet was kept constant and clear bounds were set for the animal-source foods, the endowment for a healthy diet can nevertheless be approximated. However, findings from cohort studies suggest that the occurrence of several non-communicable diseases, such as cardiovascular disease, was associated with a relatively high intake of red meat, that is, beef and pork (for example, ref. [30]). The higher recommended amounts of poultry as compared with beef in the EL Reference diet was justified by the fact that poultry meat does not show associations with increased mortality, and poultry fat moreover provided a higher content of essential polyunsaturated fatty acids (21% versus 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 when circularity principles were adopted, GHG emissions and land use could be reduced compared with the EAT-Lancet diet because feed–food competition was avoided. In Willett et al.[4], broilers perform better than, for example, beef from an environmental perspective due to their favourable feed conversion ratio. However, Willett et al.'s assessment is based on impact intensities (for example, GHG emissions per kg of food product) calculated for the current system; it was not considered whether the feed for broilers would also have been suitable as food for humans, or whether the area on which it was grown 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 in converting LCB, broilers can no longer compete with, for example, cattle. This has consequences for any dietary guidelines (local or national) that aim to reduce environmental impacts, beyond the global EAT-Lancet diet. This does not mean that broilers 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 the ability of animals to utilize

LCB. This is essential because 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. Preventing food waste in the first instance or revalorizing food waste as food should always remain the priority; only when this is not possible should food waste be used as animal feed[31]. In other countries (for example, Japan and South Korea), food waste is successfully fed to monogastric animals after a processing and sterilization step before feeding[32]. In our case we assumed 35% of food waste available is suitable to be fed to animals[32]. The nutrient content of food waste is highly dependent on the food consumed and discarded, 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 (for example, grains) is diluted by lower-quality waste products (for example, vegetables). Expanding the model employed to separate streams of food waste may increase the amount of animal-source food produced due to a greater availability of high-quality LCB. Further expanding the optimization model to include plant-source 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 (for example, minimizing GHG emissions while meeting the nutrient requirements of the human diet) could also influence the animal production systems selected.

Finally, it is important to consider the importance of future technologies for our results[33]. In our work we followed the assumptions made by Willett et al.[4]. It was, for example, assumed that fossil energy was replaced by renewable-energy sources, causing no CO_2 emissions, while crop and grass yields were based on current yields and management (obtained from the Miterra-Europe Model and Carlson et al.[34]). In the coming decades, crop yields might be expected to continue to increase due to ongoing technological developments[35,36]. Increased crop yields would not, however, alter the main findings of our study because this study focused 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-source food needed to fulfil nutritional requirements. Increased crop yields may lead to lower 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 is likely to require more nutrient inputs (especially nitrogen[37]), with associated increases in GHG emissions per tonne of product, but technological developments may also increase nutrient-use efficiencies and thereby play a compensatory role.

Conclusion
We demonstrated that feeding LCB to animals has the potential to reduce GHG emissions and land use. Our results showed that the

quantity of animal-source protein in EAT-Lancet dietary guidelines could be met, but that the precise animal-source food composition of the EAT-Lancet dietary guidelines could not be met by only feeding LCB to animals. Dietary guidelines recommend poultry meat over beef and pork, whereas in a circular food system mainly milk, dairy-beef and pork are produced. Careful consideration of the feasible substitutability between animal-source foods is urgently needed to define the role of animal products in the human diet. In this way the circularity principle of only feeding animals with LCB can be integrated into healthy and environmentally sustainable diets to further reduce environmental impacts.

Methods

In this study we extended the resource-allocation model developed by van Hal et al.[15] to include GHG emissions and land use. This model allocates co-products, food-waste resources (from the EAT-Lancet example diet derived from the EAT-Lancet dietary guidelines[4]) and grassland resources. We compared environmental impacts of the EL Reference diet with three EL Circular scenarios. Each scenario varied based on the type of grain (wholegrain or refined grain) and the animal-source food composition (Table 1).

Adjustments to the EAT-Lancet diet. We took a reference 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 (that is, more wheat and less rice; the total quantity of grain remained unchanged) based on FAOSTAT[4,38].

LCB from the EAT-Lancet diet. To calculate the amount (that is, tonnes) and area of crop required, and co-products available, reverse calculations were made using food consumption. Quantities of co-products (for example, wheat bran) from crops (for example, wheat) were calculated using FAO technical conversion factors[39,40]. In some scenarios grains were refined to increase the availability of co-products as animal feed and to better reflect current dietary habits (for example, wheat bran; Table 1). Quantities of food waste were calculated using food waste fractions developed by Gustavsson et al.[41]. This process was performed for each of the EU-27 + UK countries.

Resource allocation model. The model of van Hal et al.[15] is a resource-allocation model of the EU-27 + UK developed in General Algebraic Modelling System v.30.3. The objective of the model is to maximize animal protein output from a given availability of animal feeds while meeting the nutritional requirements of the animals.

Animal systems include livestock (dairy cattle, beef cattle, pigs, broiler chickens and laying hens) and farmed fish (Atlantic salmon and Nile tilapia). The two fish systems are a proxy for a range of species with similar characteristics (for example, 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 (for example, sows in the pig system) and reproduction stocks (for example, heifers in the dairy system) to account for the entire life cycle of the animal. The nutritional requirements of livestock and farmed fish can be found in the Supplementary Information.

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-27 + UK countries, while food waste and grassland must be used in the country in which it is produced. The availability of co-products and food waste was set by the EAT-Lancet 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 legalized[32]. Food waste could only be consumed by monogastric animals and fish due to food safety risks[32]. The availability of European grassland was based on the Miterra-Europe model[26], 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 (reported in ref. [42]). 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[43]; the nutritional value of LCB for farmed fish was obtained from the International Aquaculture Feed Formulation Database[44].

In addition to aquaculture, the model includes capture fisheries. Capture fisheries produce fish for human consumption and fish by-products (for example, fish meal) which can be fed in the animal systems. Quantities of capture fisheries (that is, harvested fish in tonnes of fresh fish) were limited to the maximum sustainable yield.

Human nutrient supply. To ensure that changes in the quantity and composition of animal-source food in the EAT-Lancet diet did not reduce the supply of nutrients to humans, the nutrient supply of each scenario was assessed against dietary nutrient recommendations from EFSA[22]. The nutrient content of each food item was based on the US Department of Agriculture food and nutrient database[45].

GHG emissions and land use from animal-source food. The resource-allocation model developed by van Hal et al.[15] was extended to include GHG emissions calculations. GHG emissions were based on the IPCC and Dutch GHG inventory methodologies[46]. It was assumed that fossil energy was replaced by renewable energy sources by 2050, causing no CO_2 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 because 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 those occurring on the farm, including manure management, enteric fermentation and grassland production. No other animal feed emissions were considered due to the food-based allocation method[47].

GHG emissions from terrestrial animals (dairy cattle, beef cattle, pigs, broiler chickens and laying hens) included CH_4 and N_2O from manure management. Methane emissions from manure management were calculated by multiplying volatile solid excretion by the methane conversion factor (that is, the conversion factor for each manure management system), B_0 (that is, the maximum methane-producing capacity for manure) and 0.67 (that is, the conversion of methane from m^3 to kg CH_4)[48]. Volatile solid excretion was calculated using digestibility of protein and organic matter of feed consumed by the animal species[49]. N_2O emissions from manure management included direct and indirect emissions (the latter resulting from the volatilization of ammonia and nitrogen (di)oxide) from nitrogen excretion in housing systems[48]. Nitrogen excretion was calculated by subtracting nitrogen retained in meat/milk/eggs from nitrogen intake.

In addition, ruminant systems included CH_4 from enteric fermentation and N_2O from grassland fertilization. CH_4 emissions from enteric fermentation were calculated by multiplying gross energy intake by Y_m (that is, percentage of gross energy in feed converted to CH_4) and dividing by 55.65 (that is, the gross energy content of methane)[48]. N_2O emissions from grassland included direct and indirect emissions (the latter resulting from the volatilization of ammonia and nitrogen (di) oxide and the leaching of nitrate) from nitrogen fertilization and manure excretion while grazing[50]. Grassland fertilization rates were estimated by the Miterra-Europe model based on the assumption that all organic fertilizer produced by grazing animals is applied to fodder crops (for example, grassland and fodder maize) in the same region and based on FAOSTAT data on nitrogen mineral fertilizer[26].

GHG emissions from farmed fish included N_2O emissions from the aquaculture system. Nitrogen in unconsumed feed and excreta (nitrogen intake minus nitrogen retained in body tissue) was multiplied by 1.8% and converted from nitrogen to N_2O (ref. [51]).

GHG emissions were summed into carbon dioxide equivalents (CO_2e; 100 yr time horizon, 28 for biogenic CH_4 and 265 for N_2O (ref. [52])), and summed with plant-source 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-source food. For plant-source food, average national crop yields and nitrogen inputs per hectare were estimated using the Miterra-Europe model[26] with 2017 as a reference year. For national crop yields and nitrogen inputs, direct and indirect N_2O emissions were calculated using an IPCC tier 2 approach[50]. A food-based allocation method was applied where all GHG emissions were allocated to the main food product (for example, wheat flour)[47]. 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-source 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, with a reference year of circa 2000[34]. Processing of crop into edible food products and food waste along the supply chain (LCB from the EAT-Lancet diet) were then considered to calculate GHG emission intensities and land use per kg of plant-source food consumed.

Reporting Summary. Further information on research design is available in the Nature Research Reporting Summary linked to this article.

Data availability

Data are available from https://doi.org/10.4121/16918732

Code availability

Model code is available from https://doi.org/10.4121/16918732.

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Author contributions

B.v.S., A.F., I.J.M.d.B., R.H., M.K.v.I., and H.H.E.v.Z. designed the research. B.v.S., A.F., J.P.L., C.M.J.H. and O.v.H. contributed to data and modelling. All authors contributed to the interpretation of results, writing and editing of the manuscript.

Competing interests

The authors declare no competing interests.

Additional information

Corresponding author(s):	Benjamin van Selm
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Software and code

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Data collection	no software used
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Study description	We assessed the GHG emissions and animal-sourced food supply when feeding animals only with co-products and food waste from the EAT-LANCET diet and grassland. To make this assessment we used a linear optimization model devolved in GAMS to optimize the distribution of feed amongst the different animal systems.
Research sample	EU-27 + UK
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