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Animal and plant-sourced nutrition: complementary not competitive

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ABSTRACT

Debate on the sustainability of the global food system often compares the environmental, economic and health impacts of plant- and animal-sourced foods. This distinction can mask the considerable variation in impacts across and within these food groups. Moreover, the nutritional benefits of these food groups are insufficiently discussed. In this review, we highlight the nutritional contribution to the current global food system of both plant- and animal-sourced foods and place their impacts on human health in the global context. We highlight how the comparison of the environmental impacts of foods via life cycle analyses can change on the basis of the functional unit used, particularly the use of mass as opposed to nutrient content or nutrient richness. We review the literature on the affordability of nutrient-adequate diets, demonstrating the presence of both plant- and animal-sourced foods in affordable nutritious diets. Finally, we address the potential of alternative food sources that are gaining momentum, to ask where they may fit in a sustainable food system. We conclude that there is a clear place for both plant- and animal-sourced foods in future sustainable food systems, and a requirement for both for sustainable global nutrition; as such, the two groups are complementary and not competitive.

Keywords: animal production, environmental footprints, human health, human nutrition, non-communicable diseases, plant production, sustainable consumption, sustainable diets.

Introduction

Delivering nutrition to a growing global population is a challenge of an increasing urgency. It is also not a straightforward challenge of increasing production of food calories or protein, since good nutrition involves delivering safe, nutritious food in sufficient bioavailable quantities to provide all essential nutrients, without incurring excess intakes (FAO/WHO 2014). Moreover, unconstrained increases in production of food at current efficiency levels risks increased damage to the environmental base on which the global food system depends. Thus, evidence-based changes to achieve a sustainable food system are required.

In 2018, the Food and Agriculture Organisation of the United Nations (FAO) recorded global production of 10.6 billion tonnes of food commodities leaving the world's farms and fisheries (FAO 2020). Of this total, 47% (5.3 billion tonnes) became food for human consumption, while 12% (1.4 billion tonnes) became animal feed. Note that this value just includes food commodities leaving the farm gate as recorded by the FAO (e.g. cereal crops), and not the mass of crops, by-products or grazed material used exclusively for feed or non-food uses, which is substantial. We can use this resource to further separate the uses of plant and animal production. Of the 9.18 billion tonnes of plant food commodities that leave the farm gate, 4.2 billion tonnes (46%) were available as food; correspondingly, of the 1.53 billion tonnes of animal food commodities (including co-products), 1.29 billion tonnes (84%) were available as food. The remaining mass was directed elsewhere, namely, losses along the supply chain, processing losses, non-food uses, seed for the following year's crops, and so on. Notably, plant food commodities constituted 95% of supply chain losses. Thus, of the 5.49 billion tonnes of food, ~23% was animal-sourced and 77% was plant-sourced.

However, these mass figures do not provide adequate information on the full value of these foods. Even if we were to consider calories instead of mass, this would not account for the many other essential nutrients present in these foods. Thus, any evidence-based changes seeking to deliver sustainable nutrition must take the full nutritional contribution of different foods into account.

In recent years, there have been increasing calls from sections of both the policy and scientific communities to move to diets that are more plant sourced-food based for perceived health and environmental advantages (Springmann *et al.* 2018; Willett *et al.* 2019; Clark *et al.* 2020; European Commission 2020; Mora *et al.* 2020; National Food Strategy 2021). While the degree of reduction of animal-sourced food production and consumption varies in these recommendations, they share this common theme. However, animal-sourced foods are well known as nutrient dense relative to energy content and play a major role in the nutrition of billions of people (Murphy and Allen 2003; Adesogan *et al.* 2020; Smith *et al.* 2021). Given the challenges of delivering nutrition to a growing number of people, how should the production of food change in the future to ensure adequate global nutrition, and what role do plant- and animal-sourced foods play?

In this review, we discuss the nutritional importance of both plant- and animal-sourced foods, to demonstrate the essential nature of both to adequate global and individual nutrition. Further, we discuss their role in the current food system, and in future sustainable food systems. As encapsulated in the definition of sustainable food systems put forward by the Committee on World Food Security, nutritional, environmental and economic sustainability are all essential aspects of a sustainable food system (HLPE 2014). We will address each of these three aspects in turn, to demonstrate how both plant- and animal-sourced foods contribute to sustainability.

Human nutrition from plant and animal sources

Nutrition is a broad term, and it is common to address aspects within nutrition when assessing food systems. Nutrient adequacy refers to the provision of adequate levels of all essential nutrients, within the upper and lower bounds needed to prevent deficiencies and avoid toxicities (Herforth *et al.* 2020). To investigate the contribution of different food groups to the provision of essential nutrients, we used the DELTA Model (ver. 1.3; www.sustainablenutritioninitiative.com) to calculate the proportion of 29 essential nutrients available for consumption from the 2018 global food production system. This model gives global totals for overall nutrient availability from different sources, and compares these with global requirement. The results of the model are shown in Fig. 1 and discussed below.

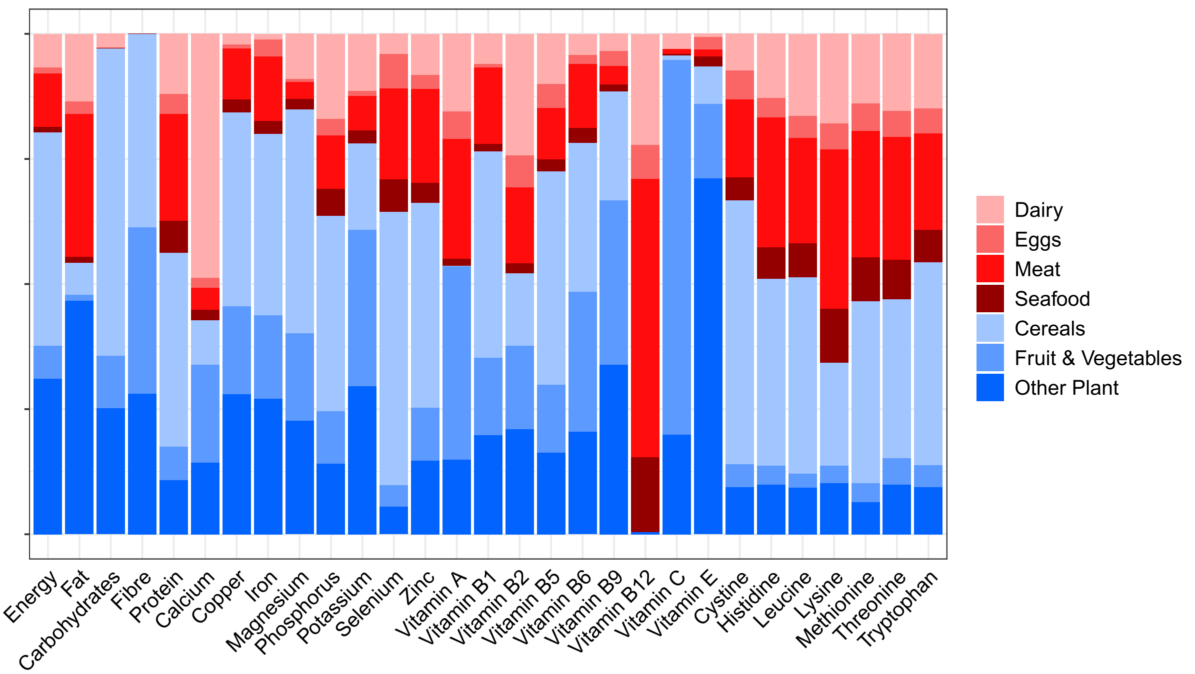

Fig. 1. Overall proportions of global nutrient availability from plant- and animal-sourced foods. Protein and the amino acids have been corrected for digestibility of the food item from which they were sourced. Source: the DELTA Model (ver. 1.3), simulated using 2018 global food system data (www.sustainablenutritioninitiative.com).

Fig. 1 clearly demonstrates the heterogeneous contributions of plant- and animal-sourced foods, and subgroups within these categories, to the global availability of different nutrients, as well as the significant contribution of both to overall nutrient supply. Carbohydrates, fibre, and several micronutrients, such as folate, vitamins C and E, are supplied entirely or almost entirely by plant-sourced foods. Within this, cereals make the major contribution of plant foods to most nutrients, being consistent with their high production volumes (nearly 3 billion tonnes globally in 2018). The exceptions are dietary fat and vitamin E, largely sourced from oilcrops. Likewise, vitamin B12 is supplied almost entirely by animal-sourced foods (principally from meat), as is the majority of the global supply of calcium (principally from dairy) and the indispensable amino acids lysine, methionine, and threonine. For all other nutrients included in the DELTA Model, and many of those that are not included (such as essential fatty acids, other amino acids, bioactive compounds, and certain vitamins), both plant- and animal-sourced foods provide significant proportions of global nutrient availability.

Fig. 1 does not capture the important role of food structures in the delivery of nutrients. While the DELTA Model accounts for the digestibility of protein and indispensable amino acids in different foods, it considers only the nutrient content of foods for all the other nutrients. It is known that in animal-sourced foods, generally, the bioavailability of the protein and amino acids is higher than in plant-sourced foods (Gilani *et al.* 2012; Rutherfurd *et al.* 2014; Mathai *et al.* 2017; Wolfe *et al.* 2018; Bailey *et al.* 2020). Fig. 2 demonstrates that global availability of protein and the indispensable amino acids is reduced by 10–15% when bioavailability is considered in addition to nutrient content. It also demonstrates that the majority of this reduction is in the plant food groups. There also exist data showing similar trends for many vitamins and minerals (e.g. calcium (Guéguen and Pointillart 2000), magnesium (Cazzola *et al.* 2020), iron, zinc, and vitamin A (FAO/WHO 2001)). Using only nutrient composition data provides significant limitations when considering the nutrient availability from any food, which could lead to erroneous conclusions on nutrient adequacy.

The current importance of both plant- and animal-sourced nutrition becomes even clearer when considering global sources of individual nutrients (Fig. 3). The DELTA Model calculates that, on a global-average level, wheat and rice are the largest contributors to energy and protein in the human diet, with milk and meat being also major contributors (Fig. 3).

The mix of both plant- and animal-sourced nutrient sources is similar for several micronutrients (Fig. 3). Thus, removal of either of these food groups would seriously alter the available sources of these nutrients and would likely leave parts of the global population challenged in obtaining nutrient sufficiency for multiple nutrients, having major consequences for health.

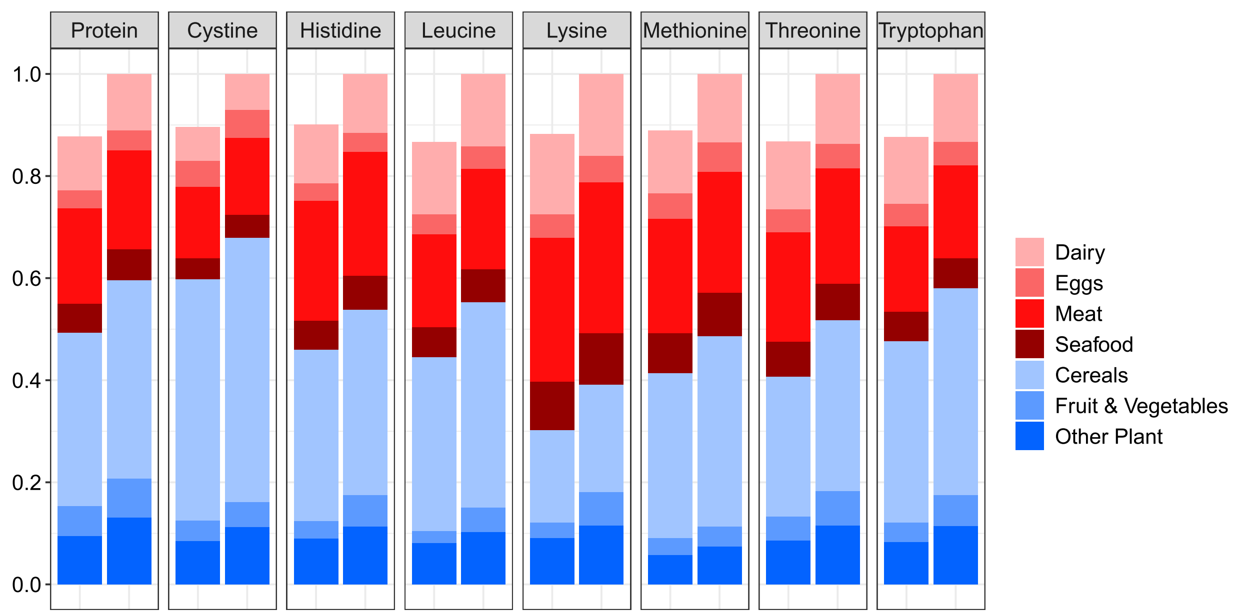

Fig. 2. Proportion of protein and indispensable amino acids available from the food system before and after the digestibility adjustments of the DELTA Model. For each nutrient, the right-hand bar shows the total nutrient content; the left-hand bar shows the proportion of the nutrient that is digestible. Considering digestibility in addition to nutrient content results in a reduction of 10–15% in the available protein and indispensable amino acids supplied by the global food system. This reduction is largely due to the lower digestibility of these nutrients from plant-sourced foods. Source: the DELTA Model (ver. 1.3), simulated using 2018 global food system data (www.sustainablenutritioninitiative.com).

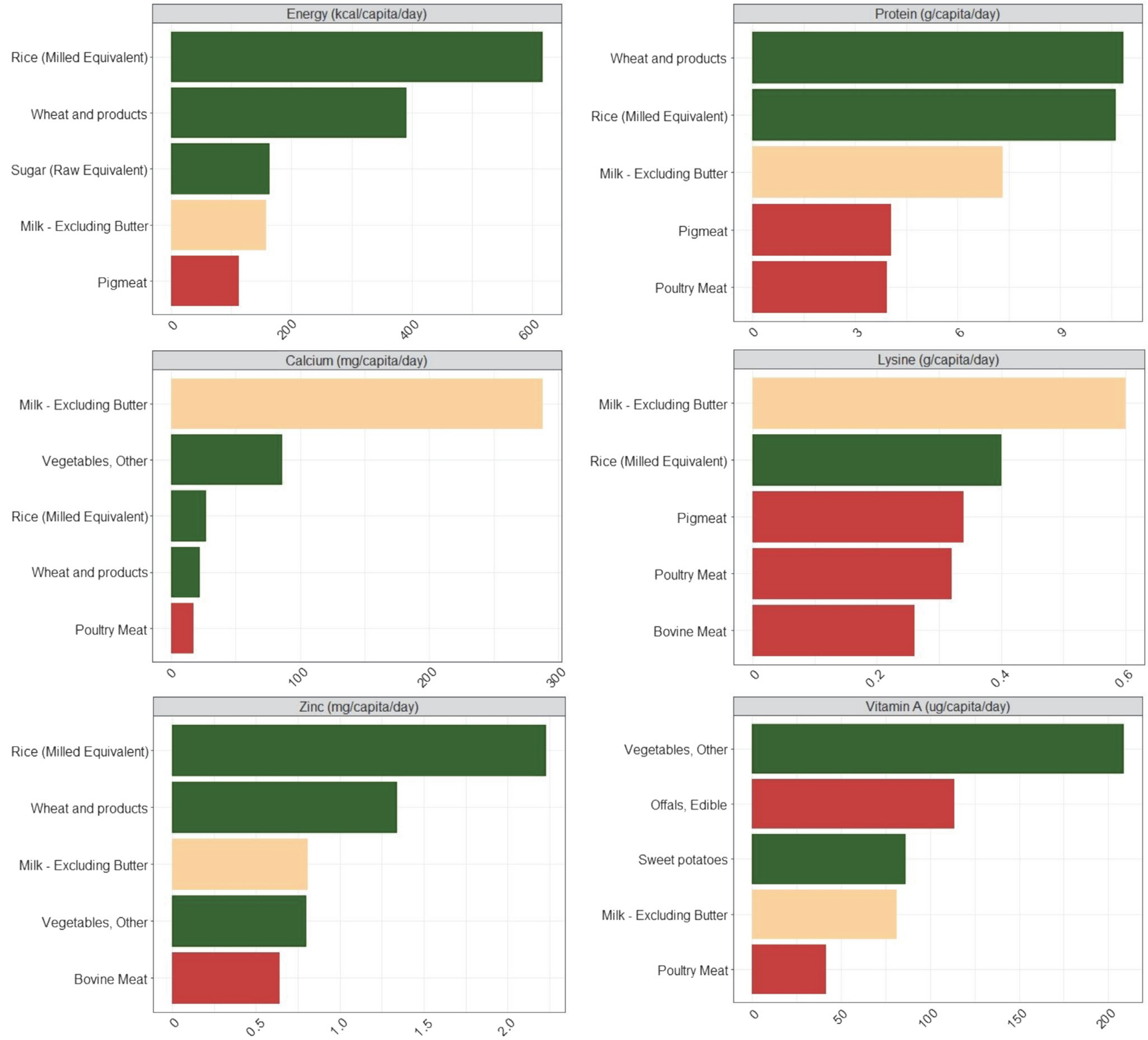

Fig. 3. Contribution of food items to global nutrient availability for selected nutrients. Charts show the top five contributing food items to supply energy, protein, calcium, lysine, zinc and vitamin A. Protein and lysine only have been corrected for digestibility from the food item. Source: the DELTA Model (ver. 1.3), simulated using 2018 global food system data (www.sustainablenutritioninitiative.com).

Health impacts of diet

There are negative health consequences associated with underconsumption and excess consumption of both individual nutrients and food groups. The scientific literature features much discussion of whether there may be health risks associated with consumption of animal-sourced foods, particularly red and processed meat (Boada *et al.* 2016), and foods high in saturated fat (Clifton and Keogh 2017). These risks are not widely accepted in the scientific literature (Alexander *et al.* 2015; Klurfeld 2018; Kruger and Zhou 2018; Johnston *et al.* 2019; Leroy and Cofnas 2019; Astrup *et al.* 2020; Qian *et al.* 2020; Iqbal *et al.* 2021; World Famers' Organisation Scientific Council 2021), for a number of reasons.

High meat intakes often coincide with obesity and smoking, as well as a reduced intake of whole grains, fruit, and vegetables (Grosso *et al.* 2017; Turner and Lloyd 2017). Adjusting for generally less healthy diets and lifestyles is a challenge for observational population studies, given the diversity of factors that can affect health, making drawing conclusions challenging. Moreover, most studies of meat consumption have been performed in high meat-consuming populations, limiting the insight that can be applied to other populations (Yip *et al.* 2018). The NutriRECS consortium, an independent scientific group that undertakes meta-analyses of clinical, nutritional and public health science to inform dietary guidelines, have advised continuation of current levels of meat consumption due to low certainty that diets with reduced quantities of these foods have a reduced risk of harmful effects (Johnston *et al.* 2019).

More importantly, excess consumption risks have a minor impact on global health in comparison to the health consequences of undernutrition. The Global Burden of Disease study, an international observational epidemiology program, demonstrated that underconsumption of nutrients and specific food groups outweighed excess consumption in associations with deaths and disability-adjusted life years (DALYs; Afshin *et al.* 2019). Diets high in sodium were the leading factor associated with deaths attributable to diet globally, at over 3 million per year in 2017 (~5% of deaths in that year; United Nations Department of Economic and Social Affairs Population Division 2017). The next greatest dietary factors associated with deaths were diets low in whole grains, fruits, nuts and seeds, vegetables, seafood omega-3 fatty acids, fibre, polyunsaturated fatty acids, and legumes. Together, the deaths attributable to diets low in these specific nutrients or food groups was more than 12 million (over 20% of global deaths). The DALYs attributable to diet showed a similar ordering (Fig. 4).

Contrastingly, diets high in processed or red meat contributed to fewer than 200 000 deaths (~0.4% of global deaths). While still a considerable number of people, this is less than 1/50th of the number attributed to diets low in specific nutrients and food groups at the global level. Moreover, an inspection of the data for socio-demographic and risk-factor groupings used in this estimation showed that zero deaths or DALYs attributed to meat were within the uncertainty interval for most groupings (supplementary table 10 in Afshin *et al.* (2019)).

The same body of research also investigated how regional consumption of food groups and specific nutrients compared with the 'optimal level of intake': the level of risk exposure that minimises the risk from all causes of death on the basis of studies included in their meta-analysis. No regions met the optimal intake levels for milk, fruits, whole grains, nuts and seeds, fibre, calcium, or polyunsaturated fatty acids (Afshin *et al.* 2019). Only a minority of regions achieved the optimal intake of vegetables, legumes, or omega-3 fatty acids. Red and processed meat was overconsumed mainly in developed global regions, with underconsumption being noted in many parts of Africa, Asia, and Oceania. It is interesting to consider the number of deaths and DALYs that could be avoided under conditions of more equitable access

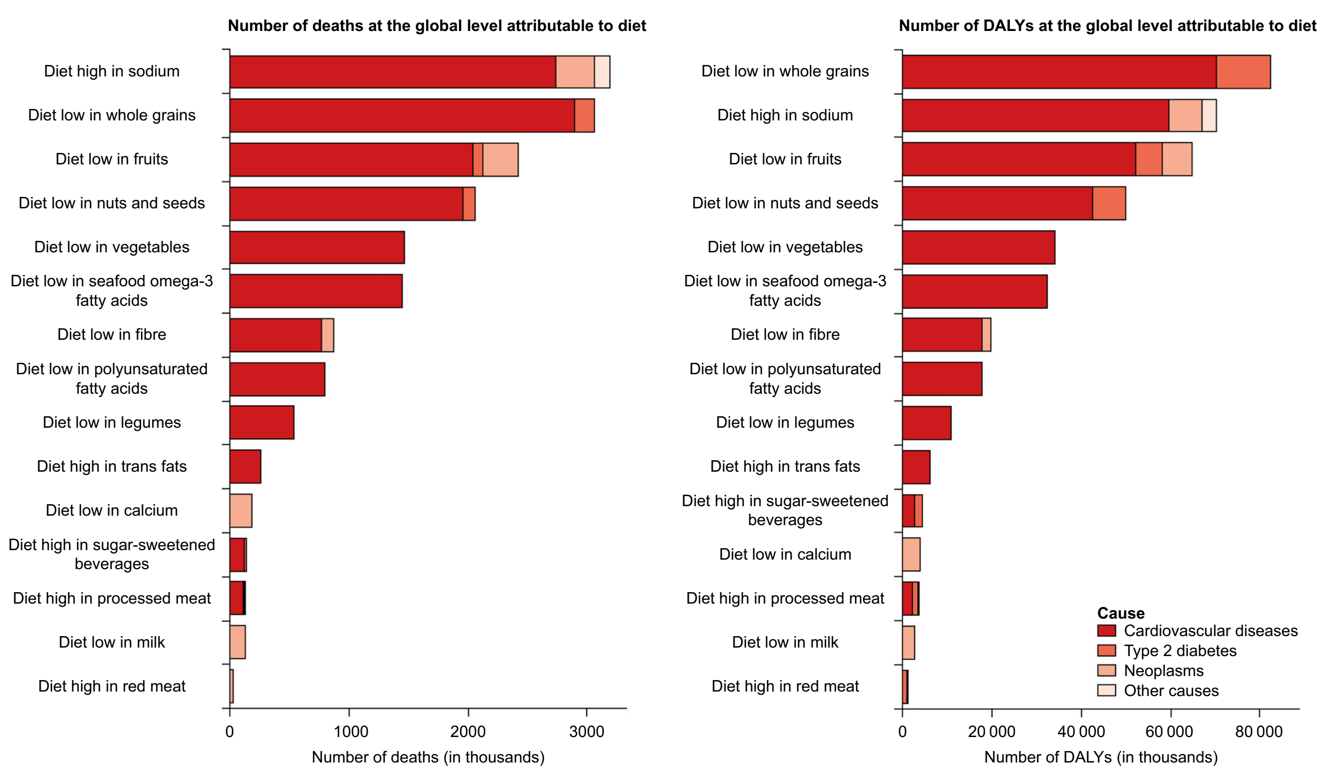

Fig. 4. Number of deaths and DALYs (disability-adjusted life years) attributable to individual dietary risks at the global level in 2017. Adapted from Afshin *et al.* (2019).

to these foods to address micronutrient deficiencies. Note that the underconsumed foods, at both the global and regional levels, are both plant- and animal-sourced.

Another important health consequence of diet is overnutrition. As a result of excess energy intakes, obesity is increasing in all global regions, rising at a rate of 2.6% of the global population per year (FAO *et al.* 2020). This is coupled with the low intakes of essential nutrients and important food groups demonstrated by Afshin *et al.* (2019). This emphasises the need for nutrient-dense foods, that is, those that deliver high concentrations of bioavailable nutrients with a low concomitant energy intake. The foods that optimise these properties vary for different nutrients, but are both plant and animal sourced.

Environmental sustainability of plant and animal production

Given that the majority of available food mass is plant-sourced, many have concluded that animal production has a disproportionately high impact on the environment for their minority contribution to food availability. However, there is far more nuance to the food system than can be drawn from overall mass totals.

Mass comparisons do not capture nutrition

In the previous section, we discussed the nutritional value of different food sources, and the importance of nutrient density. Wholegrains have a higher concentration of nutrients than do refined grains and are more associated with good health (Afshin *et al.* 2019; Reynolds *et al.* 2019). Thus, comparing the environmental footprint of wholegrains and refined grains using weight as the functional unit does not capture the greater nutritional value of the former.

This argument has been applied to protein. Greenhouse-gas (GHG) and land-use footprints of animal-sourced foods determined by life cycle analysis (LCA) vary greatly among studies and among production systems, but are generally greater than those of the equivalent mass of plant-sourced foods (Fig. 5).

A striking feature of Fig. 5 is the range in footprints for some of the food types, for example bovine meat, where the difference in land-use and GHG emissions can vary more than 10-fold, representing both differences in the suitability of the local environment for producing the food type and the degree to which best practices have been deployed within that environment. While Poore and Nemecek (2018) reported global average emissions for milk production of 2.8–3.2 kg carbon dioxide equivalents (CO_2-eq)/L, high-performing pasture-based systems in New Zealand result in a national average of less than one-third of the global average (Ledgard *et al.* 2020). Moreover, it is not yet possible to fully quantify the contribution of different production systems to carbon sequestration, both in plant matter and the soil. This is likely to add further variability between production systems and geographic locations.

The degree of difference between the environmental footprints of plant- and animal-sourced foods varies substantially depending on the functional unit used. The most commonly used functional unit, mass of the product, shows a greater divide between the footprints of the two food groups than when using protein as the functional unit (Fig. 5). Choice of functional unit depends on what the key value of the product is seen to be; for many plant- and animal-sourced foods, protein is a highly valued component.

However, there is more to food than its macronutrient content. Depending on the perceived value of the food, we could also consider environmental footprints with micronutrients as the functional unit. For example, a comparison between the footprints of the foods in Fig. 5 by using 1 kg of iron as the functional unit would be expected to favour the animal-sourced food, whereas a comparison using the functional unit of 1 kg of vitamin C would favour plant-sourced foods.

The refinement of functional units could go even further by considering bioavailability, such as, for example, using 100 g of bioavailable amino acids as the functional unit. This would enable an environmental comparison at the level of nutrients available for use by the body. This approach would be limited by available bioavailability data for each nutrient, but there already exist ample data on protein and amino acid bioavailability to perform such a comparison for these nutrients. Given the generally greater bioavailability of protein in animal-sourced foods, this comparison could be expected to further reduce the gap between the environmental footprints of the two food groups seen in Fig. 5, but such approaches are only just emerging in the field (Moughan 2021).

LCA studies must make a judgement on what the desired value of a food is for use in comparisons among them. The common use of mass as the functional unit masks the nutritional contribution of different foods. Equally, selection of a single nutritional attribute of a food will unfairly favour some over others. To avoid this bias, the use of a nutrient richness or density metric as the functional unit can be made, which encompasses a range of nutrients. While many studies have conducted LCAs of different diets, fewer have evaluated individual foods or production systems with a nutritional functional unit (Tessari *et al.* 2016; McAuliffe *et al.* 2020). However, these studies have shown interesting re-orderings of impacts for both plant- and animal-sourced foods when using nutritional functional units, with varied results among different nutrient-profiling metrics (see review by McAuliffe *et al.* (2020)).

Finally, it should be noted that many current studies have reported all GHG emissions from the global food system in CO_2-eq values, calculated using fixed ratios for other GHGs, such as methane. This is in accordance with the widely used

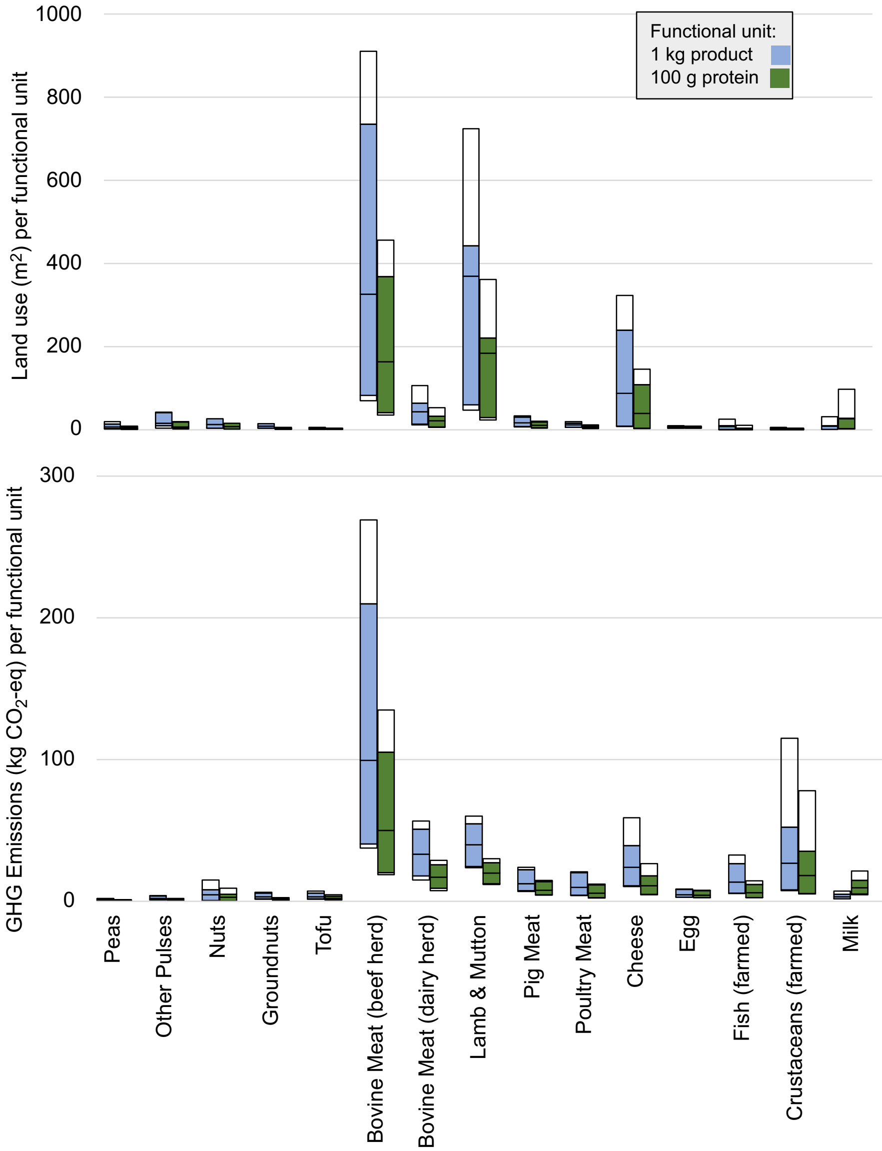

Fig. 5. Comparison of environmental footprints of several plant- and animal-sourced food products, demonstrating that the difference between plant and animal production decreases when comparing protein content rather than mass. Data are from Poore and Nemecek (2018) for pooled life cycle analysis data. The coloured boxes show the 10th to 90th percentile footprints, with the mean displayed by the horizontal line in these boxes. The transparent ends of the boxes extend to the 5th and 95th percentiles. The plots illustrate two results. First, the environmental impacts of animal-sourced foods are generally greater than those of plant-sourced foods, but also show great variation among studies and production systems. Second, the difference between the footprints of animal- and plant-sourced foods decreases when comparing on a protein basis rather than mass. GHG, greenhouse gas; CO_2-eq, carbon dioxide equivalents. See Poore and Nemecek (2018) for methodology.

100-year global warming potential (GWP_{100}) metric. The use of single scaling factors for the warming potential of different GHGs can be misleading for gases such as methane, which do not persist for millennia in the atmosphere, like CO_2, and thus contribute an approximately fixed degree of warming if their emission rate is stable (Pierrehumbert 2014). An alternative accounting method, GWP*, has been proposed and used, which focusses instead on changes in the emission rate to calculate warming impact (Lynch et al. 2020). This method is thought to better reflect the impacts of short-lived gases, such as methane, and thus better reflect the impact of high-methane production systems, such as ruminant production. However, use of GWP* is not yet widespread in its use in LCAs. Future analyses using this approach are anticipated with interest.

Land and feed use

About half of the total global agricultural land is used to feed livestock (Mottet et al. 2017). Of these 2.5 billion hectares of land, ~2 billion are grassland, the remainder being arable land. It can be argued that animal production is thus in competition for land that could be used to produce human-edible plants, or that human-edible plants are being used as feed. However, it has been estimated that only 0.68 billion hectares (34%) of current grazing land could be converted to support crops for human consumption and also that only ~14% of global animal feed mass (0.84 billion tonnes) is human-edible (Mottet et al. 2017).

Moreover, there is variation within the amounts of human-edible feed used in different animal production systems in different parts of the world; 1 kg of ruminant meat requires on average 2.8 kg human-edible feed to produce (2.2 kg in non-OECD countries, 4.2 kg in OECD countries), whereas for 1 kg of meat from monogastrics, this value is 3.2 kg (2.6 kg in non-OECD countries, 4 kg in OECD countries; Mottet et al. 2017). Many ruminant systems produce meat and milk by using almost exclusively pasture-based diets that are close to 100% human-inedible. Thus, the degree of food/feed competition varies among production systems, with monogastrics being more dependent on human-edible feedstuffs. This will translate to human nutrition; the different options for land use could be compared with the nutrition delivered from them. For example, how much of an individual's nutrient requirements could be met by a hectare of land under grazing ruminant production, compared with conversion to producing cereals for monogastric feed, or compared with producing cereals for human food, with by-products used as animal feed. This would allow us to compare the efficacy of land use for the delivery of nutrition to people.

Forecasting demand for meat animal feed and the land required to produce it, Mottet et al. (2017) predicted global feed land-area changes of between –8% and 15% between 2010 and 2025, depending on the degree of improvement in crop yields and feed conversion ratios. The largest increases in land area requirement for feed are forecast in non-OECD countries. Thus, increased efficiency of both animal and plant production, especially in developing regions, could reduce the land use footprint of global food production.

Another mechanism for reducing the land-use footprint of global food production is a transition towards the concept of 'low-cost livestock', i.e. animal-sourced food production that does not compete for arable land (van Zanten et al. 2018). This concept encourages the feeding of livestock on feed that cannot (or is not desirable to) be consumed by humans, such as forage, crop residues, co-products, and food waste. It has been found that such practices could supply nearly half of global protein requirements from animal-sourced foods, along with substantial contributions to micronutrient requirements (van Zanten et al. 2018). Moreover, low-cost livestock production could result in a reduced requirement for arable land compared to completely eliminating livestock production, due to the increased plant protein production that would be required from a global livestock-free food system (Schader et al. 2015; van Zanten et al. 2016, 2018; Röös et al. 2017). Finally, these authors often cite the importance of animal production systems in supplying manure for the fertilising of agricultural land as a further synergy between plant and animal production, reducing the need for synthetic fertiliser manufacture.

The environmental impacts of the food system extend beyond land use; GHG emissions, water use, soil erosion, and nutrient and biodiversity loss are further aspects that must be considered, and that show varying degrees of impact between food production systems. As discussed by the EAT-Lancet Commission on healthy diets from sustainable food systems, while around three-quarters of the current GHG emissions are attributable to animal products, at least this proportion of cropland use, freshwater use, and nitrogen and phosphorus application are from plant food production, with staple crops being the greatest contributor (Willett et al. 2019). It is essential that the many aspects of environmental sustainability are considered when assessing current and proposed food systems.

Economic considerations in global food system sustainability

Food production and delivery of nutrition must be both affordable for the consumer and economically viable from a production perspective if they are to be sustainable. Much research has been performed addressing the affordability of nutrition for the consumer in different parts of the world, which have demonstrated the financial challenges associated with changes away from the current food system that is dominated by plant foods, with contributions from animal foods.

While detailed plans for shifts to sustainable diets have been proposed previously (Willett et al. 2019), these are not always affordable for the consumer. It has been estimated that the EAT-Lancet planetary health diet would cost more than the household per capita income of 1.58 billion people using 2011 food prices (Hirvonen et al. 2020).

Other research has addressed the least cost of a nutrient-adequate diet. Chungchunlam et al. (2020) used US supermarket food prices matched to nutrient requirement data and produced a model that identified the least-cost nutrient-adequate diet. The diet contained both plant- and animal-sourced foods, and at USD1.98 per day was cheaper than the nutrient-adequate least-cost plant-only diet at USD3.61. A similar, but international, approach was taken by Bai *et al.* (2021), who found that the least-cost nutrient-adequate diet varied substantially in different parts of the world, with animal-sourced foods a more affordable source of nutrients in higher-income nations than in low-income nations. The affordability of nutrient-adequate diets, as a proportion of income, also varied, with the lowest affordability seen in sub-Saharan Africa. Thus, a single global recommendation for a diet that does not consider the differing food prices and incomes in different parts of the world would not be appropriate. Although shifts in food prices could be expected over time and with changes in production practices, achieving affordable sustainable diets will be challenging. Currently, both plant- and animal-sourced foods contribute to affordable nutrition.

The impact of changes to the food system on livelihoods should also be a major consideration. Agriculture is also the source of livelihoods for billions of people. It is estimated that there are at least 570 million farms worldwide, of which nearly 500 million can be considered family farms (Lowder *et al.* 2016). The dairy sector alone employs almost a quarter of a billion people through approximately 150 million farms globally, and is thus thought to directly or indirectly support the livelihoods of up to one billion people (FAO 2017). When considering a change to the food system to make any food groups more affordable, the cost and practicality of that change for food producers must also be considered.

Emerging possibilities for nutrition

In addition to existing large-scale traditional food production, novel foods such as insects, and cultured and fermentation-produced proteins have entered the debate on sustainable food systems. These foods have generated interest as potential sources of protein, with reduced environmental impacts compared with traditional, more widely consumed foods.

However, there is great variation in the environmental impacts of these protein sources. The global-warming contribution of cultured meat differs among production systems, some of which have larger impacts than does traditionally reared beef (Lynch and Pierrehumbert 2019). Cradle-to-plate analysis of chicken in comparison to numerous alternatives (including lab-grown, insect-based and mycoprotein) found that the integrated environmental impacts of chicken and mycoprotein analogues were similar, and were greater than insect-based but less than lab-grown alternatives (Smetana *et al.* 2015).

The acceptance of the consumer will also be necessary if these foods are to become widely eaten. There are many factors of consumer concern, particularly taste, for cultured meat (Bryant and Barnett 2018) and insect foods (House 2016; for which disgust is another barrier in Western cultures; La Barbera *et al.* 2018). Less is known about consumer preference for fermentation-produced protein, but this could be expected to show similar trends.

Finally, there exist questions around the investment required to scale up production of these foods, and the economic feasibility of this scale-up (Stephens *et al.* 2018; Madau *et al.* 2020). Given these uncertainties, as well as lack of information on the nutritional content and quality of these novel foods, the current food system will need to continue to deliver widespread nutrition by using existing methods (although with improvements to best practice and wider adoption of best practice) until more is known about the capacity of the alternatives.

Conclusions

Although we have discussed animal and plant production as separate entities here and addressed their respective implications in this paper, we must emphasise two points. First, plant and livestock production are deeply interconnected; a system view that combines the two is essential when considering their benefits and impacts. Second, great variation exists within these two very broad classifications of food production, and generalised conclusions about either mask the differing values of individual foods and the nutrients they supply. We strongly feel that presenting plant production versus animal production as mutually exclusive is an incorrect simplification, and hides the much more granular consideration needed for productive debate on the subject of sustainable agriculture (Leroy and Hite 2020).

It should also be noted that people do not solely aim to purchase nutrient-adequate diets; other values drive purchasing decisions. This difference between demand and requirement is important, and demand is more likely to drive changes in production. However, the foods that are demanded are not necessarily the best for human nutrition, the environment, or the expenditure of the consumer.

When considering the future of the global food system, it is essential to examine its nutritional, environmental and socioeconomic sustainability (HLPE 2014). A food system that optimises environmental and socioeconomic outcomes but fails to deliver nutrition for all will not be sustainable. There is no question that the efficiency of food production will need to improve if we are to achieve a sustainable food system. It is also clear that we will need to move to more sustainable consumption patterns and diets, including limiting food waste and overconsumption. Better integration of animal and plant production systems has the potential to facilitate more productive and sustainable food systems.

Whether taking the global perspective of nutrient provision or the individual perspective of consuming affordable, nutritious diets, the future food system will need to be one where plant-sourced nutrients are complementary to, and not competing with, animal-sourced nutrients. The system as a whole is currently plant-based and must remain so. As this plant matter feeds both humans directly, and indirectly via animal production, we believe the whole system should aim to be plant-based and animal-optimised.

References

Adesogan AT, Havelaar AH, McKune SL, *et al.* (2020) Animal source foods: sustainability problem or malnutrition and sustainability solution? Perspective matters. *Global Food Security* **25**, 100325. doi:10.1016/j.gfs.2019.100325

Afshin A, Sur PJ, Fay KA, *et al.* (2019) Health effects of dietary risks in 195 countries, 1990–2017: a systematic analysis for the Global Burden of Disease Study 2017. *The Lancet* **393**, 1958–1972. doi:10.1016/S0140-6736(19)30041-8

Alexander DD, Weed DL, Miller PE, *et al.* (2015) Red meat and colorectal cancer: a quantitative update on the state of the epidemiologic science. *Journal of the American College of Nutrition* **34**, 521–543. doi:10.1080/07315724.2014.992553

Astrup A, Magkos F, Bier DM, *et al.* (2020) Saturated fats and health: a reassessment and proposal for food-based recommendations: JACC State-of-the-Art review. *Journal of the American College of Cardiology* **76**, 844–857. doi: 10.1016/j.jacc.2020.05.077

Bai Y, Alemu R, Block SA, *et al.* (2021) Cost and affordability of nutritious diets at retail prices: evidence from 177 countries. *Food Policy* **99**, 101983. doi:10.1016/j.foodpol.2020.101983

Bailey HM, Mathai JK, Berg EP, *et al.* (2020) Most meat products have digestible indispensable amino acid scores that are greater than 100, but processing may increase or reduce protein quality. *British Journal of Nutrition* **124**, 14–22. doi:10.1017/S0007114520000641

Boada LD, Henríquez-Hernández LA, Luzardo OP (2016) The impact of red and processed meat consumption on cancer and other health outcomes: epidemiological evidences. *Food and Chemical Toxicology* **92**, 236–244. doi:10.1016/j.fct.2016.04.008

Bryant C, Barnett J (2018) Consumer acceptance of cultured meat: a systematic review. *Meat Science* **143**, 8–17. doi:10.1016/j.meatsci.2018.04.008

Cazzola R, Della Porta M, Manoni M, *et al.* (2020) Going to the roots of reduced magnesium dietary intake: a tradeoff between climate changes and sources. *Heliyon* **6**, e05390. doi:10.1016/j.heliyon.2020.e05390

Chungchunlam SMS, Moughan PJ, Garrick DP, *et al.* (2020) Animal-sourced foods are required for minimum-cost nutritionally adequate food patterns for the United States. *Nature Food* **1**, 376–381. doi:10.1038/s43016-020-0096-8

Clark M, Macdiarmid J, Jones AD, *et al.* (2020) The role of healthy diets in environmentally sustainable food systems. *Food and Nutrition Bulletin* **41**, 31S–58S. doi:10.1177/0379572120953734

Clifton PM, Keogh JB (2017) A systematic review of the effect of dietary saturated and polyunsaturated fat on heart disease. *Nutrition, Metabolism and Cardiovascular Diseases* **27**, 1060–1080. doi:10.1016/j.numecd.2017.10.010

European Commission (2020) Communication from the Commission to the European Parliament, The Council, The European Economic and Social Committee and the Committee of the Regions: a farm to fork strategy for a fair, healthy and environmentally-friendly food system. (European Commission)

FAO (2017) The global dairy sector: facts. Available at https://www.fil-idf.org/wp-content/uploads/2016/12/FAO-Global-Facts-1.pdf

FAO (2020) FAO food balance sheets [online]. United Nations Food and Agriculture Organization. Available at http://www.fao.org/faostat/en/#data/FBSH [Accessed 21 August 2020]

FAO, IFAD, UNICEF, *et al.* (2020) 'The state of food security and nutrition in the World 2020. transforming food systems for affordable healthy diets.' (FAO: Rome, Italy)

FAO/WHO (2001) Human vitamin and mineral requirements: report of a joint FAO/WHO expert consultation. FAO/WHO, Rome, Italy. Available at http://www.fao.org/3/y2809e/y2809e.pdf

FAO/WHO (2014) Second international conference on nutrition, conference outcome document: rome declaration on nutrition. FAO/WHO, Rome, Italy. Available at http://www.fao.org/3/ml542e/ml542e.pdf

Gilani S, Tomé D, Moughan P, *et al.* (2012) Report of a Sub-Committee of the 2011 FAO Consultation on 'Protein Quality Evaluation in Human Nutrition' on: the assessment of amino acid digestibility in foods for humans and including a collation of published ileal amino acid digestibility data for human foods. FAO, Rome, Italy. Available at http://www.fao.org/ag/humannutrition/35978-02317b979a686a57aa4593304ffc17f06.pdf

Grosso G, Micek A, Godos J, *et al.* (2017) Health risk factors associated with meat, fruit and vegetable consumption in cohort studies: a comprehensive meta-analysis. *PLoS One* **12**, e0183787. doi:10.1371/journal.pone.0183787

Guéguen L, Pointillart A (2000) The bioavailability of dietary calcium. *Journal of the American College of Nutrition* **19**, 119S–136S. doi:10.1080/07315724.2000.10718083

Herforth A, Bai T, Venkat A, *et al.* (2020) Cost and affordability of healthy diets across and within countries. Background paper for The State of Food Security and Nutrition in the World 2020. FAO agricultural development economics technical study no. 9. FAO, Rome, Italy.

Hirvonen K, Bai Y, Headey D, *et al.* (2020) Affordability of the EAT–Lancet reference diet: a global analysis. *The Lancet Global Health* **8**, e59–e66. doi:10.1016/S2214-109X(19)30447-4

HLPE (2014) Food losses and waste in the context of sustainable food system: a report by The High Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security. Committee on World Food Security, Rome, Italy. Available at http://www.fao.org/3/i3901e/i3901e.pdf.

House J (2016) Consumer acceptance of insect-based foods in the Netherlands: academic and commercial implications. *Appetite* **107**, 47–58. doi:10.1016/j.appet.2016.07.023

Iqbal R, Dehghan M, Mente A, *et al.* (2021) Associations of unprocessed and processed meat intake with mortality and cardiovascular disease in 21 countries [Prospective Urban Rural Epidemiology (PURE) Study]: a prospective cohort study. *The American Journal of Clinical Nutrition* **114**(3), 1049–1058. doi:10.1093/ajcn/nqaa448

Johnston BC, Zeraatkar D, Han MA, *et al.* (2019) Unprocessed red meat and processed meat consumption: dietary guideline recommendations from the nutritional recommendations (NutriRECS) consortium. *Annals of Internal Medicine* **171**, 756–764. doi:10.7326/M19-1621

Klurfeld DM (2018) What is the role of meat in a healthy diet? *Animal Frontiers* **8**, 5–10. doi:10.1093/af/vfy009

Kruger C, Zhou Y (2018) Red meat and colon cancer: a review of mechanistic evidence for heme in the context of risk assessment methodology. *Food and Chemical Toxicology* **118**, 131–153. doi:10.1016/j.fct.2018.04.048

La Barbera F, Verneau F, Amato M, *et al.* (2018) Understanding Westerners' disgust for the eating of insects: the role of food neophobia and implicit associations. *Food Quality and Preference* **64**, 120–125. doi:10.1016/j.foodqual.2017.10.002

Ledgard SF, Falconer SJ, Abercrombie R, *et al.* (2020) Temporal, spatial, and management variability in the carbon footprint of New Zealand milk. *Journal of Dairy Science* **103**, 1031–1046. doi:10.3168/jds.2019-17182

Leroy F, Cofnas N (2019) Should dietary guidelines recommend low red meat intake? *Critical Reviews in Food Science and Nutrition* 60, 2763–2772. doi:10.1080/10408398.2019.1657063

Leroy F, Hite AH (2020) The place of meat in dietary policy: an exploration of the animal/plant divide. *Meat and Muscle Biology* **4**, 1–11. doi:10.22175/mmb.9456

Lowder SK, Skoet J, Raney T (2016) The number, size, and distribution of farms, smallholder farms, and family farms worldwide. *World Development* **87**, 16–29. doi:10.1016/j.worlddev.2015.10.041
Lynch J, Pierrehumbert R (2019) Climate impacts of cultured meat and beef cattle. *Frontiers in Sustainable Food Systems* **3**, 5. doi:10.3389/fsufs.2019.00005
Lynch J, Cain M, Pierrehumbert R, *et al.* (2020) Demonstrating GWP*: a means of reporting warming-equivalent emissions that captures the contrasting impacts of short- and long-lived climate pollutants. *Environmental Research Letters* **15**, 044023. doi:10.1088/1748-9326/ab6d7e
Madau FA, Arru B, Furesi R, *et al.* (2020) Insect farming for feed and food production from a circular business model perspective. *Sustainability* **12**, 5418. doi:10.3390/su12135418
Mathai JK, Liu Y, Stein HH (2017) Values for digestible indispensable amino acid scores (DIAAS) for some dairy and plant proteins may better describe protein quality than values calculated using the concept for protein digestibility-corrected amino acid scores (PDCAAS). *British Journal of Nutrition* **117**, 490–499. doi:10.1017/S0007114517000125
McAuliffe GA, Takahashi T, Lee MRF (2020) Applications of nutritional functional units in commodity-level life cycle assessment (LCA) of agri-food systems. *The International Journal of Life Cycle Assessment* **25**, 208–221. doi:10.1007/s11367-019-01679-7
Mora O, Le Mouël C, de Lattre-Gasquet M, *et al.* (2020) Exploring the future of land use and food security: a new set of global scenarios. *PLoS One* **15**, e0235597. doi:10.1371/journal.pone.0235597
Mottet A, de Haan C, Falcucci A, *et al.* (2017) Livestock: on our plates or eating at our table? A new analysis of the feed/food debate. *Global Food Security* **14**, 1–8. doi:10.1016/j.gfs.2017.01.001
Moughan PJ (2021) Population protein intakes and food sustainability indices: the metrics matter. *Global Food Security* **29**, 100548. doi:10.1016/j.gfs.2021.100548
Murphy SP, Allen LH (2003) Nutritional importance of animal source foods. *The Journal of Nutrition* **133**, 3932S–3935S. doi:10.1093/jn/133.11.3932S
National Food Strategy (2021) The Plan. National Food Strategy. Available at https://www.nationalfoodstrategy.org/
Pierrehumbert RT (2014) Short-lived climate pollution. *Annual Review of Earth and Planetary Sciences* **42**, 341–379. doi:10.1146/annurev-earth-060313-054843
Poore J, Nemecek T (2018) Reducing food's environmental impacts through producers and consumers. *Science* **360**, 987–992. doi:10.1126/science.aaq0216
Qian F, Riddle MC, Wylie-Rosett J, *et al.* (2020) Red and processed meats and health risks: how strong is the evidence? *Diabetes Care* **43**, 265–271. doi:10.2337/dci19-0063
Reynolds A, Mann J, Cummings J, *et al.* (2019) Carbohydrate quality and human health: a series of systematic reviews and meta-analyses. *The Lancet* **393**, 434–445. doi:10.1016/S0140-6736(18)31809-9
Röös E, Bajželj B, Smith P, *et al.* (2017) Greedy or needy? Land use and climate impacts of food in 2050 under different livestock futures. *Global Environmental Change* **47**, 1–12. doi:10.1016/j.gloenvcha.2017.09.001
Rutherfurd SM, Fanning AC, Miller BJ, *et al.* (2014) Protein digestibility-corrected amino acid scores and digestible indispensable amino acid scores differentially describe protein quality in growing male rats. *The Journal of Nutrition* **145**, 372–379. doi:10.3945/jn.114.195438
Schader C, Muller A, Scialabba NE-H, *et al.* (2015) Impacts of feeding less food-competing feedstuffs to livestock on global food system sustainability. *Journal of The Royal Society Interface* **12**, 20150891. doi:10.1098/rsif.2015.0891
Smetana S, Mathys A, Knoch A, *et al.* (2015) Meat alternatives: life cycle assessment of most known meat substitutes. *The International Journal of Life Cycle Assessment* **20**, 1254–1267. doi:10.1007/s11367-015-0931-6
Smith NW, Fletcher AJ, Dave LA, *et al.* (2021) Use of the DELTA model to understand the food system and global nutrition. *The Journal of Nutrition* **151**(10) 3253–3261. doi:10.1093/jn/nxab199
Springmann M, Clark M, Mason-D'Croz D, *et al.* (2018) Options for keeping the food system within environmental limits. *Nature* **562**, 519–525. doi:10.1038/s41586-018-0594-0
Stephens N, Di Silvio L, Dunsford I, *et al.* (2018) Bringing cultured meat to market: technical, socio-political, and regulatory challenges in cellular agriculture. *Trends in Food Science & Technology* **78**, 155–166. doi:10.1016/j.tifs.2018.04.010
Tessari P, Lante A, Mosca G, *et al.* (2016) Essential amino acids: master regulators of nutrition and environmental footprint? *Scientific Reports* **6**, 26074. doi:10.1038/srep26074
Turner ND, Lloyd SK (2017) Association between red meat consumption and colon cancer: a systematic review of experimental results. *Experimental Biology and Medicine* **242**, 813–839. doi:10.1177/1535370217693117
United Nations Department of Economic and Social Affairs Population Division (2017) World Mortality 2017 – Data Booklet (ST/ESA/SER.A/412). United Nations Department of Economic and Social Affairs Population Division, Rome, Italy. Available at https://www.un.org/en/development/desa/population/publications/pdf/mortality/World-Mortality-2017-Data-Booklet.pdf
van Zanten HHE, Meerburg BG, Bikker P, *et al.* (2016) Opinion paper: the role of livestock in a sustainable diet: a land-use perspective. *Animal* **10**, 547–549. doi:10.1017/S1751731115002694
van Zanten HHE, Herrero M, Van Hal O, *et al.* (2018) Defining a land boundary for sustainable livestock consumption. *Global Change Biology* **24**, 4185–4194. doi:10.1111/gcb.14321
Willett W, Rockström J, Loken B, *et al.* (2019) Food in the anthropocene: the EAT–Lancet Commission on healthy diets from sustainable food systems. *The Lancet* **393**, 447–492. doi:10.1016/S0140-6736(18)31788-4
Wolfe RR, Baum JI, Starck C, *et al.* (2018) Factors contributing to the selection of dietary protein food sources. *Clinical Nutrition* **37**, 130–138. doi:10.1016/j.clnu.2017.11.017
World Famers' Organisation Scientific Council (2021) Consumption of unprocessed red meat is not a risk to health. World Famers' Organisation. Available at https://www.wfo-oma.org/wp-content/uploads/2021/07/SC-WFO-Synopsis-Paper-on-Unprocessed-Red-Meat-Consumption_final.pdf
Yip CSC, Lam W, Fielding R, *et al.* (2018) A summary of meat intakes and health burdens. *European Journal of Clinical Nutrition* **72**, 18–29. doi:10.1038/ejcn.2017.117

Data availability. The data that support this study will be shared upon reasonable request to the corresponding author.

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