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Incorporation of novel foods in European diets can reduce global warming potential, water and land use by over 80%

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Abstract

Global food systems face the challenge of providing healthy and adequate nutrition through sustainable means, which is exacerbated by climate change and increasing protein demand by the world's growing population. Recent advances in novel food production technologies demonstrate potential solutions for improving the sustainability of food systems. Yet, diet level comparisons are heretofore lacking and are needed to fully understand the environmental impacts of incorporating novel foods in diets. Here we estimate the potential of reducing global warming potential, water use, and land use by replacing animal source foods with novel or plant-based foods in European diets. Using a linear programming model, we optimized omnivore, vegan, and novel food diets for minimum environmental impacts with nutrition and feasible consumption constraints. Replacing animal source foods in current diets with novel foods reduced all environmental impacts by over 80% and still met nutrition and feasible consumption constraints.

Burgeoning food demand from growing and urbanizing populations, paralleled with increases in consumption of animal source foods (ASF), drive an ever-larger pressure from food systems on the environment [1,2]. While causing one third of anthropogenic greenhouse gas emissions (GHGEs) globally [3], agriculture is also the leading contributor of the earth system surpassing planetary boundaries in biodiversity loss and nutrient flows [2]. Concurrently, the double burden of malnutrition, associated with poor/insufficient diets, further indicates food systems are failing to meet health needs [4]. Such recent research has catalyzed broad conclusions which urgently compel changes toward sustainable diets [5–7].

Many products, here termed 'novel/future foods' (NFFs), have the potential to reduce environmental impacts of diets while meeting essential nutritional needs in broader populations [8]. Novel foods are those produced from new production technologies or are under novel regulatory frameworks such as cell-culturing technologies—cultured meat, eggs, milk, plants, algae, bacteria, and fungi [9]. Future foods are those for which our production capacity has potential to scale up and/or increase in consumption due to emerging climate change mitigation concerns such as insects and spirulina; some foods may overlap in both novel/future categories such as mussels (*Mytilus* spp.) or chlorella (*Chlorella vulgaris*) produced with novel technologies [8]. Such NFFs may provide nutritious alternatives to ASF while meeting multiple sustainability goals [8,9]. Compared to currently available plant-based protein-rich (PBPR) options like legumes, pulses, and grains, NFFs can have a more complete array of essential nutrients such as protein, calcium, vitamin B-12, and omega-3 long-chain polyunsaturated fatty acids and are more land- and water-efficient than current ASF [8]. Additionally, alternative fortified food products can be developed but the taste/texture of meat is a key driver in the development of cultured meat in particular [10]. In this paper, we combine novel and future foods into a selection of NFFs for which data on environmental impacts is available [8].

Studies on alternative dietary pattern scenarios (e.g., vegetarian, vegan, or flexitarian) [11–13] or currently consumed dietary patterns (e.g., Mediterranean, New Nordic Diets) [14–16] confirm that large shifts from current diets towards more plant-based diets are needed. Vegan and flexitarian or partially omnivore diets, mainly reducing meat consumption, will be important diet shifts for synergistic benefits to health and environmental outcomes [17,18]. However, due to less favorable profiles in terms of some nutrients in plant-based options such as pulses and grains, diet level comparisons with omnivore and plant-based diets are also needed to investigate the feasibility of including NFFs in future diets to meet nutritional needs with lower impacts. Additionally, studies comparing multiple environmental impacts of diets including NFFs are lacking, and a broadened understanding of the NFFs which best balance the trade-offs in impacts and nutrition can inform the development of sustainable options for future diets and recommendations [18,19].

Here, we estimate the prospect of reducing global warming potential (GWP), scarcity-weighted water use (WU), and land use (LU) of current European diets (CD). More specifically, we optimized the average European diet according to three diet types, which varied based on their inclusion of ASF, PBPR alternatives, and NFFs. All NFF, omnivore (OMN) and vegan (VEG) diets were optimized to meet nutritional adequacy and feasible consumption constraints.

1 Results

1.1 Current Average and Optimized Diets

Some food groups were consistently decreased in the optimized diets, irrespective of minimized objective function—notably, all beverages, dairy, meats, fish/seafood, animal fats, starchy roots/tubers, and spices/condiments (Table 1). Large increases in (fortified) liquid PBPR alternatives were needed to meet calcium and vitamin D requirements in all modeled diets except the VEG minimum GWP. PBPR alternatives in the optimized diets increased many times over their intake as compared to the CD (Supplementary Figure 1). Similarly, increases in other PBPR and vegetables were common among all optimized diets, with the exception of legumes in the NFF minimum LU diet.

Certain food groups, however, had different directions and magnitudes of change depending on which impact was minimized when compared to the current diet. Groups such as grains, eggs, fruit, snacks, sugar, and plant-fats showed different magnitudes and direction of change depending on minimized impact. For example, grains decreased in OMN and NFF minimized LU diets but increased in the VEG minimum LU diet as well as in all minimized GWP and WU diets. Plant fats decreased in all minimized WU diets and increased in all minimum GWP and LU diets. Eggs were also included in the OMN minimum GWP diet. Liquid plant-based alternatives were not included in the VEG minimum GWP diet, but instead were replaced by grains, fruits, and plant-fats. In the NFF minimum LU diet, NFFs increased with corresponding reductions legumes/nuts and grains.

1.2 Novel/Future Foods Selected

In the NFF optimizations, different NFFs were selected for each minimized environmental impact. The primarily selected NFFs in the initial optimization—not the sensitivity analyses—were cultured milk, with intake of 45-155 g/day depending on minimized impact, and insect meal (34-113 g/day). The third most selected NFF differed by minimized objective function: microbial protein (0.02 g/day) was selected in the NFF minimum GWP diet, cultured meat was selected in the minimum WU diet (0.10 g/day), and mycoprotein in the minimum LU diet (29 g/day) (see optimized results by product, group and diet type in Supplementary data).

1.3 Optimized Diets – Environmental impacts

Error! Reference source not found. In comparison with CD, optimized OMN and VEG diets reduced GWP, WU, and LU by 81-84% (Table 2). NFF diets reduced GWP by 83%, WU by 85%, and LU by 87% compared to CD. NFF diets had 4-34% fewer overall impacts than the OMN and VEG optimized diets; there was one exception, the VEG diet minimized for GWP had 8% less impact than the NFF diet minimized for GWP (see impact ranges by food group in Supplementary Figure 2).

Meats comprised most (>50%) of the GWP and LU in the CD and they shared a large portion of the WU impacts with the 'Other' group, which is comprised of sugars, all beverages (except liquid dairy and plant-based dairy alternatives), spices/condiments, and snacks (Figure 1). Not only do the optimized diets have over 80% lower environmental impacts than the CD, but in the optimized diets the majority of the GWP and LU were from the PBPR alternatives (here denoting liquid and solid in meat imitates, tofu, plant-based milks, and legumes/nuts), plant-fats, and other groups. The majority of WU impacts were from fruits, vegetables, and grains in the optimized diets.

The main food groups contributing to macronutrient intake in each optimized diet depended on which environmental impact that was minimized (Supplementary Figure 3). It is important to note for the VEG diet models that we needed to remove the vitamin B12 and D constraints, since no feasible solution was possible with these vitamin requirements. In the future, it is likely that PBPR alternatives and NFF products would be fortified with vitamins B12 and D and other micronutrients and such diets would therefore include B12 and D from other sources.

1.4 Sensitivity Analyses

In the first sensitivity analysis (NFF.1), we excluded insect meal and cultured milk, as they were the predominantly selected NFFs in the initial optimizations. Once insect meal and cultured milk were excluded, microbial protein was the primarily selected NFF in the minimized LU diet (111 g/day), cultured meat (29 g/day) in the minimum WU diet, and kelp was selected in the minimum GWP diet (17 g/day). Compared to the original NFFs diets, the NFF.1 diets had 6% higher GWP, 16% higher WU, and 18% higher LU, when each was minimized. Yet, all NFF.1 diets had over 82% fewer impacts than the CD. Additionally, even without all NFFs available in the optimizations, these sensitivity analyses show that optimized NFF diets have 82-85% fewer impacts than CD (unoptimized), regardless of which environmental impact is minimized.

The final two sensitivity analyses focused on ASF requirements for the OMN models and allowing for NFF and ASF in the same optimization. Since the initial optimized OMN diets became essentially almost entirely vegan—only including small amounts of dairy, offal, eggs, and animal-fats—we tested how the impacts would change if the models required no more than a ±80% change in current intake of all ASF. Meaning, the sensitivity OMN.1 model was forced to include at least 20% of the current mean intake of meats, dairy, fish/seafood, animal-fats, and eggs (Supplementary Figure 4). The OMN.1 optimization included the minimum allowable amount of all ASF, except eggs in minimum GWP and LU and dairy in minimum WU diets, with greater impacts than the initial (almost vegan) OMN models, 42% higher GWP, 23% higher WU impacts, and 41% higher LU. Yet, in comparison with the current diet, there were still large reductions in impacts: 70% lower GWP, 79% lower WU, and 68% lower LU.

Lastly, the OMN-NFF model examined what the optimization would select if allowed to include both ASFs and NFFs. The OMN-NFF diets were subject to the original nutrition and feasible consumption constraints on intake of all food items, including between the 5th and 95th percentile of all ASFs (Figure 2). All OMN-NFF diets had less impacts than current diets (>83% for all categories) and the OMN.1 diet (28-62%). Additionally, the OMN-NFF diets had slightly less impacts than the original OMN diets (where NFFs were not allowed), with 4% less GWP, 7% less WU, and 37% less LU when each was minimized, respectively. These results indicated that the inclusion of small amounts of ASFs could lower the impacts of diets which also include NFFs while meeting nutritional needs. In the minimum GWP OMN-NFF diet, all ASF were removed, and insect meal, microbial protein, and cultured milk were the selected NFFs. When minimizing WU, the OMN-NFF diet included small amounts of meat offal, cream, cheese, and mixed fats whilst also including a variety of NFFs—cultured meat, microbial protein, insect meal, and cultured milk. In the minimum LU OMN-NFF diet, cream and mixed fats are the only ASF selected, and NFFs selected included insect meal, microbial protein, cultured milk, mycoprotein, and kelp. See full sensitivity analysis results in Supplementary data.

2 Discussion

This study identified diets that greatly reduce environmental impacts compared to current diets in Europe and include NFFs as replacement for ASF. [17,20]As we minimized diets for environmental impacts and assumed large changes were needed from current diets, our models therefore achieve higher relative impact reductions than other comparable optimizations [18]. Yet, in agreement with previous studies, our models show similar reductions in overall environmental impact of optimized diets when compared to CDs [17,19]. [2122]Our models tended to have lower GWP impacts than reviews of optimized diets indicate (measured in GHGEs) [23]. For example, many studies find on average 30-50% reduction in GWP of their optimized diets compared to baseline diets, but theoretical maximum decreases of 70% [12] to 78% [18]. Our diet models (from 1.00-1.14 kg CO_2/day) are similar to such theoretical European diets minimized for GWP at 0.95 kg CO_2 eq./day [18]. Such optimistically lower environmental impacts in our models are likely due to our wider consumption constraints and inclusion of a variety of novel products.

Allowing for ASF to be replaced by NFFs resulted in notably lower impacts. Similar reductions across impacts are possible when ASF are replaced by PBPR alternatives and plant fats. This is where our models differ from most diet optimization studies; our greater than 5th percentile per food item constraint allowed most ASF to be essentially eliminated from an omnivore diet whereas in other studies, the common objective function is to minimize the difference from currently consumed diets [19,23]. Yet, even in our sensitivity analyses, where we forced the optimization to retain at least 20% of the mass of each ASF item, the OMN diets show between 83-88% lower impacts than current diets. Meats account for a large portion of the impacts of current diets [7,24]. Even when allowed, livestock products are consistently reduced and often eliminated from optimized diets [23], meaning conventional ASF are less environmentally efficient even when nutritional content is considered. Reductions in meats in particular are responsible for around 60% lower environmental impact in optimized diets [25]. Our findings suggest that diets could be more land, water, and carbon efficient if people would be amenable to more abstemious consumption. The findings also indicate that by adjusting current diets and/or including NFFs and even small amounts of selected ASFs, it is possible to reduce environmental impacts to similar levels as optimized vegan diets. The selection of mainly insect meal, cultured milk, microbial protein, and mycoprotein by the optimization indicates these products have the best balance of trade-offs among nutritional content and lowest environmental impact given current data. However, only a few NFFs were selected, and indeed the selection of relatively few types of products in all models may indicate the overspecialization common in linear programming which limits investigation of interdependent variables and the need for diversity in the diet [7].

Since we optimized separately for three different environmental impacts, the question that remains is which of the diets should be followed. There were trade-offs and synergies among the diets optimized for different environmental impacts. Synergistically, large increases in legumes (especially in the WU diets) and vegetables (especially in the LU diets) and large decreases in all ASF and starchy roots/tubers were consistent despite minimized impact or diet type. Some food groups depict environmental impact trade-offs as they may have more efficient resource use in one category than others; for example, grains were reduced in the WU diets but increased in the GWP and LU diets. As with other models, we found that the diets tended to be similar in which foods were included, the relative amounts in each food group, and that most if not all ASFs are excluded even with the inclusion of NFFs or PBPR foods, which suggests synergies among minimized impacts rather than tradeoffs [22,23].

Given the significant role of ASFs cross-culturally and myriad other functions of livestock in food systems, diets completely devoid of ASF, such as those following our optimizations, may be difficult to realistically adopt at a large scale [24,26]. Additionally, concurrent reductions in micronutrients need to be managed through protein source replacement with nutritious options and carefully designed fortification and supplementation policies [27]. Indeed, even if optimization models yield encouraging results for replacing conventional ASFs with NFFs, the nuances of feasible consumption must be considered, driven by motives of taste/health, familiarity/attitudes, food neophobia/disgust, and social norms [10]. Although it varies among countries, acceptance of PBPR alternatives is greater than that of cultured meat and insects [10], with perceived naturalness and familiarity being main concerns in Europe [29]. Yet, acceptance of NFFs can increase with positive information highlighting environmental, health (e.g., micronutrient supplementation, antioxidant/anti-inflammatory properties), and animal-welfare benefits, though is still dependent in large part on taste and price [28,30]. Some claim that NFFs provide additional possibilities for 'dietary resilience' in the face of uncertain future climate change due to their prospect to provide essential nutrition through unforeseen disturbances [28].

This study is limited by the sparse availability of LCA data on NFFs, and these products constitute the limits of current data availability. We therefore recommend future research to expand the impact assessment for a full understanding of the environmental, socio-cultural, and health implications when including NFFs in whole diets. Future studies should assess the capacity for producing these NFFs for entire populations, in Europe or at individual country levels. Further assessment of the food security and socio-cultural aspects of affordability, availability, and cultural acceptability in future diets scenarios including NFFs is needed. Indeed, the affordability and viability of certain NFFs such as cultured meat are prerequisites to inclusion in future diets [9]. We also acknowledge that myriad other actions, which were not a focus of this paper, such as a combination of policy changes, education initiatives, sustainable production methods, closures of yield gaps, and waste reduction, will also be required for more sustainable future food systems. Our study is the first of its kind to assess the inclusion and impacts of NFFs in whole diets instead of assessing these products individually. The findings of this study demonstrate that including NFFs in whole diets and replacing conventional ASF with PBPR and NFF alternatives has the potential to reduce GWP, WU, and LU by more than 80%.

Hence, this study adds to the growing body of literature which confirms diet shifts towards the increased use of PBPR foods and investments into the development, production, and strategies for adoption of NFFs have great potential to reduce environmental impacts while providing nutritious options. NFFs may provide options for diversifying diets but require other, intermediate means for promotion and consumption, such as education on the similarity with familiar foods, market accessibility through lower prices for consumers, and incentivizing procurement for institutional and corporate food businesses. Given complexities and acknowledgement that there is no such thing as a panacea, action is needed on all fronts to move towards such diets and sustainable future food systems.

3 Materials and Methods

3.1 Product Database

3.1.1 Current Diets

We followed the methods from Gazan et al.'s (2018) "SustTable Database" to compile a database for optimization of diets using multiple sustainability metrics for foods [31]. We obtained food consumption data on average (chronic) intake of food items in g/capita/day for the year 2013 from the European Food Safety Authority (EFSA) Comprehensive European Food Consumption Database compiled from 34 national food consumption surveys (n = 66,492 individuals) in 22 EU countries [32]. We selected the food products at FoodEx Level 2 except where more detail was needed (here, only liquid PBPR alternatives and grains). FoodEx aggregates quantities (in grams) of food items into 4 levels: Grains and grain-based products (Level 1), Grain milling products (level 2), Wheat milling products (level 3), and Wheat flour, Durum (level 4). Selected food items totaled 124 individual food products, aggregated into 18 food groups. We moved items such as butter and mixed fats to their own 'Animal Fats' group, and fine pastry wares (e.g., cookies) from 'Grains' to 'Snacks'. 'Meats', here a subcategory of ASF (which also included fish/seafood, dairy, animal-fats, and eggs) denoted terrestrial animal flesh in whole or processed products such as beef, chicken, pork, meat offal, and meat pastries. Though meats do have varying impacts by type of product, our categorization is for setting constraints and understanding the role of ASF in overall diets. Mussels (*Mytilus* spp.), fish, and crustaceans are included in the Fish/Seafood food group. See all products, food groups, and data in Supplementary data.

We linked each of the 124 individual food items from EFSA FoodEx Level 2 to data on product nutrient composition in the US Department of Agriculture (USDA) FoodData Central, chosen for its comprehensive inclusion of macro- and micronutrients and amino acids [33,34]. Iodine and omega-3 long chain polyunsaturated fatty acid data were not available[33,34]. When matching EFSA data to USDA FoodData, we selected PBPR food alternatives, including tofu and plant-based milk-replacements, which are typically fortified in some European countries with vitamins D, B2, and B12 and/or calcium. We focused on the European population, assuming healthy adults who are active and get most (if not all) of their nutrition from foods with no vitamin supplementation. The exception was vitamin D; we assumed that in addition to an intake of about 5 micrograms per day from food, vitamin D supplementation is needed to ensure adequate status. See Supplementary Table 1 for full list of fortified foods and their added vitamins and minerals.

The environmental impacts of the foods were based on life cycle assessment (LCA) studies [35,36]. Our system boundaries were from cradle to consumer—included cooking at consumer, if necessary. The LCA inventory data for the 124 food items included in current European diets was sourced from the Agribalyse 3.0 LCA Database [37] using the OpenLCA 1.10.3 software [38]. Agribalyse is a multi-indicator French Life Cycle Inventory (LCI) Analysis database with data for over 2500 products produced in France. We assumed the French data reproduces similar relative transportation and production differences across Europe. Agribalyse considers transportation emissions of products imported from outside of Europe. The ReCiPe 2016 Midpoint (H) method [39] was used to calculate the global warming potential and land use, and the AWARE method [40] was used to calculate scarcity-weighted water use of the food items.

We matched the products in the Agribalyse database with the EFSA FoodEx Level 2 coding of the food items.

3.1.2 Novel/Future Foods

We selected nine NFFs to be included in the study because those products have the possibility to be produced in the future at-scale with the nutrient profiles to replace conventional ASF [41]. We also selected NFFs where the data for their production is currently available [8,9]. NFFs included here were cultured meat, ovalbumin, microbial protein (hydrogen oxidizing bacteria), microalgae (*Chlorella vulgaris*), insect meal (*Hermetia illucens*), cultured milk, cloudberry cell culture (*Rubus chamaemorus*), kelp (*Saccharina latissima*), and mycoprotein.

Environmental impact data for the NFFs was obtained from LCAs in recently published (or forthcoming) literature [42–47]. The microbial protein was assumed to contain 5% moisture and 65% protein [42]. The impacts of cell-cultured ovalbumin were given per kg of dried powder with an 8% moisture and 92% protein content [46]. Cultured milk was assumed to consist of 97% of oat milk and 3% of cultured milk protein (casein) by weight. For cultured milk protein, the environmental impacts were based on the same LCA data as what was used for cultured ovalbumin since an LCA study for cultured milk protein indicates that the unallocated impacts are at the same level as cultured ovalbumin [48]; amino acid composition was assumed to be the same as that of liquid milk. Results for microalgae from Smetana et al. (2017) were originally calculated using the IMPACT 2002+ method. We therefore remodeled the product system with the SimaPro 9.1.0.11 PhD software package [49] using the inventory data for the scenario provided. This allowed us to recalculate the environmental impacts using comparable LCA methods, which additionally allowed for the modelling of uncertainties of the system. The environmental impact of cultured meat was calculated per kg of cultured meat with dry matter content of 30% and protein content of 19%. The cultured meat scenario used the same LCA methods as above [47]. Cloudberry cell culture LCA data used best-case scenario energy data and assumed dried product with 5% moisture and 19% protein content [45]. Impacts of mycoprotein is from aggregated reports of LCA at Swedish consumer [50]. Dried kelp, or sea belt, LCA impacts were calculated with the same methods from the Agribalyse database. Electricity consumption for all products was modelled using the French electricity mix in the life cycle inventory while the French non-irrigation characterization factor was used to assess the impact of water use. Since we were modeling European diets, we tested the sensitivity of the model to the use of French electricity data. We ran the same NFF optimizations with electricity from Europe (without Switzerland) and found that the use of the French data was a valid assumption. There was $< \pm 0.5\%$ difference in all of the overall diet impacts and only slight changes to the amounts but not to the types of NFFs selected (see Sensitivity Analyses).

Direct matching of LCA methods was not possible in some cases because material provided in publications and by author correspondence was not sufficient for calculating the impacts with the same methods. For the insect meal, we used Smetana et al.'s (2019) *Hermetia illucens* insect biomass attributional LCA with IMPACT 2002+ method [51] mean data only [35].

We added aspects of the life cycle not considered in the original LCAs of the NFFs to match the system boundaries—cradle to consumer—for the conventional, current diet products; these additional steps included transportation, packaging, and retail impacts. For protein powder products, we added the required steps similar to those of dried nuts, for cultured milk we used the inputs of liquid milk, and for cultured meat those of minced meat. We obtained nutrition composition data of items or closely matching items to the NFFs from the (USDA) FoodData Central or from published studies (see Supplementary Table 2 for data sources on nutrition and Supplementary data for environmental impact calculations).

3.2 Diet Optimization

3.2.1 Linear Programming

We applied a linear programming optimization method using the lpSolve package in R version 4.1.0 [17,18]. Optimization problems map a search space of decision variables into a solution space yielding optimized levels given the objective function [52]. Our objective function was to find diets which minimized three environmental impacts for three different diet types: omnivore *optional* diets (OMN), vegan diets (VEG), and novel/future foods (NFF) diets. We optimized the three diets by minimizing for each of three separate impacts: GWP (kg CO_2 eq.), WU (m^3), and LU (m^2 arable land eq.), resulting in nine optimized diets, plus three more diets resulting from sensitivity analyses. Each diet was constrained to fulfill nutritional requirements and feasible consumption constraints (see section 3.2.3 and Supplementary Table 3 for full list of constraints in each diet model). The three main diet models were differentiated by their excluded food groups: OMN diets excluded only NFFs, VEG diets excluded all ASFs and NFFs, and NFF diets excluded only ASFs. Further, we estimated the environmental impacts of the current European diet for comparison with the optimized diets.

3.2.2 Nutrition constraints

We set optimization constraints for the diets to meet daily reference values of macro/micronutrients for EFSA/Nordic Nutrition Recommendations (NNR) adult diets with the same energy intake as the current European diet (2481 kcal/day) [33,53]. We used only the constraints provided by the boundaries of the recommendations. For some nutrients, only one boundary applies; for example, an upper and lower boundary on total polyunsaturated fatty acids but only an upper limit on total saturated fatty acids. Essential amino acid requirements were from UN FAO/WHO (2007)[54] amino acid requirements for an adult, reference weight 70 kg from EFSA [55]. See Supplementary Table 3 for all nutrition constraints.

3.2.3 Feasible consumption constraints

We set optimization constraints for individual products to remain within the 5th-95th percentile of mass per product in current diet consumption to ensure model diets stayed within feasible consumption limits. Following the methods of previous optimizations [12] and conclusions of the EAT-Lancet Report [7], we assumed that large shifts in diets will be needed, likely beyond what currently would be considered culturally acceptable. For the NFF and VEG diets, we set the animal source food groups—meats, seafood, dairy, eggs, animal fats—equal to zero. Since most of the NFFs are not currently consumed, there is no consumption data, their cultural acceptability is not yet well understood, and we instead included feasible consumption constraints. We set feasible consumption constraints on the NFFs products based on replacement of designated proxies for ASF (see calculations in Supplementary data). The NFFs, hypothesized to replace the ASF, were given allowed intake constraints calculated to provide the same percentage of protein from proxy ASFs—liquid milk for cultured milk, meats for cultured meats, etc. NFF constraints were set from 0 g/day to the current mean protein intake of the proxy product plus 0.5 standard deviation. Noted exceptions were microalgae, kelp, and plant cell culture, known to have specific upper limits on safe daily intake [56–58]. Further, since vegan diets in Europe significantly differ from non-vegetarian/omnivore diets, we also used proxy items as the feasible consumption constraints for individual PBPR alternatives—cheese for tofu, dairy for milk replacements, etc. [59]. Additionally, since current liquid plant-based alternatives are the main PBPR alternatives that are fortified with vitamin D, vitamin B12, vitamin B2, and calcium, increases were expected in the optimized diets. Therefore, a group constraint was implemented for liquid PBPR alternatives to remain within realistic intake at mean plus 0.5 standard deviation of current dairy milk consumption (≤297 g/day). To maintain realistic food group intakes for recommended dietary diversity and daily consumption of a variety of fruits and vegetables, we set food group constraints for fruits and vegetables based on the recommendations of the 'planetary health diet' from the EAT-Lancet Report, ≥200 g/day for vegetables, and ≥100 g/day for fruits [7]. We set the total intake of alcoholic beverages ≤20 g/day [55].

3.2.4 Uncertainty Analyses

We conducted an uncertainty analysis using Monte Carlo with 100 iterations per product when we ran the ReCiPe Midpoint(H)/AWARE LCA impact methods [60]. We ran the linear optimization on each product with 100 Monte Carlo (MC) iterations per impact, yielding the mean and standard deviation of impact calculated by food product of all optimized diets. Due to negative WU values for some products, we used only the mean water scarcity value resulting from the MC iterations for all the NFFs. The cause of negative values resulting from MC runs is more thoroughly discussed elsewhere [42,61], so we decided to use the baseline results of the LCA for each optimization.

3.2.5 Sensitivity Analyses

We ran three different sensitivity analyses to estimate how sensitive our models were to individual changes in the data and constraints. Once we modeled the (initial) optimized NFF diets, in the first sensitivity analysis (NFF.1), we removed the NFFs which were selected in the highest amount in the model—here, insect meal and cultured milk. We then compared the difference in environmental impacts between this sensitivity analysis optimizations and the initial NFF optimization, where all NFFs were allowed.

To understand how requiring the model to include some ASF in OMN diets would affect the environmental impacts, we optimized an OMN diet (OMN.1) with limits on ±80% of the current mean intake (g/day) of ASF—meats, dairy, eggs, fish/seafood, animal-fats. Several previous diet models indicate large reductions (≥80%) in ASF are required for minimized environmental impact [23,62]. Finally, to understand how NFFs may or may not be privileged over ASF in the model, we ran a last sensitivity analysis which allowed both ASF and NFF (OMN-NFF), subject to the original nutrition constraints and feasible consumption constraints on the intake of all food items. All NFFs and PBRP alternatives were allowed, and ASF were allowed to vary from the 5th-95th percentile of their intake per item in the CD.

3.3 Data Availability

All data generated or analyzed during this study are included in this published article (and in the Supplementary Information and Supplementary data files) or available at the public Git Repository: https://version.helsinki.fi/rachel.mazac/NFFs-repo.git.

3.4 Code Availability

The code generated during and used during the current study are available in R and are available at the public Git Repository: https://version.helsinki.fi/rachel.mazac/NFFs-repo.git.

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Author Contributions

Rachel Mazac: Conceptualization, Formal analysis, Investigation, Project administration, Visualization, Writing - original draft. **Jelena Meinilä**: Data curation, Validation, Writing - review & editing. **Liisa Korkalo**: Data curation, Validation, Writing - review & editing. **Natasha Järviö**: Data curation, Validation, Writing - review & editing. **Mika Jalava**: Methodology, Writing - review & editing. **Hanna L. Tuomisto**: Conceptualization, Funding acquisition, Supervision, Writing - review & editing.

Conflicts of Interest

Liisa Korkalo was a board member of the company TwoDads at the time of this work. The authors declare no conflict of interest in the funding, process, or publication of this work.

Tables

Table 1. Composition of food groups in optimized diets. *Mass (in average g/day) of food group intake by diet type (current European average diet (CD), and optimized omnivore (OMN), vegan (VEG), and novel/future foods (NFF) diets) as minimized for Global Warming Potential (Min GWP), scarcity weighted water use (Min WU), and land use (Min LU) while respecting the nutritional and feasible intake constraints. No shading: decreased from CD, dark grey shading: increased from CD.*

	CD	OMN			VEG			NFF		
		Min GWP	Min LU	Min WU	Min GWP	Min LU	Min WU	Min GWP	Min LU	Min WU
Alcoholic Beverages	163	0.30	9	7	0.30	20	20	0	4	19
Animal-Fats	10	0	1	0	0	0	0	0	0	0
Dairy	263	0.01	45	90	0	0	0	0	0	0
Eggs	13	29	4	0	0	0	0	0	0	0
Fish/Seafood	26	1	2	0	0	0	0	0	0	0
Fruits	147	100	100	106	158	100	106	100	151	106
Grains	198	329	164	467	366	231	467	323	113	421
Juice	108	55	97	0	95	42	0	61	100	0
Legumes/Nuts	19	35	39	65	35	39	66	35	2	67
Liquid Plant-based Alt.	1	297	297	297	0	35	297	297	297	297
Meats	125	0	0	0.29	0	0	0	0	0	0
Non-Alcoholic Beverages	1089	544	544	544	543	543	543	543	543	544
Novel-Foods	0	0	0	0	0	0	0	89	317	243
Plant-based Alt.	1	133	196	195	86	87	196	109	58	125
Plant-Fats	18	57	48	0	59	63	13	55	30	11
Snacks	64	22	121	25	25	142	25	13	121	25
Spices/Condiments	25	19	12	13	19	12	10	16	11	11
Starchy/Tubers	98	0.34	7	1	2	7.93	4	1	7	1
Sugar	27	33	5	0	2	0.28	0	42	18	0
Vegetables	131	200	470	200	200	481	200	200	448	200

Table 2. Diet environmental impacts and optimization constraints. *Total environmental impact (mean ± SD) calculated for optimized omnivore (OMN), vegan (VEG) and Novel and Future Foods (NFF) diets per day by minimum objective function and not optimized current diet (CD) for comparison. Uncertainty shown in ± SD calculated from 100 optimizations with 100 Monte Carlo iterations for each product in the diets. Optimization constraints for each diet by feasible consumption, nutrition, and*

restricted food groups; more details on the constraint values in Supplementary Table 3. Novel/Future Foods (NFFs), Global Warming Potential (GWP).

	Current Diet (CD)	Omnivore Diet (OMN)	Vegan Diet (VEG)	NFFs Diet (NFF)
Environmental Impacts				
GWP (kg CO_2 eq.)	6.61	1.14 ± 0.03	1.00 ± 0.02	1.09 ± 0.03
Scarcity-weighted water use (m^3)	7.46	1.22 ± 0.03	1.26 ± 0.03	1.15 ± 0.03
Land Use (m^2a eq.)	5.95	1.13 ± 0.02	1.13 ± 0.02	0.75 ± 0.02
Optimization Constraints				
Feasible Consumption	-	All food products within 5^{th}-95^{th} percentile current diet consumption, Vegetables ≥200g/day, Fruits ≥100 g/day, Liquid Plant-based Alternatives ≤297 g/day, Alcoholic beverages ≤20 g/day, water = mean of CD		
Nutrition	-	Daily intake on: kcal, fat, carbohydrates, protein, fiber, calcium, iron, potassium, manganese, magnesium, sodium, phosphorus, selenium, zinc, folate, niacin, riboflavin, thiamin, essential amino acids, and vitamins A, C, D*, B12*, B6, E, and K		
Food Groups Excluded	-	NFFs	Meats, Dairy, Eggs, Fish/Seafood, Animal-Fats, NFFs	Meats, Dairy, Eggs, Fish/Seafood, Animal-Fats

*Vitamins D and B12 not included in vegan nutrition constraints.

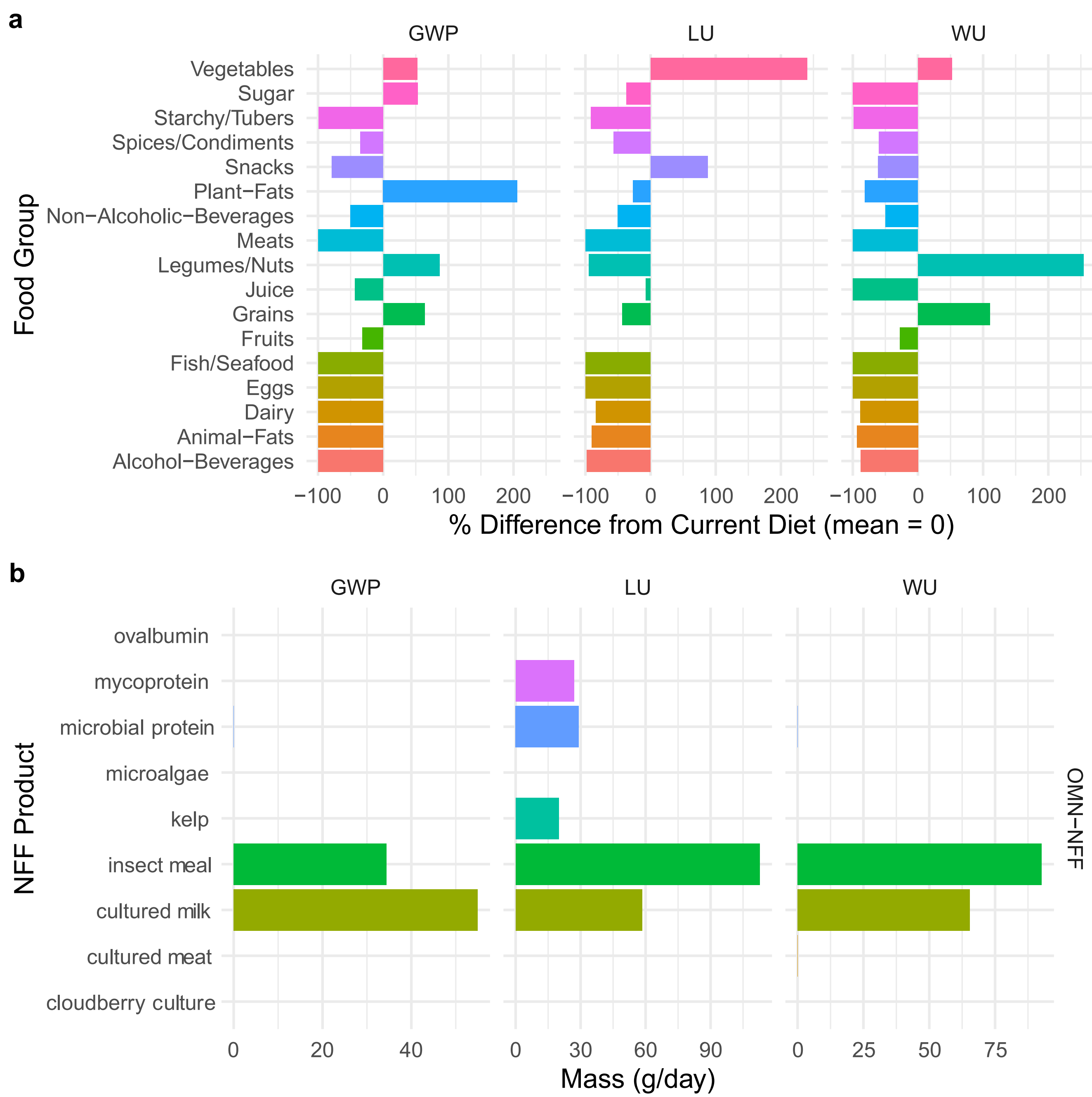
Figure Legends

Figure 1. Environmental impact by food group in diets. *Contribution of different food groups to the global warming potential (GWP), land use (LU), and water use (WU) of the current diet (CD) (top) and optimized diets (bottom) with all nutrition and*

feasible consumption constraints; omnivore (OMN), vegan (VEG), and novel/future foods (NFFs) diets; 'Other'—Snacks, Sugars, Juice, Non-alcoholic Beverages, Alcoholic Beverages, and Spice/Condiments).

Figure 2. Sensitivity analyses: *a) percent change by food group from the current diet in optimized sensitivity analysis omnivore and Novel/Future Foods diets (OMN-NFF) with all nutrition and feasible consumption constraints, all novel/future foods (NFFs) and animal-source foods (ASF) allowed, minimized for global warming potential (GWP), land use (LU), and water use (WU); b) Total mass (average g/day) of NFFs selected in the optimization with all NFFs and ASF available by impact minimized on the*

right: water use (WU), land use (LU), and global warming potential (GWP); NOTE: Plant-based alternatives are removed since they are increased over 1000% from current diet intakes.



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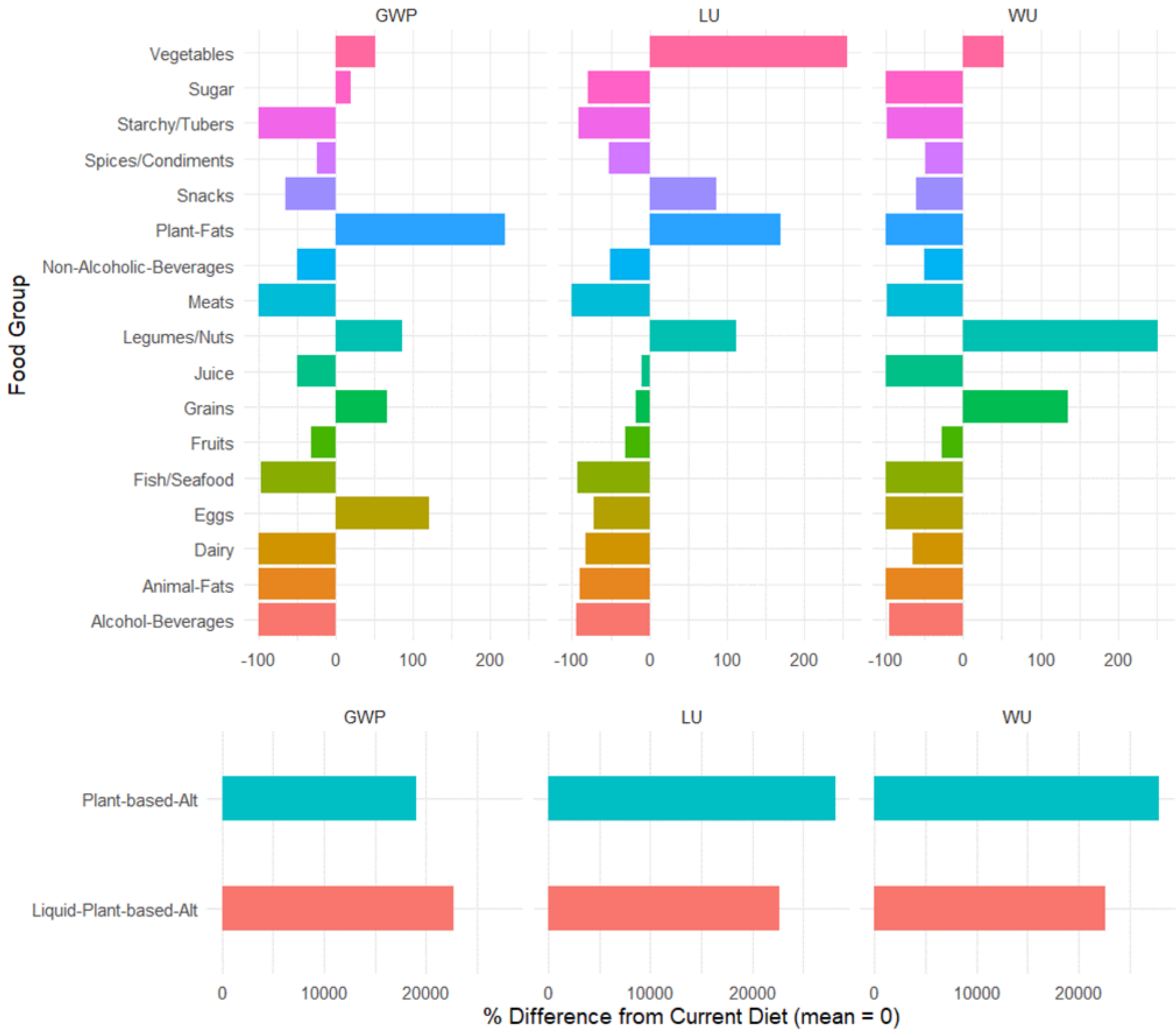
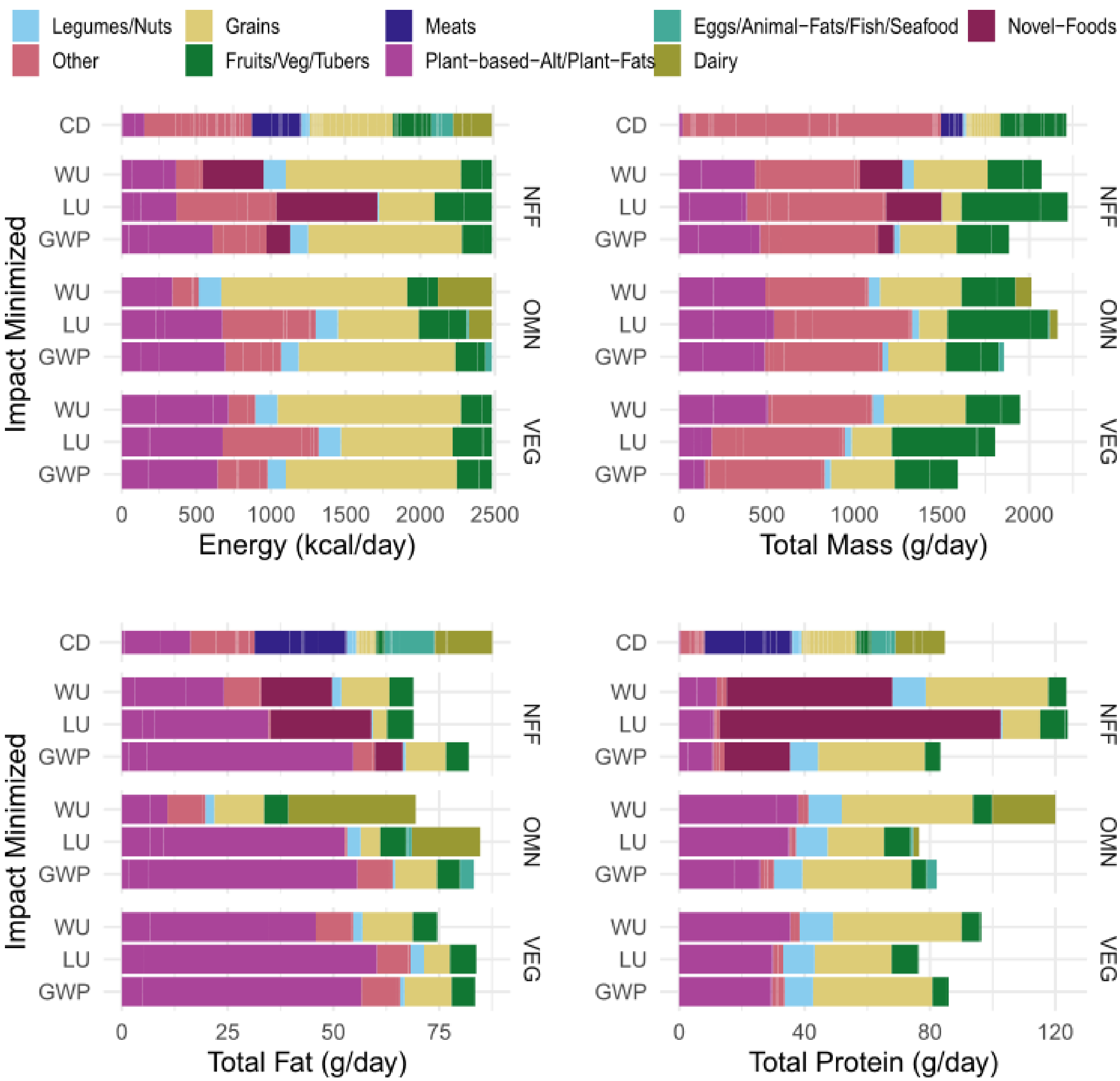
Supplementary Information

Supplementary Figure 3. Percent change of the optimized amounts of each food group. *Omnivore (OMN) diet percent change by food group from current European diet (mean intake = 0) by impact minimized--Global Warming Potential (GWP), Land Use (LU, and scarcity-weighted water use (WU)--while meeting all nutrition and feasible consumption constraints; note: plant-based alternatives are increased large percentages over the intake in current diets and are shown below in a separate panel: liquids include oat, soy, rice, and almond milk, and solids are tofu and plant-based meat imitates.*

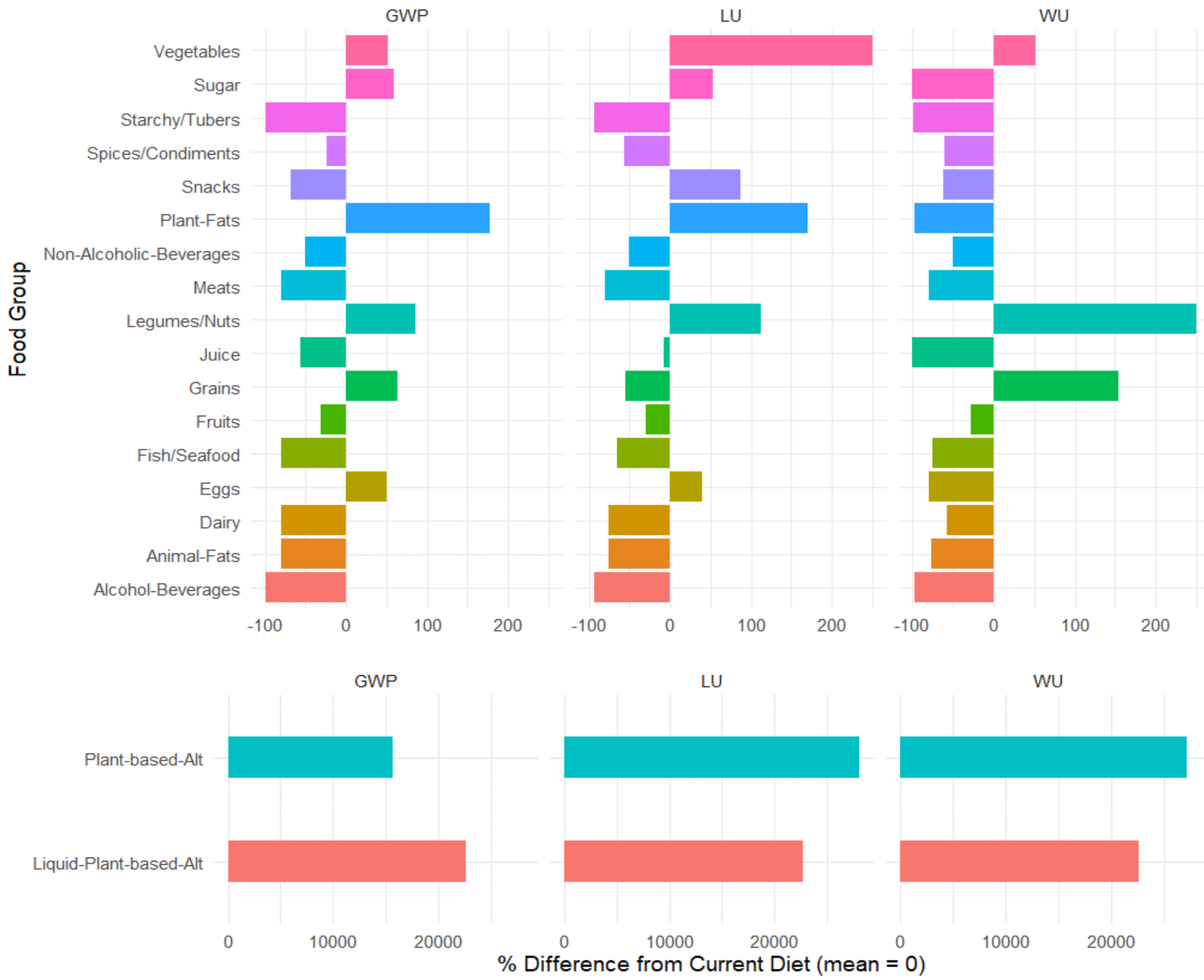


Supplementary Figure 4. Uncertainty analysis impact range by food group. *Mean and quartiles of minimized total impact for optimized—including nutritional and cultural constraints listed—omnivore (OMN), vegan (VEG), and Novel/Future Food (NFF)* *diets separated by food group; column 1: minimized GWP (kg CO_2 eq.), column 2: minimized Land Use (m_2a eq.), and column 3: minimized Scarcity-weighted water use (m^3).*

Supplementary Figure 5. Nutrient composition of diets. *Macronutrients (protein and fat in g/day and energy in kcal/day) and mass (average g/day) of the current diet (CD) and the optimized diets based on minimized objective function with nutritional and feasible consumption constraints. OMN: omnivore diets, NFF: novel/future foods diets, VEG: vegan diets. The "Other" food group here includes Snacks, Sugars, Juice, Non-alcoholic Beverages, Alcoholic Beverages, and Spice/Condiments. Diet type minimized: Global Warming Potential (GWP), land use (LU), scarcity-weighted water use (WU).*



Supplementary Figure 6. Sensitivity analysis OMN.1. *Percent change by food group from the current diet in optimized sensitivity analysis omnivore diet (OMN.1) with all nutrition and feasible consumption constraints and ±80% of the current mean intake of animal source foods required, minimized for global warming potential (GWP), land use (LU), and water use (WU).*



Supplementary Table 3. Fortified products. *List of fortified and non-fortified foods in the product database; 0 indicates the product is not fortified with the specified nutrient, X indicates the product is fortified with the specified nutrient.*

		Fortification																			
Product	USDA description	Ca	Vit D	Vit B-12	Fe	K	Mn	Mg	Na	P	Se	Zn	folate	niacin	riboflavin	thiamin	Vit A	Vit C	Vit B6	Vit E	Vit K
Liquid milk	Milk, nonfat, fluid, without added vitamin A and vitamin D (fat free or skim)	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Concentrated milk	Milk, canned, evaporated, without added vitamin D and vitamin A	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Fermented milk products	Average yogurt, fruit, vanilla, plain without added vitamin D	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Milk derivatives	Milk, dry, whole, without added vitamin D	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Almond drink	Beverages, almond milk, unsweetened, shelf stable, with added calcium, vitamins B-12 and D	X	X	X	-	-	-	-	-	-	-	-	-	-	X	-	-	-	-	-	-

	and without added vitamin A																				
Imitation cream	Soymilk, original and vanilla, with added calcium, vitamins B-12 and D and without added vitamin A	X	X	X	-	-	-	-	-	-	-	-	-	-	X	-	-	-	-	-	-
Oats drink	Beverages, almond milk, unsweetened, shelf stable, with added calcium, vitamins B-12 and D and without added vitamin A	X	X	X	-	-	-	-	-	-	-	-	-	-	X	-	-	-	-	-	-
Rice drink	Beverages, almond milk, unsweetened, shelf stable, with added calcium, vitamins B-12 and D and without added vitamin A	X	X	X	-	-	-	-	-	-	-	-	-	-	X	-	-	-	-	-	-
Soya drink	Soymilk, original and vanilla, with added calcium, vitamins B-12 and D, and without added vitamin A	X	X	X	-	-	-	-	-	-	-	-	-	-	X	-	-	-	-	-	-

Soya yoghurt	Soymilk, original and vanilla, with added calcium, vitamins B-12 and D, and without added vitamin A	X	X	X	-	-	-	-	-	-	-	-	-	-	X	-	-	-	-	-	-
Tofu	Tofu, raw, firm, prepared with calcium sulfate	X	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Mixed fruit and vegetable juice	Beverages, vegetable and fruit juice blend, 100% juice, with added vitamins A, C, E	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	X	X	-	X	-

Supplementary Table 4. Data sources for environment and nutrition data of the novel/future foods.

	Environmental Impact Data	*Nutritional Composition*
Cultured Meat	Low energy scenario (Tuomisto et al., forthcoming)	Ground beef, 100% lean [1]
Cell Cultured Ovalbumin	Tr_OVA [2]	Dried egg white powder [1]
Microbial Protein	Solein produced by autotrophic hydrogen-oxidizing bacteria [3]	Solein powder [4]
Microalgae (Chlorella vulgaris)	*Chlorella* in heterotrophic fermenter [5]	*Chlorella vulgaris* powder [1,6]
Insect meal (Hermetia illucens)	*H. illucens* meal [7]	Fly/cricket meal [7–10]
Cultured Milk	97% oat drink [11], 3% ovalbumin powder [12]	Liquid Milk [1]
Cloudberry Cell Culture (Rubus chamaemorus)	Best case energy use [13]	Cloudberry, dry mass [14,15]
Mycoprotein	LCA at Swedish consumer [16]	Mycoproteins [17], Quorn [18]
Kelp (Saccharina latissima)	Sea belt (*S. latissima*), dried or dehydrated [11]	Seaweed, Canadian Cultivated EMI-TSUNOMATA, dry [1]

Supplementary Table 5. Optimization Constraints. *Constraints used in optimizations with filters (group, product, or nutrient variable), direction of boundary (sign), the value, and comment explaining the constraint and source. Diet types are identified by their monikers (OMN-omnivore, VEG-vegan, NFF-novel/future foods) and include the 'switch' for the constraint (X is present in optimization) when optimizing each diet. Sensitivity analyses constraints are included at the bottom. ASF - Meats| Fish/Seafood |Dairy |Eggs |Animal-Fats. OMN - Omnivore optimized diet, VEG - Vegan optimized diet, NFF - Novel/Future Foods optimized diet, AI - Adequate Intake, AR - Average Requirement, PRIs - Population Reference Intake, RI - Reference Intake Range, EFSA - European Food Safety Administration, NNR - Nordic Nutrition Recommendations, EAT - EAT-Lancet Report*[19].

Group, product, or nutrient variable	*Sign*	*Value*	*Details*	*OMN*	*VEG*	*NFF*	*NFF.1*	*OMN.1*	*OMN-NFF*
NOT Novel-Foods	>=	5th %	all prods >= 5th percentile mass, not NFFs	X	X	-	-	-	-
NOT Novel-Foods	<=	95th %	all prods <= 95th percentile mass, not NFFs	X	X	-	-	-	-
NOT ASF	>=	5th %	all prods >= 5th percentile mass, not animal-based foods	-	X	X	X	-	-
NOT ASF	<=	95th %	all prods <= 95th percentile mass, not animal-based foods	-	X	X	X	-	-
ASF	=	0	all animal-based products = 0	-	X	X	X	-	-
Novel-Foods	=	0	novel foods = 0	X	X	-	-	X	-
Vegetables	>=	200	Vegetables >= 200 g/day, EAT	X	X	X	X	X	X
Fruits	>=	100	Fruits >= 100 g/day, EAT	X	X	X	X	X	X
Liquid-Plant-based-Alt	<=	297.09	Liquid Plant Based Alternatives group total <= 297.09 g/day from mean+0.5 SD of liquid dairy milk intake	X	X	X	X	X	X
Alcohol-Beverages	<=	20	Alcohol-Beverages group total <= 20 g/day, EFSA	X	X	X	X	X	X
water	=	mean	water intake = mean current diet intake (g/day)	X	X	X	X	X	X
kcal	=	2481	Current diet mean energy intake, kcal	X	X	X	X	X	X
Total fat	>=	69	Adults, NNR, >18 yrs., 25-40 E% of current diet (2481 kcal), ~9 kcal/g fat, RI	X	X	X	X	X	X

Total fat	<=	110	Adults, NNR, >18 yrs., 25-40 E%of current diet (2481kcal), ~9 kcal/g fat, RI	X	X	X	X	X	X
carbs	>=	279	Adults, EFSA, >18 yrs., 45-60 E% of current diet (2481 kcal), 4 kcal/g carbs, RI	X	X	X	X	X	X
carbs	<=	372	Adults, EFSA, >18 yrs., 45-60 E% of current diet (2481 kcal), 4 kcal/g carbs, RI	X	X	X	X	X	X
protein	>=	62	Adults, protein, NNR 10-20 E% of current diet (2481 kcal), ~4kcal/g, RI	X	X	X	X	X	X
protein	<=	124	Adults, protein, NNR 10-20 E% of current diet (2481 kcal), ~4kcal/g, RI	X	X	X	X	X	X
Total fiber	>=	25	Female, EFSA, >18 yrs, g/day, AI	X	X	X	X	X	X
calcium.mg	>=	750	Female, EFSA, >25 yrs., mg/day, AR	X	X	X	X	X	X
iron.mg	>=	7	Female, EFSA, >18 yrs., mg/day, AR	X	X	X	X	X	X
potassium.mg	>=	3500	Female, EFSA, >18 yrs., mg/day, AI	X	X	X	X	X	X
manganese.mg	>=	3	Female, EFSA, >18 yrs., mg/day, AI	X	X	X	X	X	X
magnesium.mg	>=	300	Female, EFSA, >18 yrs., mg/day, AI	X	X	X	X	X	X
sodium.mg	<=	2400	Female, up Sodium, NNR, mg/day, AI	X	X	X	X	X	X
phosphorus.mg	>=	550	Female, EFSA, >18 yrs., mg/day, AI	X	X	X	X	X	X
selenium.ug	>=	70	Female, EFSA, >18 yrs., µg/day, AI	X	X	X	X	X	X
zinc.mg	>=	9.3	Male, EFSA, >18, 600 mg/d of phylate intake, mg/day, AR	X	X	X	X	X	X
folate.ug	>=	250	Female, EFSA, >18 yrs., µg/day, AR	X	X	X	X	X	X
niacin.mg	>=	2.3	Female, EFSA, >18 yrs., mg/day, AR	X	X	X	X	X	X
riboflavin.mg	>=	1.3	Female, EFSA, >18 yrs., mg/day, AR	X	X	X	X	X	X
thiamin.mg	>=	0.072	Female, EFSA, >18 yrs., mg/day, AR	X	X	X	X	X	X
vitA.ug	>=	570	Male, EFSA, >18 yrs., µg/day, AR	X	X	X	X	X	X
vitB12.ug	>=	4	Female, EFSA, >18 yrs., µg/day, AR	X	-	X	X	X	X
vitC.mg	>=	90	Male, EFSA, >18 yrs., mg/day, AR	X	X	X	X	X	X
Fatty acids total polyunsaturated	>=	14	Female/Male, polyunsat fatty acids, NNR 5-10 E% of current diet (2481 kcal), ~9kcal/g, RI	X	X	X	X	X	X

Fatty acids total polyunsaturated	<=	28	Female/Male, polyunsat fatty acids, NNR 5-10 E% of current diet (2481 kcal), ~9kcal/g, RI	X	X	X	X	X	X
vitB6.mg	>=	1.5	Male, EFSA, >18 yrs., mg/day, AR	X	X	X	X	X	X
vitD.ug	>=	5	Male, EFSA, >18 yrs., µg/day, reduced and supplements assumed	X	-	X	X	X	X
vitE.mg	>=	11	Female, EFSA, >18 yrs., mg/day, AI	X	X	X	X	X	X
vitK.ug	>=	70	Male, EFSA, >18 yrs., µg/day, AI	X	X	X	X	X	X
Fatty acids total monounsaturated	<=	115	Female, EFSA, >18yrs., g/day, AI	X	X	X	X	X	X
Fatty acids total saturated	<=	28	Female/Male, NNR, < 10% E of current diet (2481 kcal), ~9 kcal/g, RI	X	X	X	X	X	X
lysine	>=	2.1	Lysine (g/day), 30 mg/kg/day, FAO/WHO, EFSA adult ref. wt. 70 kg	X	X	X	X	X	X
leucine	>=	2.73	Leucine (g/day), 39 mg/kg/day, FAO/WHO, EFSA adult ref. wt. 70 kg	X	X	X	X	X	X
isoleucine	>=	1.4	Isoleucine (g/day), 20 mg/kg/day, FAO/WHO, EFSA adult ref. wt. 70 kg	X	X	X	X	X	X
valine	>=	1.82	Valine (g/day), 26 mg/kg/day, FAO/WHO, EFSA adult ref. wt. 70 kg	X	X	X	X	X	X
threonine	>=	1.05	Threonine (g/day), 15 mg/kg/day, FAO/WHO, EFSA adult ref. wt. 70 kg	X	X	X	X	X	X
phenylalanine	>=	1.75	Phenylalanine [or Tyrosine] (g/day), 25 mg/kg/day, FAO/WHO, EFSA adult ref. wt. 70 kg	X	X	X	X	X	X
tryptophan	>=	0.28	Tryptophan (g/day), 4 mg/kg/day, FAO/WHO, EFSA adult ref. wt. 70 kg	X	X	X	X	X	X
methionine	>=	0.728	Methionine (g/day), 10.4 mg/kg/day, FAO/WHO, EFSA adult ref. wt. 70 kg	X	X	X	X	X	X
cystine	>=	0.287	Cysteine (g/day), 4.1 mg/kg/day, FAO/WHO, EFSA adult ref. wt. 70 kg	X	X	X	X	X	X
histidine	>=	0.7	Histidine (g/day), 10 mg/kg/day, FAO/WHO, EFSA adult ref. wt. 70 kg	X	X	X	X	X	X

Cultured milk	=	0	SENSITIVITY ANALYSIS NFF.1: cultured milk = 0	-	-	-	X	-	-
Insect meal	=	0	SENSITIVITY ANALYSIS NFF.1: insect meal = 0	-	-	-	X	-	-
NOT ASF	>=	5^{th} %	SENSITIVITY ANALYSIS OMN.1: all prods >= 5th percentile mass, not animal-based foods	-	-	-	-	X	-
NOT ASF	<=	95^{th} %	SENSITIVITY ANALYSIS OMN.1: all prods <= 95th percentile mass, not animal-based foods	-	-	-	-	X	-
ASF	>=	Mean	SENSITIVITY ANALYSIS OMN.1: all animal-based products (except Animal Fats) <= 80% mean intake per product	-	-	-	-	X	-
ASF	<=	Mean	SENSITIVITY ANALYSIS OMN.1: all animal-based products (except Animal Fats) <= 80% mean intake per product	-	-	-	-	X	-
all products	>=	5^{th} %	SENSITIVITY ANALYSIS OMN-NFF: NFFs and ASFs allowed, all foods >= 5th percentile consumed	-	-	-	-	-	X
all products	<=	95^{th} %	SENSITIVITY ANALYSIS OMN-NFF: NFFs and ASFs allowed, all foods remain <= 95th percentile consumed	-	-	-	-	-	X

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