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Future foods: towards a sustainable and healthy diet for a growing population

A. Parodi[1], A. Leip[2], I.J.M. De Boer[1], P.M. Slegers[3], F. Ziegler[4], E.H.M. Temme[5], M. Herrero[6], H. Tuomisto[7], H. Valin[8], C.E. Van Middelaar[1], J.J.A. Van Loon[9] & H.H.E. Van Zanten*[1]

[1]Animal Production Systems group, Wageningen University & Research, P.O. Box 338, 6700 AH Wageningen, the Netherlands.

[2]European Commission, Joint Research Centre, Via Fermi 2749, 21027 Ispra, Italy.

[3] Operations Research and Logistics, Wageningen University & Research, P.O. Box 8130, 6700 EW Wageningen, the Netherlands.

[4]Agrifood and Bioscience, RISE Research Institutes of Sweden, P.O. Box 5401, 40229 Göteborg, Sweden.

[5] National Institute for Public Health and the Environment (RIVM), P.O. Box 1, 3720 BA Bilthoven, The Netherlands.

[6] Commonwealth Scientific and Industrial Research Organisation (CSIRO), 306 Carmody Road, St Lucia, Queensland 4067, Australia.

[7] Helsinki Institute of Sustainability Science (HELSUS) and Department of Agricultural Sciences, Faculty of Agriculture and Forestry, University of Helsinki, P.O. Box 27, 00014, Helsinki, Finland.

[8] Ecosystems Services and Management Program, International Institute for Applied Systems Analysis, A-2361 Laxenburg, Austria.

[9] Laboratory of Entomology, Wageningen University & Research, P.O. Box 16, 6700 AA Wageningen, the Netherlands.

Abstract

Altering diets is increasingly acknowledged as an important solution to feed the world's growing population within the planetary boundaries. In our search for a planet-friendly diet, the main focus has been on eating more plant-source foods, and eating no or less animal-source foods, while the potential of future foods, such as insects, seaweed or cultured meat has been underexplored. Here we show that compared to current animal-source foods, future foods have major environmental benefits while safeguarding the intake of essential micronutrients. The complete array of essential nutrients in the mixture of future foods makes them good quality alternatives for current animal-source foods compared to plant-source foods. Moreover, future foods are land-efficient alternatives for animal-source foods, and if produced with renewable energy, they also offer greenhouse gas benefits. Further research on nutrient bioavailability and digestibility, food safety, production costs, and consumer acceptance will determine their role as main food sources in future diets.

Main

Altering diets is increasingly acknowledged as an important step towards achieving several of the Sustainable Development Goals (SDGs). Throughout human history, foods derived from plants, livestock and fish have formed the backbone of our global diet, however in recent years, other food sources, such as insects, cultured meat, or seaweed are gaining global attention[1–3]. The interest in these so-called 'future foods' has increased as a response to the conflicting contribution of current mainstream foods - especially animal-source foods (ASF) – to securing a nutritious and sustainable diet for a growing human population.

On the one hand, terrestrial and aquatic ASF supply nearly 40% of the world's proteins[4] and play a critical role in reducing malnutrition, especially in low-income countries, by providing essential macro- and micronutrients[5,6]. Milk, for instance, includes relatively high amounts of calcium, beef is a high-quality source of bioavailable vitamin B12 and zinc, and seafood contains high concentrations of essential omega-3 fatty acids. On the other hand, the high intake of red and processed meat in high-income countries is associated with non-communicable diseases, such as coronary heart disease and cancer[7,8]. Moreover, global production levels of ASF place severe pressures on the environment via their emissions to air, water and soil, and their use of natural resources. The global livestock sector, for example, releases about 14.5% of all anthropogenic greenhouse gases (GHG), pollutes ground and surface waters, and uses about 40% of all arable land[9–11]. Animals increasingly are fed agricultural and fisheries products that humans could have consumed directly, causing a so-called food-feed competition. As the demand for ASF is projected to increase further[12], these above described concerns are likely to worsen.

In our search for foods that reduce environmental impact, we have seen an increasing focus on future foods[13]. Although these are often claimed to be nutritious and produced with a lower impact on the environment than most ASF, the existing nutritional and environmental work has not yet been consistently synthesised and analysed. In our study, we combined the nutritional profile with the environmental impacts of future foods under a single framework (also called functional unit). This enabled us to compare them with main conventional plant-source foods (PSF), and aquatic and terrestrial ASF. The aim of this study, therefore, was to assess the environmental potential of future foods as alternatives for ASF compared with conventional protein foods, while maintaining the intake of essential macro- and micronutrients. Our study includes the essential macro- and micronutrients present in ASF which could lead to public health concerns if ASF were to be replaced with other foods in human diets.

Future foods

We define future foods as those foods of which our ability to produce significant volumes is rapidly developing thanks to technological developments that offer the potential to up-scale production levels and/or reduce production costs with concern for the environment. Based on data availability, we selected nine future foods consisting of terrestrial foods, i.e., cultured meat, mycoprotein (*Fusarium venenatum*), black soldier fly larvae (*Hermetia illucens*), housefly larvae (*Musca domestica*), mealworm larvae (*Tenebrio mollitor*), and aquatic foods, i.e., chlorella (*Chlorella vulgaris*), spirulina (*Arthrospira platensis*), sugar kelp (*Saccharina latissima*) and mussels (*Mytilus spp.*) (Figure 1). We compiled their nutritional profiles and environmental impacts and compared them with those of important plant-source protein suppliers and with conventional aquatic and terrestrial ASF (Figure 1).

Results

The nutritional profile of future foods

Our results show that the complete array of essential macro-and micronutrients present in future foods makes them better alternatives for ASF than PSF. All future foods, except sugar kelp, show a similar or higher dry matter protein content than plant and animal-source foods (Fig. 2a) and are able to provide essential amino acids (Fig. S5). In addition to protein, most future foods also contain similar amounts of other macro- and micronutrients (Fig 2. b-f). A diet consisting of PSF only could increase the risk of developing a deficiency in vitamin B12 and omega-3 fatty acids eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA).

A mixture of future foods can provide us with all essential macro- and micronutrients we need. Calcium, for instance, currently provided mainly by milk[5], can be provided by sugar kelp or black soldier fly larvae (Fig. 2b). Iron, mostly sourced from red meat and eggs, can be found in most future foods, especially in chlorella and spirulina (Fig. 2c) where the iron content is so high that their intake should be limited to avoid exceeding iron upper intake levels. Zinc, abundant in all terrestrial ASF and PSF, also appears in future foods like sugar kelp, all insect species, and mussels, at levels comparable to or higher than in beef (Fig. 2d). In terms of vitamins, most future foods contain similar vitamin A concentrations as ASF, except sugar kelp and spirulina, with the latter having concentrations up to 20 times higher than eggs, the ASF richest in vitamin A (Fig. 2e). Even though vitamin A is either absent or poorly represented in the evaluated PSF, other PSF rich in β-carotene, such as sweet potatoes, can be used to overcome vitamin A deficiencies[14]. In contrast, due to the absence of vitamin B12 in all commonly consumed PSF, those following a vegan diet are advised to take vitamin B12 supplements to avoid health risks[15]. Vitamin B12, however, is found in large amounts in all aquatic future foods and in black soldier fly larvae (Fig. 2f).

Lastly, the two omega-3 fatty acids, EPA and DHA, which in nature are mainly synthesised by microalgae and cyanobacteria and then bioaccumulated through the trophic chain in seafood[16,17], are well represented among aquatic future foods, but absent in PSF (Figure 2g). The EPA and DHA content in insects and ASF are either directly linked to dietary levels of these fatty acids or to the low transformation rates of α-linolenic acid (ALA) into EPA and DHA[18–20].

The environmental impact of future foods

For the production of all essential nutrients, future foods require considerably less land than conventional ASF, except those from fisheries (which are by definition zero), when normalised to equal nutrient intake. Housefly, chlorella, spirulina and mussels have the lowest land use of the future foods (Fig. 3). Compared with the production of PSF, production of future foods requires equal amounts or less land for most essential nutrients (Supplementary Figure 6). Future foods therefore are land-efficient alternatives for non-fisheries ASF, and thus can contribute to reducing the competition for land between food, feed, fibre and fuel production. Because land-use is centrally coupled to other agricultural environmental impacts[10,21], a future food system with reduced land-use might have the potential to avoid additional land use change and associated impacts.

The land area required to produce ASF is mainly determined by the amount of land needed to graze animals or produce feed[11]. Similarly, land required to produce future foods is mainly determined by the type of 'feed-stock' used. For instance, studies exploring a hypothetical large-scale production system showed that under a set of reasonable though untested assumptions, the land required to produce cultured meat could be reduced by about 30% if we fed cultured cells with cyanobacteria instead of crops[22,23]. Likewise, land required to produce insects is substantially reduced when insects are fed with biomass that humans cannot or do not want to eat (here referred to as leftover streams), instead of with food crops[24,25]. Aquatic future foods such as chlorella and spirulina have lower land requirements compared to ASF, and can be produced in brackish or saline water areas unsuitable for crop production. Most mussel and seaweed farms, on the other hand, do not require any land, as these activities take place in the sea and nutrients are obtained from the water, and in the case of seaweed, also through photosynthesis. This form of non-fed aquaculture makes mussels and seaweed not only a nutritious and low-impact food, but also a production system that can help to reduce excess nutrient loads in eutrophied coastal waters and increase biodiversity[26,27]. It should be highlighted, however, that it is important to locate mussel and seaweed production in clean waters, otherwise they can accumulate water-borne contaminants and pathogens[28].

Mycoprotein, sugar kelp, all insects and mussels show similar nutrient GHG intensities (i.e. GHG emissions per unit of nutrient) to the best performing ASF and seafood (i.e., eggs, milk and tuna), and higher nutrient GHG intensities than PSF (Fig. 4, see Supplementary Figure 7). Chlorella and spirulina, show, on average, higher GHG intensities for protein and zinc than most ASF (Fig. 4). However, studies report large differences in GHG intensities for spirulina and chlorella (See Supplementary Table 7 and Supplementary Methods (SI.3.3.2) for a detailed explanation).

The sources of GHG emissions differ among future foods, PSF, seafood, and ASF. For terrestrial ASF, enteric fermentation (methane (CH_4)), feed production (carbon dioxide (CO_2) and nitrous oxide (N_2O)) and manure management (CH_4 and N_2O) are the main sources of emissions[9]. In wild fisheries, the level of GHG emissions mainly depends on fuel consumption of fishing vessels per unit of fish landed. This in turn depends on the fishing method used and the status of the fished stock[29]. For an intensive tilapia farm, however, about 87% of the GHG emissions relate to feed production[30].

Conversely, GHG emissions of future foods mainly originate from high energy-consuming processes and the current use of fossil energy sources. To produce mycoprotein, for example, energy is required to maintain constant temperatures during the fermentation process, as well as for heat treatments and centrifugation[31]. Similarly, most of the GHG emissions and energy use of cultured meat occurs during the cultivation process, which requires constant temperatures[22]. Chlorella and spirulina require high energy-consuming processes for cultivation, dewatering, and drying in order to make these foods marketable. In insect production systems, GHG emissions are mainly caused by the use of electricity for heating the rearing environment in temperate climates, drying the larvae, and feed production. GHG emissions associated with the production of insects, however, can be minimised by feeding them nutritious leftover streams[32]. As in traditional livestock rearing, insect rearing results in direct GHG emissions of CH_4 and N_2O. Expressed per kg of body weight gain, however, mealworms emit 20 times less CH_4 and 50 times less N_2O emissions than pigs[33]. Unlike insects, bivalves like mussels do not require feed inputs during farming because as filter-feeders, they feed on planktonic organisms occurring in the water flowing through the farm. They, however, produce direct GHG emissions through the release of CO_2 during shell production[34]. These emissions are generally not accounted for in life cycle assessment studies, and could potentially increase GHG emissions from mussel farming[34]. If mussel shells, on the other hand are accounted as carbon sink[26], the CO_2 emissions from shell production could be compensated. The role of mussels in the oceans' carbon cycle is currently in need of more research.

As the GHG emissions associated with producing future foods mainly result from using fossil-intensive energy sources, a transition towards renewable energy sources would reduce their GHG intensity. Even though this argument also holds for ASF, non-CO_2 GHG emissions associated with ASF production, such as enteric CH_4 emissions; CH_4 and N_2O emissions from manure management; and N_2O emissions from fertilizer application,[9] cannot be mitigated by employing renewable energies. The reduction of CH_4 and N_2O emissions will require additional innovations, such as feeding animals with safe leftover streams, innovative manure management systems, or precision fertilization. Well-managed grazing livestock can potentially offer GHG benefits through the process of soil carbon sequestration but, so far, the overall effect on livestock emissions seem negligible and time-limited (see Supplementary Discussion SI.5)[35,36,37]. For these reasons, we hypothesize that the GHG mitigation potential of future foods in a renewable energy society is likely to be higher than that of ASF.

Discussion

We show that essential nutrients are present in raw future foods, but to what level these nutrients will be conserved after processing remains unknown for most minerals and vitamins. Moreover, the extent to which these nutrients are bioavailable and digestible is only known for specific foods and nutrients. *In-vitro* models have shown, for example, that protein digestibility of different insects ranges from 67% to 98%[35–37] and that bioavailability of micronutrients such as iron, calcium and zinc in edible insects is similar or higher to that in beef[38]. Similarly, the *in-vitro* digestibility of seaweed protein ranges from 56% to 90%[39]. Protein digestibility of mycoprotein, spirulina and chlorella was found to be 15%, 25% and 30% lower than that of milk casein, respectively[40,41]. Resistant cell walls together with the presence of specific compounds (see Supplementary Discussion SI. 7) might limit the digestibility of both seaweed and microalgae, but efficient and non-costly cell-disruption techniques (e.g. heat and mechanical treatments or enzymatic lysis) provide options for making algal proteins more digestible[42,43]. Spirulina production is supported by the World Health Organization in the fight against malnutrition, and studies indicating that chlorella and spirulina can help to ameliorate iron and folate deficiencies[44,45] or increase the total-body vitamin A reserves[46] confirm that these nutrients can be absorbed in the human body. Vitamin B12, which is only synthesised by certain bacteria and archaea, is found in bioavailable forms in mussels, seaweed species, and chlorella[47], but not in spirulina, which contains an inactive vitamin B12 analogue that cannot be absorbed in the human gut[48]. Further research, therefore, is needed to assess and improve the concentration of bioavailable nutrients in future foods and their digestibility. In addition to bioavailability, future foods need to be further explored in relation to food safety (see Supplementary Discussion SI.6) and allergies, as there is evidence suggesting that people allergic to shrimp are at risk when eating mealworms or other edible insects[49]. It is therefore important to emphasise that future foods should be consumed as part of a diverse diet, ensuring that specific nutrient requirements are fulfilled and upper intake limits of nutrients are not exceeded. This can be achieved by rationing their amounts in diets and by using adequate preparation methods[50,51] or processing technologies[52,53] to improve the availability and digestibility of nutrients. More information on bioavailability, digestibility, allergies, and food safety is crucial to help us better understand the potential role of future foods in human diets.

Overall, we show that the environmental benefits of future foods are associated with high nutrient use efficiencies, use of green technologies, and the use of leftover streams. Even though some of those arguments can also be applied to the current production of ASF, future foods have potential characteristics that can lead to substantially lower environmental impact. Insects, for example, fed on leftover streams that have sufficiently high nutrient contents, have higher reproduction rates, shorter maturation periods, lower energy investment for growth, and higher protein use efficiencies, than conventional production animals[54,55]. In addition, as the whole insect larva is edible, there are no losses associated with non-edible biomass (*e.g.* bones, feathers, skin, etc.). Rearing insects on nutritious leftover streams has been shown to have especially high environmental benefits[25,32]. Some of these residual streams, however, could also be fed to livestock and significantly reduce the environmental impact of livestock[5,56]. Due to the relatively higher growth rate of insects, the environmental impact of livestock nevertheless will remain higher in most situations. Cultured meat and mycoprotein, also offer the possibility to produce edible biomass, and considering that their production takes place in controlled environments, there are numerous opportunities for using technology to achieve higher efficiencies and to minimise losses through recycling mechanisms and precise input-supply[57]. For cultured meat, however, challenges such as the development of serum-free nutrition media and the design of large-scale bioreactors should be solved first. Spirulina and chlorella are primary producers that, in contrast to crops, can be produced on marginal lands, while other aquatic future foods such as seaweed and mussels have the capacity to absorb excess nutrients from coastal areas that are otherwise not accessible for food production. Farming in the oceans is much less optimised than on land, and even though current mussel and seaweed farming are efficient, they could be considerably improved by e.g. breeding and adjusting production technologies to local conditions to increase productivity and quality. Exploiting these characteristics, in combination with renewable energy systems operating in the same production areas where future foods are produced may, therefore, help the transition towards a more sustainable food system. We are only in the very early phases of finding applications for these new raw materials, either as main foods or food components.

Despite the importance of our findings, the selection of future foods and their environmental impact was constrained by the availability of life cycle assessment studies. Different species of insects, microalgae and cyanobacteria, seaweeds, or bacteria, with a more promising nutritional and environmental performance than the future foods included here may be even better candidates for future diets. Moreover, our analysis has only covered the impact categories of land use and climate change. The impact of future foods on other environmental issues, such as water pollution, eutrophication, acidification, biodiversity and air quality, should be further explored.

With the exception of cultured meat, all future foods are currently commercially available. Crucial factors to scale up these foods from their traditional production regions to other world regions include the control of food safety hazards, the development of innovations targeting production upscaling, and the concomitant reduction of production costs (as these are currently high compared to ASF) as well as making these foods attractive and affordable to present and coming generations. Future foods have the potential to become a significant element in future sustainable healthy diets. To make this happen, private and public interventions will be required to foster their adoption and help in the transformation towards sustainable food systems.

Methods

Selection of future foods

We searched the available literature for environmental impact assessment (so-called life cycle assessment (LCA)) studies that enabled us to recalculate the environmental impact of both conventional and future foods per kilogram of dry matter product, assuming a cradle-to-factory gate approach. The search resulted in the selection of the following terrestrial future foods: cultured meat, mycoprotein (*Fusarium venenatum*) commercially available as “Quorn”, the larvae of three insects: black soldier fly, housefly and yellow mealworm (*Hermetia illucens*, *Musca domestica* and *Tenebrio molitor*); and aquatic future foods: the cyanobacteria spirulina (*Arthrospira platensis*), the microalgae chlorella (*Chlorella vulgaris*), one brown seaweed (*Saccharina latissima*), and blue mussels (*Mytilus spp.*).

Five traditional plant species considered as important sources of proteins in current diets were selected and included in the analysis to put the nutritional and environmental impacts of future foods in perspective. The selection of these species was based on different criteria: common beans for being the pulse with the highest production volume, wheat, rice and maize for being the crops that supply the highest amounts of plant protein globally, and soybean for its high protein content (see Supplementary Methods SI.1).

The selection of terrestrial ASF was based on the most consumed animal products on a global scale: beef, pork, chicken, eggs and milk (see Supplementary Methods SI.1). For aquatic ASF, we selected tilapia (*Oreochromis niloticus*), which is the farmed fish produced in the largest volumes and for which LCA data is available, and skipjack tuna (*Katsuwonus pelamis*), which is the wild caught fish species with the highest volume used for direct human consumption for which LCA data is available[58].

Nutritional composition

The nutritional composition of all future foods, except for mussels, was obtained from the available literature (Supplementary Table 1). For blue mussels we used the USDA nutrient database[59]. As the nutritional composition of cultured meat is unavailable, we assumed that cultured meat had the same nutritional content as beef, chicken and pork, and only used these data for the environmental impact section. This assumption is justified because various cultured meat developers across the world are currently investing in the culturing of cells of cattle, pigs and poultry[60] and because cultured meat can be tailored as it is possible to decide the quality and quantity of fat and micronutrients. However, it is important to highlight that certain nutrients present in conventional meats which are synthetized by gut microorganisms (e.g., vitamin B12, omega 3 fatty acids)[61,62] are likely to be absent in cultured meat unless supplemented. For PSF, seafood and terrestrial ASF, the nutritional composition was obtained from the USDA nutrient database[59] (see Supplementary Table 2 for NBD numbers). The nutrient content of all foods corresponds to the edible portion of raw samples.

As the nutritional contribution of ASF such as beef, pork and chicken varies between different parts of the animal (e.g. ham, shoulder, loin, etc.), the following equation was applied to calculate the average nutritional content per kg of product:

$$T = \sum_i \mathrm{n}_i * \mathrm{P}_i$$

where T is a specific nutrient content for a whole animal, n_i is the concentration of a nutrient in part i (*e.g.* wing, breaks, leg, etc.), P_i is the proportion of part i in the total edible weight of the animal (see Supplementary Table 3 for values) and $\sum_i \mathrm{P}_i = 1$

Per study and per food, we expressed the concentration of each nutrient in 100 g of dry matter product and subsequently, we expressed the nutrient content present in 1 g of dry matter protein of each food. This enabled us to compare how much of other macro- and micronutrients are supplied when each food is used as a protein source. We calculated the mean and the standard error of the mean per nutrient and per food, based on the total number of nutritional values collected (Supplementary Tables 1 and 5).

Environmental impact

We used 27 Life Cycle Assessment (LCA) studies to calculate the environmental impact of all future foods. We included two environmental impact categories for which quantitative data was available and for the attention paid to these two impacts in the discussion on livestock production and the environment: climate change expressed in kg CO_2e and land use (LU) expressed in m^2 per year. To make the multiple studies comparable under a same functional unit, the results of the LCA studies were first recalculated to express the environmental impacts per kg of product on a dry matter basis, with a system boundary from cradle-to-factory gate (see Supplementary Table 7). To avoid the influence of any methodological effect (e.g., different types of allocation used in different studies) in our analysis and conclusions, we tried to minimise the impact of allocation. For future foods, no allocation between final co-products was needed as the production of future food does not result in multiple outputs. Insects, for example, can be consumed as a whole, while grains need to be processed and therefore yield multiple outputs (e.g. flour and wheat middling). During the production of future foods, inputs are used. When possible, we used data that allocated 100% of the impact from feed production to the main feed product, thus considering possible other products (i.e. straw) as by-products. Such data were available in the study from Tuomisto & De Matos (2011). Some studies used allocation of environmental impacts of specific inputs (i.e. feed ingredients); these data were used as such without recalculation. Assumptions for all LCA studies can be found in the Supplementary Methods (SI.2). The recalculated units per kg of dry matter product can be found in the Supplementary Table 7.

The environmental impacts of animal and plant-source foods were derived from Leip et al. (2014 & 2015)[10,63] and are based on the Common Agricultural Policy Regional Impact Analysis (CAPRI) model. For PSF, allocation was applied for cereals allocating about 3% of the emissions to straw. For ASF, allocation was based on the nitrogen content of the final products. In CAPRI, meat and milk are produced by different activities. Calve-raising and heifers produce the meat; milk cows no longer grow, and emissions are almost fully allocated to milk, except for a small part allocated to calves (meat). The same principle is true for laying hens and fattening chicken. Therefore, the effect of the allocation method related animal products (the end product) is low. For some feeds (cereals, oil cakes), allocation is used; this is similar to the future foods discussed above.

We used the direct and indirect GHG emissions of all European Union countries. GHG emissions of PSF corresponded to direct and indirect N_2O emissions associated with manure and fertilizer application on soils, crop-grazing, crop residues, and indirect N_2O emissions associated with leaching and ammonia volatilization. In addition, we included CO_2 emissions resulting from fertilizer production, seed production, plant protection, use of machinery, and electricity consumption on the farm. Emission estimates of PSF include further emissions from land use (cultivated histosols), but exclude emissions of carbon sequestration in permanent or managed grasslands[64]. For ASF, we accounted for the following emission sources: all those described for PSF for the required feed; N_2O emissions associated with manure management (housing and storage) and land use change for feed production; CH_4 emissions associated with enteric fermentation, manure management, and land use change for feed production; CO_2 emissions associated with feed transport and feed processing; and GHG emissions from land use change for feed production (i.e., carbon losses from above-ground biomass and organic soils). Emissions from feed production are not limited to production within the EU, but emissions from imported feeds are included [64,65].

The impacts of ASF were transformed from 1 kg of fresh carcass weight to 1 kg of dry matter edible product using the conversion factors listed in Supplementary Table 6. The impacts of

PSF were transformed to 1 kg of dry matter edible product. Supplementary Table 7 shows the re-calculated impacts for both plant and animal-source foods.

The environmental impact of fished Skipjack tuna and farmed Tilapia was obtained from the LCA literature. For assumptions and sources, see Supplementary Methods (SI.4).

Using equations 2 and 3, we calculated the environmental impact of each food source for a given nutrient:

$$A_{s,n} = \frac{B_n \, x \, 100}{C_{s,n}} \quad (2)$$

$$Y_{n,i} = \frac{A_{s,n} \, x \, E_{s,i}}{1000} \quad (3)$$

where $A_{s,n}$ is the amount (in grams) of a food source *s* needed to satisfy the daily requirement for nutrient *n*, B_n is the daily requirement for nutrient *n* and $C_{s,n}$ is concentration of nutrient *n* in 100 g dry matter of a food. With the value of $A_{s,n}$, equation 3 was used to calculate $Y_{n,i}$, the environmental impact *i* of a food to satisfy the daily requirement of nutrient n, where $A_{s,n}$ is the amount of a source needed to satisfy the daily requirement for nutrient *n* and $E_{s,i}$ is the environmental impact for the different impact categories *i* (greenhouse gas emissions and land use) for 1 kg of dry matter of a protein source *s*.

$A_{s,n}$ and $Y_{n,i}$ were calculated for all the values reported in the literature. Thus, if two studies found different calcium and protein content for the same food, we calculated the $A_{s,n}$ for each study. If a study did not report the protein content, we used an averaged protein content based on other studies. Subsequently, the $Y_{n,i}$ was calculated for all the land use and GHG emissions reported in the literature and then summarised by the mean and the standard error of the mean per food and nutrient (for values see Supplementary Table 8).

The daily requirements were obtained from the Nutrient Reference Values-Requirements (NRVs-R) given by the Codex Alimentarius for labelling purposes[66] (See Supplementary Table 4 for specific values). As the Codex Alimentarius does not include the daily requirements of omega-3 fatty acids, we used a value of 250 mg for eicosapentaenoic acid (EPA) plus docosahexaenoic acid (DHA) for adults, indicated by the European Food Safety Authority as an adequate intake of these nutrients[67].

Data availability

The data supporting the findings of this study are available in this paper and its supplementary information files.

Code availability

Custom R scripts developed for the analyses and visualisations in this manuscript are available from the authors on request.

References

1. Van Huis, A. *et al. Edible insects. Future prospects for food and feed security*. (FAO, 2013). doi:10.1017/CBO9781107415324.004

2. Post, M. J. Cultured beef: medical technology to produce food. *J. Sci. Food Agric.* **94,** 1039–1041 (2014).

3. Wells, M. L. *et al.* Algae as nutritional and functional food sources: revisiting our understanding. *J. Appl. Phycol.* **29,** 949–982 (2016).

4. FAO. FAOSTAT. (2017). Available at: http://www.fao.org/faostat/. (Accessed: 1st July 2018)

5. Van Zanten, H. H. E. *et al.* Defining a land boundary for sustainable livestock consumption. *Glob. Chang. Biol.* **24,** 4185–4194 (2018).

6. Herrero, M. *et al.* Farming and the geography of nutrient production for human use: a transdisciplinary analysis. *Lancet Planet. Heal.* **1,** 33–42 (2017).

7. Wang, X. *et al.* Red and processed meat consumption and mortality: dose–response meta-analysis of prospective cohort studies. *Public Health Nutr.* **19,** 893–905 (2016).

8. Sun, Q. *et al.* Red Meat Consumption and Mortality. *Arch. Intern. Med.* **172,** 555 (2012).

9. Gerber, P. *et al. Tackling Climate Change Through Livestock. A global assessment of emissions and mitigation opportunities*. (FAO, 2013).

10. Leip, A. *et al.* Impacts of European livestock production: nitrogen, sulphur, phosphorus and greenhouse gas emissions, land-use, water eutrophication and biodiversity. *Environ. Res. Lett.* **10,** 115004 (2015).

11. Mottet, A. *et al.* Livestock: On our plates or eating at our table? A new analysis of the feed/food debate. *Glob. Food Sec.* **9,** 1–8 (2017).

12. Alexandratos, N. & Bruinsma, J. *World agriculture towards 2030/2050: The 2012 revision.* (FAO, 2012).

13. Alexander, P. *et al.* Could consumption of insects, cultured meat or imitation meat reduce global agricultural land use? *Glob. Food Sec.* **15,** 22–32 (2017).

14. Low, J. W. *et al.* A Food-Based Approach Introducing Orange-Fleshed Sweet Potatoes Increased Vitamin A Intake and Serum Retinol Concentrations in Young Children in Rural Mozambique. *J. Nutr.* **137,** 1320–1327 (2007).

15. Pawlak, R., Lester, S. E. & Babatunde, T. The prevalence of cobalamin deficiency among vegetarians assessed by serum vitamin B12: a review of literature. *Eur. J. Clin. Nutr.* **68,** 541–548 (2014).

16. Gladyshev, M. I., Sushchik, N. N. & Makhutova, O. N. Production of EPA and DHA in aquatic ecosystems and their transfer to the land. *Prostaglandins Other Lipid Mediat.* **107,** 117–126 (2013).

17. Kainz, M., Arts, M. T. & Mazumder, A. Essential fatty acids in the planktonic food

web and their ecological role for higher trophic levels. *Limnol. Oceanogr.* **49,** 1784–1793 (2004).

18. Hixson, S. M. *et al.* Long-Chain Omega-3 Polyunsaturated Fatty Acids Have Developmental Effects on the Crop Pest, the Cabbage White Butterfly Pieris rapae. *PLoS One* **11,** e0152264 (2016).

19. Liland, N. S. *et al.* Modulation of nutrient composition of black soldier fly (Hermetia illucens) larvae by feeding seaweed-enriched media. *PLoS One* **12,** e0183188 (2017).

20. Hussein, M. *et al.* Sustainable production of housefly (Musca domestica) larvae as a protein-rich feed ingredient by utilizing cattle manure. *PLoS One* **12,** 1–19 (2017).

21. Heck, V., Hoff, H., Wirsenius, S., Meyer, C. & Kreft, H. Land use options for staying within the Planetary Boundaries – Synergies and trade-offs between global and local sustainability goals. *Glob. Environ. Chang.* **49,** 73–84 (2018).

22. Tuomisto, H. L. & Texteira de Mattos, M. Environmental Impacts of Cultured Meat Production. *Environ. Sci. Technol* **45,** 6117–6123 (2011).

23. Tuomisto, H. L., Ellis, M. J. & Haastrup, P. *Environmental impacts of cultured meat : alternative production scenarios*. *Proceedings of the 9th International Conference on Life Cycle Assessment in the Agri-Food Sector (LCA Food 2014). 1360-1366.* (2014).

24. Van Zanten, H. H. E. *et al.* From environmental nuisance to environmental opportunity: Housefly larvae convert waste to livestock feed. *J. Clean. Prod.* **102,** 362–369 (2014).

25. Salomone, R. *et al.* Environmental impact of food waste bioconversion by insects: Application of Life Cycle Assessment to process using Hermetia illucens. *J. Clean. Prod.* **140,** 890–905 (2017).

26. Aubin, J., Fontaine, C., Callier, M. & Roque d'orbcastel, E. Blue mussel (Mytilus edulis) bouchot culture in Mont-St Michel Bay: potential mitigation effects on climate change and eutrophication. *Int. J. Life Cycle Assess.* **23,** 1030–1041 (2018).

27. Hasselström, L., Visch, W., Gröndahl, F., Nylund, G. M. & Pavia, H. The impact of seaweed cultivation on ecosystem services - a case study from the west coast of Sweden. *Mar. Pollut. Bull.* **133,** 53–64 (2018).

28. Lhafi, S. K. & Kühneb, M. Occurrence of Vibrio spp. in blue mussels (Mytilus edulis) from the German Wadden Sea. *Int. J. Food Microbiol.* **116,** 297–300 (2007).

29. Ziegler, F. *et al.* Expanding the concept of sustainable seafood using Life Cycle Assessment. *Fish Fish.* **17,** 1073–1093 (2016).

30. Henriksson, P. J. G., Belton, B., Jahan, K. M.-E.- & Rico, A. Measuring the potential for sustainable intensification of aquaculture in Bangladesh using life cycle assessment. *Proc. Natl. Acad. Sci. U. S. A.* **115,** 2958–2963 (2018).

31. Wiebe, M. G. QuornTM Myco-protein - Overview of a successful fungal product. *Mycologist* **18,** 17–20 (2004).

32. Smetana, S., Palanisamy, M., Mathys, A. & Heinz, V. Sustainability of insect use for

feed and food: Life Cycle Assessment perspective. *J. Clean. Prod.* **137,** 741–751 (2016).

33. Oonincx, D. G. A. B. *et al.* An exploration on greenhouse gas and ammonia production by insect species suitable for animal or human consumption. *PLoS One* **5,** e14445 (2010).

34. Ray, N. E., O'Meara, T., Wiliamson, T., Izursa, J.-L. & Kangas, P. C. Consideration of carbon dioxide release during shell production in LCA of bivalves. *Int. J. Life Cycle Assess.* **23,** 1042–1048 (2018).

35. Ramos-Elorduy, J. Insects: A sustainable source of food? *Ecol. Food Nutr.* **36,** 247–276 (1997).

36. Yang, Q. *et al.* Nutritional composition and protein quality of the edible beetle Holotrichia parallela. *J. Insect Sci.* **14,** 139 (2014).

37. Marono, S. *et al.* Crude Protein Digestibility of Tenebrio Molitor and Hermetia Illucens Insect Meals and its Correlation with Chemical Composition Traits. *Ital. J. Anim. Sci.* **14,** 3889 (2015).

38. Latunde-Dada, G. O., Yang, W. & Aviles, M. V. In Vitro Iron Availability from Insects and Sirloin Beef. *Agric. Food Chemestry* **66,** 8420–8424 (2016).

39. Fleurence, J. in *Proteins in Food Processing* 197–213 (Woodhead Publishing, 2004). doi:10.1533/9781855738379.1.197

40. Edwards, D. G. & Cummings, J. H. The protein quality of mycoprotein. *Proc. Nutr. Soc.* **69,** (2010).

41. Mišurcová, L., Kráčmar, S., Klekdus, B. & Vacek, J. Nitrogen Content, Dietary Fiber, and Digestibility in Algal Food Products. *Czech J. Food Sci* **28,** 27–35 (2010).

42. Maehre, H. K., Edvinsen, G. K., Eilertsen, K. E. & Elvevoll, E. O. Heat treatment increases the protein bioaccessibility in the red seaweed dulse (Palmaria palmata), but not in the brown seaweed winged kelp (Alaria esculenta). *J. Appl. Phycol.* **28,** 581–590 (2016).

43. Kose, A., Ozen, M. O., Elibol, M. & Oncel, S. S. Investigation of in vitro digestibility of dietary microalga Chlorella vulgaris and cyanobacterium Spirulina platensis as a nutritional supplement. *3 Biotech* **7,** 170 (2017).

44. Selmi, C. *et al.* The effects of Spirulina on anemia and immune function in senior citizens. *Cell. Mol. Immunol.* **8,** 248–54 (2011).

45. Nakano, S., Takekoshi, H. & Nakano, M. Chlorella pyrenoidosa Supplementation Reduces the Risk of Anemia, Proteinuria and Edema in Pregnant Women. *Plant Foods Hum. Nutr.* **65,** 25–30 (2010).

46. Li, L. *et al.* Spirulina can increase total-body vitamin A stores of Chinese school-age children as determined by a paired isotope dilution technique. *J. Nutr. Sci.* **1,** e19 (2012).

47. Watanabe, F. & Bito, T. Vitamin B 12 sources and microbial interaction. *Exp. Biol.*

Med. **243,** 148–158 (2018).

48. Watanabe, F. *et al.* Pseudovitamin B(12) is the predominant cobamide of an algal health food, spirulina tablets. *J. Agric. Food Chem.* **47,** 4736–41 (1999).

49. Broekman, H. C. H. P. *et al.* Is mealworm or shrimp allergy indicative for food allergy to insects? *Mol. Nutr. Food Res.* **61,** 1–9 (2017).

50. Lüning, K. & Mortensen, L. European aquaculture of sugar kelp (Saccharina latissima) for food industries: iodine content and epiphytic animals as major problems. *Bot. Mar.* **58,** 449–455 (2015).

51. Maehre, H. K., Edvinsen, G. K., Eilertsen, K.-E. & Elvevoll, E. O. Heat treatment increases the protein bioaccessibility in the red seaweed dulse (Palmaria palmata), but not in the brown seaweed winged kelp (Alaria esculenta). *J. Appl. Phycol.* **28,** 581–590 (2016).

52. Ursu, A.-V. *et al.* Extraction, fractionation and functional properties of proteins from the microalgae Chlorella vulgaris. *Bioresour. Technol.* **157,** 134–139 (2014).

53. Bußler, S., Rumpold, B. A., Jander, E., Rawel, H. M. & Schlüter, O. K. Recovery and techno-functionality of flours and proteins from two edible insect species: Meal worm (Tenebrio molitor) and black soldier fly (Hermetia illucens) larvae. *Heliyon* **2,** e00218 (2016).

54. Oonincx, D. G. A. B. & De Boer, I. J. M. Environmental Impact of the Production of Mealworms as a Protein Source for Humans - A Life Cycle Assessment. *PLoS One* **7,** e51145 (2012).

55. Oonincx, D. G. A. B., Van Broekhoven, S., Van Huis, A. & Van Loon, J. J. A. Feed conversion, survival and development, and composition of four insect species on diets composed of food by-products. *PLoS One* **10,** 1–20 (2015).

56. Van Zanten, H. H. E., Mollenhorst, H., Bikker, P., Herrero, M. & De Boer, I. J. M. The role of livestock in a sustainable diet: a land-use perspective. *Animal* **10,** 547–549 (2016).

57. Post, M. J. Cultured meat from stem cells: Challenges and prospects. *Meat Sci.* **92,** 297–301 (2012).

58. FAO. *The state of world fisheries and aquaculture 2016. Contributing to food security and nutrition for all.* (FAO, 2016).

59. USDA. USDA National Nutrient Database. (2017). Available at: https://ndb.nal.usda.gov/ndb/. (Accessed: 4th February 2017)

60. Post, M. J. Proteins in cultured beef. *Proteins Food Process.* 289–298 (2018).

61. Moll, R. & Davis, B. Iron, vitamin B12 and folate. *Medicine (Baltimore).* **45,** 198–203 (2017).

62. Jenkins, T. C., Wallace, R. J., Moate, P. J. & Mosley, E. E. BOARD-INVITED REVIEW: Recent advances in biohydrogenation of unsaturated fatty acids within the rumen microbial ecosystem1. *J. Anim. Sci.* **86,** 397–412 (2008).

63. Leip, A., Weiss, F., Lesschen, J. P. & Westhoek, H. The nitrogen footprint of food products in the European Union. *J. Agric. Sci.* **152,** 20–33 (2014).

64. Weiss, F. & Leip, A. Greenhouse gas emissions from the EU livestock sector: A life cycle assessment carried out with the CAPRI model. *Agric. Ecosyst. Environ.* **149,** 124–134 (2012).

65. Leip, A. *et al.* Evaluation of the livestock sector's contribution to the EU greenhouse gas emissions (GGELS) - final report. 323 (2010).

66. FAO & WHO. *Codex Alimentarius. Guidelines on nutrition labelling. Codex Alimentarius.* (1985).

67. EFSA. Scientific opinion on dietary reference values for fats, including saturated fatty acids, polyunsaturated fatty acids, monounsaturated fatty acids, trans fatty acids, and cholesterol. European Food Safety Authority. *EFSA J.* **8,** 1461 (2010).

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Author contributions

A.L. and H.V.Z. designed the research. A.P. and H.V.Z. conceived and led the project, reviewed the literature, analysed the data, and wrote the paper. The following authors analysed the data and edited the paper: A.L., I.D.B., C.V.M., M.H. and H.V. on environmental impacts, P.M.S. on microalgae, F.Z. on seafood, E.H.M.T. on nutrition, H.T. on cultured meat and J.V.L. on insects.

Competing interests

The authors declare no competing interests.

Materials and Correspondence

Correspondence to H.H.E. Van Zanten.