Future-proof and sustainable healthy diets based on current eating patterns in the Netherlands

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ABSTRACT

Background: To keep global warming <1.5°C as recommended by the Intergovernmental Panel on Climate Change (IPCC), eating patterns must change. However, future diets should be modeled at a national level and respect cultural acceptability.

Objectives: We aimed to identify diets among Dutch adults satisfying nutritional and selected environmental requirements while deviating minimally from the baseline diet among Dutch adults.

Methods: We calculated per capita food system greenhouse gas emission (GHGE) targets derived from the IPCC 1.5-degree assessment study. Using individual adult dietary intake from the National Food Consumption Survey in the Netherlands (2007–2010) to form a baseline, we used quadratic optimization to generate diets that followed the baseline Dutch diet as closely as possible, while satisfying nutritional goals and remaining below GHGE targets. We considered 12 scenarios in which we varied GHGE targets [2050: 1.11 kg of carbon dioxide equivalent (kg CO_2-eq) per person per day (pppd); 2030: 2.04 kg CO_2-eq pppd; less strict 2030: 2.5 kg CO_2-eq pppd; no target], modeled eating patterns (food-based dietary guidelines; flexitarian; pescatarian; lacto-ovo-vegetarian; vegan), and conducted exploratory analyses (food diversity; acceptability; food chain interdependency).

Results: Optimized solutions for 2030 required major decreases (<33% of baseline values) in consumption of beef, pork, cheese, snacks, and butter and increased consumption (>150% of baseline values) of legumes, fish and shellfish, peanuts, tree nuts, vegetables, soy foods, and soy drink. Eight food groups were within 33%–150% of the baseline diet among Dutch adults. The optimized solution complying to the lowest GHGE target (2050) lacked food diversity, and the (lacto-ovo) vegetarian and vegan optimized diets were prone to nutritional inadequacies.

Conclusions: Within Dutch eating habits, satisfying optimization constraints required a shift away from beef, cheese, butter, and snacks toward plant-based foods and fish and shellfish, questioning acceptability. Satisfying 2050 food system GHGE targets will require research in consumer preferences and breakthrough innovations in food production and processing. *Am J Clin Nutr* 2020;112:1338–1347.

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Introduction

Food systems are important contributors to global greenhouse gas emissions (GHGEs), as well as to land occupation and degradation, biodiversity loss, nutrient flow disruption, freshwater depletion, and depletion of fossil fuels (1, 2). To meet the 2030 and 2050 GHGE targets of the Paris Agreement or the Intergovernmental Panel on Climate Change (IPCC) report (3), transitions are needed in food systems and diets.

A global reference diet that considers the health and environmental sustainability aspects of eating patterns was recently published in the EAT–*Lancet* report (4). The authors call for country-specific analyses, using individual consumption data if possible, while staying in line with their proposed global reference diet. Recent publications have attempted to define this at a national level. An example is the Swiss scenario which showed that achieving a sustainable diet would entail a greatly

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Supplemental Tables 1–8 and Supplemental Methods are available from the "Supplementary data" link in the online posting of the article and from the same link in the online table of contents at https://academic.oup.com/ajcn/.

Data described in the article, code book, and analytic code will be made available upon request pending [e.g., application and approval, payment, other].

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Abbreviations used: FBDG, food-based dietary guideline; GHGE, greenhouse gas emission; IPCC, Intergovernmental Panel on Climate Change; kg CO_2-eq, kilograms of carbon dioxide equivalent; LCA, life-cycle assessment; pppd, per person per day; PRI, population reference intake.

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reduced intake of meat and vegetable oils, and a moderate reduction in cereals, roots, and fish products, while increasing the intake of legumes, nuts, seeds, fruits, and vegetables (5). Another study used nonlinear optimization to design diets for 152 countries that met cultural, environmental, and dietary constraints (6). However, both studies used aggregated data based on food balance sheets, which leaves room for relatively much uncertainty.

In this study, we aimed to identify diets among Dutch adults that satisfied nutritional requirements and remained below GHGE targets but that deviated only minimally from the baseline diet among Dutch adults. Like previous studies (7, 8), we used quadratic optimization to derive future diets from the baseline food consumption data, which were based on the most recently available national food consumption survey. Novel to this study, we calculated per capita food system GHGE targets for 2030 and 2050 designed to limit the global average temperature rise to 1.5°C. Using projected emission factors and different scenarios, we optimized diets to comply with different sets of constraints. We also studied how food-based dietary guidelines (FBDGs) and eating patterns of flexitarians, pescatarians, (lacto-ovo) vegetarians, and vegans affected the results. Finally, we considered 3 scenarios focusing on food diversity, acceptability, and interdependency between food production chains.

Methods

The model

Future diets that were nutritionally adequate and met food system GHGE targets were generated using a quadratic optimization algorithm are described in detail in the **Supplemental Methods**: optimization algorithm. Solutions were found by minimizing the summation of the quadratic differences in the consumption amounts (g) of each food item, while satisfying specific constraints for each scenario. The results of any optimization satisfied all nutritional requirements and GHGE targets, and minimized deviation from the baseline diet among Dutch adults, according to the metric of the computation algorithm. Computations were implemented using Optimeal® 3.0, a software package developed by Blonk Consultants in cooperation with the Netherlands Nutrition Centre (9).

Baseline diet among Dutch adults

Dietary data were obtained from 2 independent 24-h dietary recalls collected by unannounced phone calls in a 3-y period within the scope of the Dutch National Food Consumption Survey (2007–2010) (10), and processed as in a previous study (7). To gain insight into habitual food consumption, the 24-h dietary recalls were spread among all days of the week and the different seasons (10). More details about the study protocol are presented in the Supplemental Methods: Dutch National Food Consumption Survey Protocol.

First, the original list of 1599 food items matched to the Dutch Food Composition Table (11) was reduced by, among other things, replacing branded food products with their generic counterparts and raw products with their ready-for-consumption versions. Product selection was also guided by the availability of data required for the calculation of GHGEs, coverage within each food group, and the presence of (lacto-ovo) vegetarian alternatives. The reduced list had 207 generic food products, including beverages, covering 77% of consumed weight and 56% of the energy intake across the 3819 participants of the survey (males and females aged 7–69 y).

Second, restricted to the reduced list of 207 products, we modeled a baseline diet using the 2-d average diet of the 699 adults (men and women) aged 31–50 y. Here, we rounded to 0 g the intake of food items representing <1% of the mass intake of a food group. Rounding food items with very small amounts to 0 g produces a modeled baseline diet that is more realistic and meaningful from a 1-wk time frame. Finally, we proportionally adjusted the intake of other food items within each food group to match the observed mean consumed energy intake, covering 100% of the original energy intake of the diet. **Supplemental Table 1** provides a comparison between the modeled diets resulting from the aforementioned process and the Dutch National Food Consumption Survey (10) average diets. The overall nutrient composition of the modeled diets was similar but not identical. We considered, however, that it was similar enough for the analytical purposes of this study.

Further details about the process described above are available in the Supplemental Methods: selection of products for optimization and fine tuning of the baseline diet. **Supplemental Table 2** provides the full list of products. **Supplemental Table 3** shows the detailed composition of the baseline diet among Dutch adults as obtained using these steps.

Nutritional data and requirements

Nutrient composition of foods was primarily obtained from the Dutch Food Composition Table (11), used to register the 24-h recall answers from the Dutch National Food Consumption Survey (2007–2010) (10), whereas amino acid composition was derived from the National Nutrient Database of the USDA (12), using the matching indicated in **Supplemental Table 4**. The combined data set contained data on 61 nutritional properties, including macronutrients, vitamins, minerals, amino acids, and dietary fiber.

Lower limits of nutritional requirements were derived from the Dutch dietary reference values and more specifically population reference intake (PRI). If values for PRI were not available, values for adequate intake were used. Upper limits of requirements were based on values for the tolerable upper intake level (13–21). **Table 1** lists these nutritional requirements.

Environmental impact data and food system GHGE targets

For each food item we used life-cycle assessment (LCA) to calculate GHGEs, fossil energy use, and land occupation (22, 23). We conducted the LCAs as part of a larger research program, for which references are included in **Supplemental Table 5**. The LCAs considered the different countries of origin of crops for the Netherlands, taking account of agricultural activities such as application of fertilizers, and emissions from activities due to transport, processing, packaging, distribution, retail (e.g., lighting and cooling), cooling at home, food preparation, and waste treatment. Wastage was accounted for at all life-cycle stages. All LCAs spanned the full life cycle, from

TABLE 1 Daily energy and nutrient requirements for the Dutch diet, and intake amounts of the baseline diet among Dutch adults and 2030 scenario

Property	Lower limit	Upper limit	Baseline diet among Dutch adults	2030 scenario
Energy, kcal	2125	2375	2420[1]	2375
Protein, g	54.5	140.6	97	89
Fat, g	50	100	96.5	89.5
Saturated fat, g	—	25	33.6[1]	20.3
Polyunsaturated fat, g	—	30	19.5	23.8
Linoleic acid, g	5	—	16.4	19.6
α-Linolenic acid, g	2.5	—	2.25[1]	2.50
Trans fatty acids, g	—	2.5	1.11	0.44
Cholesterol, mg	—	—	219	152
Carbohydrates, g	225	393.8	256	266
Fiber, g	32	—	21.6[1]	32.0
Water, g	2400	3900	3260	3164
Alcohol, g	—	15	11	10
DHA and EPA, mg	200	1000	160[1]	1000
Retinol activity equivalent, μg	740	3000	751	1001
Thiamin, mg	0.94	—	0.92[1]	0.94
Riboflavin, mg	1.6	—	1.55[1]	1.60
Niacin, mg	15	—	22.2	23.9
Vitamin B-6, mg	1.5	25	1.59	1.58
Folate, μg	300	1000	259[1]	329
Vitamin B-12, μg	2.8	—	4.95	5.59
Vitamin C, mg	75	—	86.7	84.9
Vitamin D, μg	3.3	75	3.37	3.5
Vitamin E, mg	12	300	14.7	12.0
Vitamin K, μg	105	—	143	211
Calcium, mg	955	2500	1170	955
Phosphorus, mg	550	3000	1770	1839
Iron, mg	13.5	25	11.3[1]	14.5
Sodium, mg	—	2400	2790[1]	2205
Potassium, mg	3500	—	3850	4022
Magnesium, mg	325	565	383	554
Zinc, mg	8	25	12.6	11
Selenium, μg	70	300	51.9[1]	70.0
Copper, mg	0.9	5	1.21	2.19
Iodine, μg	150	600	188	232
Tryptophan, g	0.33	—	1.04	1.01
Threonine, g	1.23	—	3.35	2.97
Isoleucine, g	1.64	—	4.05	3.52
Leucine, g	3.20	—	7.35	6.39
Lysine, g	2.46	—	6.66	4.68
Methionine, g	0.85	—	2.13	1.65
Cysteine, g	0.34	—	1.17	1.24
Valine, g	2.13	—	4.87	4.29
Histidine, g	0.82	—	2.78	2.17

[1] Value fails to satisfy the requirement.

farm to fork, and the geographical scope of the LCAs is the Netherlands.

In order to adjust the GHGEs of each food item to forecasted scenarios for 2030 and 2050, we used a climate impact trend analysis described in a report entitled "The Menu of Tomorrow" (24). For each food group, we derived changes in agricultural production, as well as trends in the supply processes that are part of the agricultural production system, such as energy and fertilizer production. These trends were then translated into implications for each life-cycle stage, resulting in the forecasted emission factors for 2030 and 2050 (see Supplemental Table 3). For instance, in cultivation of crops it is expected that nitrogen use efficiency will increase, as it has done in the past in the Netherlands, leading to increased yield and reduced nitrogen application by better fertilization and soil management. This is further explained in the Supplemental Methods: forecasting the environmental impacts of products.

We considered 3 different GHGE targets, all expressed as GHGEs per person per day (pppd): the 2030 target of 2.04 kg of carbon dioxide equivalent (kg CO_2-eq) pppd and the 2050 target of 1.11 kg CO_2-eq pppd, both derived from the IPCC 1.5-degree assessment study (3); and a less strict target of 2.5 kg CO_2-eq pppd was also considered. This less strict target might be realistic should other sectors reduce GHGE impact to a great extent. The calculation of these targets is explained in detail in the Supplemental Methods: translating the global climate change targets into personal targets from food. Fossil energy use and land occupation were measured, but were not used as targets for the optimization.

Scenarios

We considered 3 types of optimization scenarios: different food system GHGE targets, different eating patterns, and exploratory scenarios. Satisfying all nutritional requirements was part of every scenario.

First, 4 optimization scenarios used different food system GHGE targets. The 2030 scenario met the 2030 GHGE target using emission factors forecasted for 2030 whereas the 2050 scenario met the 2050 GHGE target using emission factors forecasted for 2050. To determine the relative importance of the GHGE targets, we modeled 2 additional variations of the 2030 scenario: a scenario with no GHGE target (no-GHGE-target scenario) and a scenario with a less strict GHGE target (relaxed-GHGE-target scenario). This less strict target might be realistic if and when other sectors reduce GHGE impact more than initially agreed upon, allowing more possibilities for GHGEs from food production. The scenarios for different eating patterns and for the exploratory analyses were all further variations of the initial 2030 scenario and used the 2030 GHGE target.

We then modeled scenarios using 5 eating patterns. Here the initial scenario was based on FBDGs (FBDGs scenario): to the 2030 scenario we added the dietary requirements derived from the Dutch Health Council's dietary guidelines (17). Each of the items in the Dutch dietary guidelines was translated into computation requirements as **Supplemental Table 6** details. Four specific eating patterns were modeled by including additional restrictions: a flexitarian diet, with 35 g meat/d [50% of the maximum amount of meat recommended by the Netherlands Nutrition Centre (15)]; a pescatarian diet, without any meat; a (lacto-ovo) vegetarian diet, without any meat or fish and shellfish; and a vegan diet, without any animal products.

Finally, 3 exploratory optimization scenarios considered food diversity, acceptability, and interdependency between food production systems. In the diversity scenario, we added the Wheel of Five (25) requirements to the FBDGs scenario, resulting in the most complete dietary advice for the Netherlands. The Netherlands Nutrition Centre's Wheel of Five recommends that 85% of all calories should come from the following 5 food groups: nonalcoholic and nonsugar beverages; bread, grains, and potatoes; fish and shellfish, pulses, meat, eggs, nuts, and dairy; margarine and cooking fats; and fruits and vegetables. It also recommends that foods in each food group should be consumed every day. In the acceptability scenario we kept the dietary solutions even closer to the baseline diet among Dutch adults by limiting dietary changes to 33%–150% of the baseline amounts (g) of each food group. This range was informed by the typical log normally shaped, and thus asymmetric, distribution of food group intake (26, 27). Finally, in the food chain interdependency scenario we considered the coproduction of dairy and beef. Here we fixed the amount of dairy other than cheese and butter to the level of the results of the 2030 scenario, and set the amount of beef from dairy cows to 1 g beef for every 46 g milk (28–31). This ratio is based on the production of milk and beef in animal husbandry of dairy cows.

Sensitivity analysis

The robustness of the 2030 scenario to uncertainties in the nutritional and environmental data was tested via 1000 Monte Carlo simulations. We assumed that all nutritional and environmental characteristics represented the average characteristics of each of the 207 foods in our analysis. In each round of the simulation, a random realization of the average nutritional and environmental characteristics was used, and the dietary solution for the 2030 scenario was recalculated. The variability of the nutritional (e.g., vitamin C or calcium) and environmental (i.e., GHGEs, fossil energy use, and land occupation) characteristics was approximated using a normal distribution with a relative SD of 12.5% for all characteristics and foods. The 5th and 95th percentiles of the distribution of the 1000 Monte Carlo results gave an indication of the robustness of the results of the 2030 scenario to uncertainties in the underlying environmental sustainability indicators and nutrient composition data.

Results

Table 1 shows the amounts of nutrients for the baseline diet among Dutch adults and for the 2030 scenario. Supplemental Table 3 shows the detailed composition of all scenarios, **Supplemental Table 7** shows nutrient values for all scenarios, and **Supplemental Table 8** shows the food group intake for all scenarios. The baseline diet among Dutch adults that we calculated did not meet all nutritional requirements, in line with findings of the Dutch National Food Consumption Survey report (10); specifically, it was too high in energy (kcal), saturated fat, and sodium and too low in α-linolenic acid (18:3n–3), fiber, the omega-3 fatty acids DHA (22:6n–3) and EPA (20:5n–3), thiamin, riboflavin, folate, iron, and selenium. The solutions for all scenarios attempted to correct the nutritional inadequacies in the baseline diet among Dutch adults.

Table 2 shows the optimized diets for the 4 scenarios in which we varied food system GHGE target amounts. For each food group, we have specifically highlighted in the text below consumption differences that were <33% or >150% of the baseline diet among Dutch adults, in line with the threshold used in the acceptability scenario. To achieve a nutritionally adequate diet with no limits on GHGEs (no-GHGE-target scenario), the main differences with the baseline diet among Dutch adults were a higher consumption of vegetables, fish and shellfish, legumes, soy foods, and tree nuts and elimination of butter. This diet had lower GHGEs than the baseline diet among Dutch adults, slightly lower land use, but higher fossil energy use. The additional dietary changes needed to achieve the 2030 GHGE target (2030 scenario) were a higher consumption of peanuts and soy drink (fortified with vitamin B-12 and calcium), elimination of beef and snacks, and lower consumption of pork and cheese. In the 2030 scenario, consumption of fish and shellfish, peanuts, and tree nuts was higher than in the no-GHGE-target scenario. Consumption of legumes was higher than in the baseline diet, but lower than in the no-GHGE-target scenario. Intakes of grains and starches, fruits, dairy other than cheese and butter, unsaturated oils, sugar and confectionary, cakes, soups and bouillon, and beverages were within 33%–150% of the baseline diet among Dutch adults. This diet also had a lower fossil energy use and land occupation than the baseline diet among Dutch adults. The sensitivity test of

TABLE 2 Food intake (g/d) and environmental indicators of the baseline diet among Dutch adults and for 4 scenarios with varying food system GHGE targets[1]

Food group	Baseline diet among Dutch adults	No-GHGE-target scenario	Relaxed-GHGE-target scenario	2030 scenario (sensitivity range[2])	2050 scenario
Grains and starches					
Rice, wheat, corn, and other	225	268	278	289 (278, 295)	293
Potatoes and cassava	114	112	112	109 (105, 112)	86
Vegetables					
Dark green vegetables	51	93	80	65 (58, 77)	145
Red and orange vegetables	50	77	59	38 (33, 46)	33
Other vegetables	45	76	73	70 (62, 80)	153
Fruits					
All fruit	116	134	119	99 (94, 105)	16
Dairy foods					
Cheese	39	26	19	3 (0, 10)	0
Liquid dairy	371	364	368	363 (348, 376)	128
Butter	6	0	0	0 (0, 0)	0
Protein sources					
Beef and lamb	44	37	0	0 (0, 0)	0
Chicken and other poultry	30	26	22	11 (5, 17)	0
Pork	56	24	17	10 (5, 19)	0
Eggs	11	13	15	17 (12, 21)	0
Fish and shellfish	18	44	54	48 (42, 57)	52
Dry beans, lentils, and peas	4	37	30	23 (17, 31)	0
Soy foods	0	5	6	5 (1, 9)	0
Tree nuts	2	20	35	55 (44, 59)	63
Peanuts	14	20	28	36 (30, 40)	17
Added fats					
Unsaturated oils	28	16	12	10 (8, 16)	27
Sugars and snacks					
Sugar and confectionary	44	36	31	23 (14, 31)	0
Cakes	56	37	37	31 (24, 36)	23
Snacks	9	6	2	0 (0, 0)	0
Other foods					
Condiments and sauces	24	12	14	9 (5, 13)	0
Soups and bouillon	63	61	53	36 (29, 42)	0
Beverages					
Alcoholic beverages	212	210	200	203 (200, 205)	132
Nonalcoholic beverages	2118	2117	2112	2102 (2097, 2105)	1797
Soy drink[3]	9	10	14	19 (15, 23)	96
Greenhouse gas emissions, kg CO_2-eq pppd	4.21	3.65	2.5	2.04	1.11
Fossil energy use, MJ pppd	37.2	40.5	32.8	27.8	19.6
Land occupation, m^2a pppd	4.65	4.34	3.26	3.11	2.79

[1]kg CO_2-eq, kilograms of carbon dioxide equivalent; MJ, megajoules; m^2a, square meters annually; pppd, per person per day.
[2]The robustness of the 2030 scenario to uncertainties in the nutritional and environmental data was tested via 1000 Monte Carlo simulations.
[3]Soy drink is a fortified product with vitamin B-12 and calcium.

the 2030 scenario suggested quite robust results at food group level.

The relaxed-GHGE-target scenario contained more cheese, chicken, and pork and lower amounts of tree nuts than the 2030 scenario, but still no beef. The diet in the 2050 scenario was limited to only a few food groups. Compared with the 2030 scenario, consumption of cheese, chicken, pork, eggs, legumes, soy foods, sugar and confectionary, soups and bouillon, and condiments and sauces was completely removed, whereas consumption of total vegetables, tree nuts, and soy drink was higher.

Table 3 shows the results of the eating pattern scenarios. None of the optimized eating patterns contained beef. The flexitarian scenario contained the most meat (chicken and pork). In the (lacto-ovo) vegetarian scenario, egg and tree nut consumption was greatly increased. The (lacto-ovo) vegetarian and vegan scenarios did not meet the requirements for DHA and EPA for which fish and shellfish is a main source. The vegan scenario only met requirements for vitamin B-12 and calcium through high consumption of fortified soy drink.

Table 4 shows the results of the exploratory scenarios. In the diversity scenario, products from cakes, condiments and sauces, snacks, soups and bouillon, and sugar and confectionary were a priori limited to 15% of total energy intake. As a consequence, the optimized diet contained more nonmeat protein sources and unsaturated oils than the baseline diet among Dutch adults. In the acceptability scenario, meat consumption (including beef) remained higher than in the 2030 scenario, as did consumption of cheese and unsaturated oils, whereas consumption of legumes, soy foods, and tree nuts was lower. In

TABLE 3 Food intake (g/d) and environmental indicators for the FBDGs scenario and for the flexitarian, pescatarian, (lacto-ovo) vegetarian, and vegan scenarios[1]

Food group	2030 scenario (sensitivity range[2])	FBDGs scenario	Flexitarian scenario	Pescatarian scenario	Lacto-ovo vegetarian scenario	Vegan scenario
Grains and starches						
Rice, wheat, corn, and other	289 (278, 295)	268	267	270	267	281
Potatoes and cassava	109 (105, 112)	107	106	108	100	32
Vegetables						
Dark green vegetables	65 (58, 77)	77	80	72	66	182
Red and orange vegetables	38 (33, 46)	41	41	51	36	50
Other vegetables	70 (62, 80)	82	80	78	98	181
Fruits						
All fruit	99 (94, 105)	200	200	200	200	200
Dairy foods						
Cheese	3 (0, 10)	0	0	1	8	0
Liquid dairy	363 (348, 376)	360	354	368	336	0
Butter	0 (0, 0)	0	0	0	0	0
Protein sources						
Beef and lamb	0 (0, 0)	0	0	0	0	0
Chicken and other poultry	11 (5, 17)	8	17	0	0	0
Pork	10 (5, 19)	7	18	0	0	0
Eggs	17 (12, 21)	16	13	21	68	0
Fish and shellfish	48 (42, 57)	49	45	53	0	0
Dry beans, lentils, and peas	23 (17, 31)	20	20	20	20	20
Soy foods	5 (1, 9)	1	0	2	0	0
Tree nuts	55 (44, 59)	57	58	54	82	39
Peanuts	36 (30, 40)	35	35	34	25	0
Added fats						
Unsaturated oils	10 (8, 16)	12	11	22	24	5
Sugars and snacks						
Sugar and confectionary	23 (14, 31)	23	19	22	4	38
Cakes	31 (24, 36)	27	23	30	46	0
Snacks	0 (0, 0)	0	0	0	0	0
Other foods						
Condiments and sauces	9 (5, 13)	7	4	8	5	52
Soups and bouillon	36 (29, 42)	29	24	33	31	236
Beverages						
Alcoholic beverages	203 (200, 205)	200	200	200	193	163
Nonalcoholic beverages	2102 (2097, 2105)	2099	2097	2100	2081	1953
Soy drink[3]	19 (15, 23)	19	20	20	14	532
Greenhouse gas emissions, kg CO_2-eq pppd	2.04	2.04	2.04	2.04	2.04	2.04
Fossil energy use, MJ pppd	27.8	28.2	27.7	28.1	26.8	30.03
Land occupation, m^2a pppd	3.11	3.11	3.13	3.1	3.58	2.77

[1]FBDG, food-based dietary guideline; kg CO_2-eq, kilograms of carbon dioxide equivalent; MJ, megajoules; m^2a, square meters annually; pppd, per person per day.

[2]The robustness of the 2030 scenario to uncertainties in the nutritional and environmental data was tested via 1000 Monte Carlo simulations.

[3]Soy drink is a fortified product with vitamin B-12 and calcium.

the food chain interdependency scenario, where the consumption of beef was required, the consumption of cheese, pork, and chicken was lower than in the 2030 scenario.

Discussion

The results of this study suggest that the 2030 food system GHGE target cannot be achieved by only correcting nutritional inadequacies, indicating that additional dietary changes are needed. We do show, however, that it is possible to meet the 2030 and 2050 GHGE targets, but large shifts in diets might be needed and the feasibility of those changes may be limited. Our results also suggest that it is possible to achieve climate targets and nutritional adequacy with specific eating patterns; however, fortification and/or supplementation will be required. In most of the optimization scenarios consumption of beef was nil, but our food chain interdependency scenario achieved the 2030 GHGE target with limited consumption of beef.

The 33%–150% range that we chose for selecting relevant changes might have influenced our results. In the 2030 scenario, increased consumption of eggs and decreased consumption of chicken, unsaturated oils, and condiments and sauces were on the borderline of the 33%–150% range. Some relatively large changes might be more feasible than relatively smaller changes. For example, a 100% reduction of butter consumption corresponds with a small change in grams (from 6 to 0 g/d) but might be more feasible than a relatively smaller reduction of chicken and poultry by 65% (from 30 to 11 g/d).

TABLE 4 Food intake (g/d) and environmental indicators for the diversity, acceptability, and food-chain-interdependency scenarios[1]

Food group	2030 scenario (sensitivity range[2])	Diversity scenario	Acceptability scenario	Food-chain-interdependency scenario (dairy)
Grains and starches				
Rice, wheat, corn, and other	289 (278, 295)	299	338	289
Potatoes and cassava	109 (105, 112)	109	93	107
Vegetables				
Dark green vegetables	65 (58, 77)	68	77	65
Red and orange vegetables	38 (33, 46)	41	17	35
Other vegetables	70 (62, 80)	91	67	71
Fruits				
All fruit	99 (94, 105)	200	76	95
Dairy foods				
Cheese	3 (0, 10)	0	13	1
Liquid dairy	363 (348, 376)	368	272	363
Butter	0 (0, 0)	0	2	0
Protein sources				
Beef and lamb	0 (0, 0)	0	14	8
Chicken and other poultry	11 (5, 17)	15	46	5
Pork	10 (5, 19)	5	24	7
Eggs	17 (12, 21)	23	17	16
Fish and shellfish	48 (42, 57)	44	27	47
Dry beans, lentils, and peas	23 (17, 31)	21	5	20
Soy foods	5 (1, 9)	0	0	3
Tree nuts	55 (44, 59)	54	3	58
Peanuts	36 (30, 40)	23	21	38
Added fats				
Unsaturated oils	10 (8, 16)	44	21	9
Sugars and snacks				
Sugar and confectionary	23 (14, 31)	4	32	23
Cakes	31 (24, 36)	1	40	27
Snacks	0 (0, 0)	0	3	0
Other foods				
Condiments and sauces	9 (5, 13)	0	8	6
Soups and bouillon	36 (29, 42)	12	21	29
Beverages				
Alcoholic beverages	203 (200, 205)	200	166	200
Nonalcoholic beverages	2102 (2097, 2105)	2093	2012	2098
Soy drink[3]	19 (15, 23)	22	14	22
Greenhouse gas emissions, kg CO_2-eq pppd	2.04	2.04	2.04	2.04
Fossil energy use, MJ pppd	27.8	28.3	25.7	27.1
Land occupation, m^2a pppd	3.11	3.33	2.76	3.15

[1]kg CO_2-eq, kilograms of carbon dioxide equivalent; MJ, megajoules; m^2a, square meters annually; pppd, per person per day.
[2]The robustness of the 2030 scenario to uncertainties in the nutritional and environmental data was tested via 1000 Monte Carlo simulations.
[3]Soy drink is a fortified product with vitamin B-12 and calcium.

Our results suggest that reducing consumption of beef, pork, poultry, cheese, butter, and snacks and increasing consumption of legumes, fish and shellfish, peanuts, tree nuts, vegetables, soy foods, and soy drinks are critical to achieve GHGE targets while maintaining a healthy eating pattern. Dairy products other than cheese, grains, and starches can be consumed in amounts similar to those of the baseline diet among Dutch adults. Higher fruit consumption is not necessary to either satisfy nutritional requirements or reach GHGE targets, but does provide improved health benefits according to FBDGs (17).

Our use of quadratic optimization to search for diets that are close to the baseline diet among Dutch adults and that also satisfy nutritional and climate change requirements is an approach that has been used in other contexts where similar food and dietary data were available (6, 24, 32). The fact that we chose quadratic programming to minimize deviations of the modeled diets from the baseline diet does not guarantee diverse and acceptable diets. Others have used linear and nonlinear programming (33–35) or simulated new diets by expert-informed replacement of food products, e.g., the EAT–*Lancet* report (4). An analysis of diets in 4 European Union countries (36) took national food patterns into account by means of regression analysis of GHGEs and land occupation for major food groups, followed by expert-informed isocaloric substitution of main food groups. To obtain more realistic and acceptable model solutions, models are being developed that account for intrinsic relations between foods and consumer preferences in daily menus (E Mertens, A Kuijsten, A Kanellopoulos, M Dofková, L Mistura, L D'Addezio, A Turrini, C Dubuisson, S Havard, E Trolle, S Biesbroek, J Bloemhof, J M Geleijnse, P Veer van 't, unpublished results, 2019).

Sustainable diets should be affordable, so even though price was out of scope in our analysis, price should be considered in the development of acceptable, healthy, sustainable diets (37). A recent study in the United Kingdom showed that healthy diets that meet GHGE targets can be created for all income quintiles (38). Indeed, tailoring changes to income groups is expected to make dietary changes more achievable. In addition, taste profiles and texture should be considered when proposing healthier and more sustainable diets (39).

Modeling diets for 2050 was technically feasible, but the solutions in this scenario lacked food diversity and deviated greatly from baseline eating patterns. Results showed that nutritional adequacy for essential fish fatty acids and vitamin B-12 requires attention. In our results, the risk of vitamin B-12 and calcium deficiency was alleviated by fortified soy products, which points at the potential role of other biomimicry products such as plant-based meat substitutes and/or supplementation by pills or powder-based food. Although fortification and supplementation will increase the total environmental impact slightly, this is unlikely to cancel out the net beneficial effects of altered dietary habits. Innovations in agriculture and food technology may lead to an altered food supply, new recipes, and new eating patterns. Moreover, this article has not considered the consequences for trade and global shifts in supply and demand due to shifts in consumer choices. Thus, the time horizon of 2050 is associated with many uncertainties owing to lack of insight into future environmental footprints, nutritional properties, and dietary habits. Nevertheless, these results show that attention to essential nutrients is warranted in the food systems transition.

Comparability with other studies can be challenging owing to their use of different data sources, such as food balance sheets (4, 5, 40). When food consumption is estimated via food balance sheets, the conversions from commodity production to consumer food items are not always properly included. For instance, parts of cereal production are consumed as alcoholic beverages or as added ingredients in pastries or sauces. Although 24-h recalls also do not guarantee exact annual consumption, they are considered a preferred and more precise data collection method relative to indirect methods (41, 42). We therefore believe that using direct dietary assessments of final consumer food items is more refined and more useful for providing dietary advice than only considering indirect measurements, such as produced commodities. Studies have been done using consumer food items, specifically for the Netherlands (7, 8). However, we calculated GHGE targets to limit temperature rise due to global warming to 1.5°C and used projected emissions factors for the food products for 2030 and 2050.

Our environmental assessment was intended to be as comprehensive as possible in order to deliver an accurate estimation of both environmental impacts and reduction potential, in line with a recent report by the IPCC (43). Unlike the EAT–*Lancet* report, our LCAs included retailing practices and home food preparation as well as fossil carbon dioxide emissions in addition to methane and nitrous oxide. We also considered fossil energy use and land occupation. Although we did not add targets for these indicators, we did show that the impacts on fossil energy use and land occupation were reduced in the 2030 scenario by 25% and 33%, respectively. Other environmental metrics, such as water use or biodiversity losses, could improve our analysis. Because these metrics are not fully agreed on by experts and there are no data available for all LCAs, we chose to omit them for now. The impact on climate change due to direct land use change (e.g., deforestation) was not accounted for. The method to calculate impact due to direct land use change requires data on the past 20 y, whereas in our optimization scenarios we look forward to 2030 and 2050. This means that the required data for the scenarios are not yet available and because land use change can hardly be forecasted it was omitted from this study.

Our results show that future diets, complying to GHGE targets and meeting nutritional constraints, should contain less meat—especially beef—and more plant-based food products. These findings are in line with a report from the Food, Agriculture, Biodiversity, Land, and Energy (FABLE) consortium which investigated pathways to sustainable land use and food systems for 18 countries (44). For countries that are in the same geographical region as the Netherlands, such as Finland and the United Kingdom, this report found directions of change toward 2050 similar to those identified in the current study, namely a decrease in meat consumption (48%–66%) and a significant increase in vegetables, legumes, eggs, and fish and shellfish. In another study in 4 European countries, besides energy intake, total meat consumption and the proportion of ruminant meat explained a substantial part of the variation in GHGEs and land occupation for different diets (36). Based on regression models, isocaloric substitution by grain products of 5% energy from meat would decrease GHGEs and land occupation by 10% and 15%, respectively. Although an increase in plant-based products has been suggested by several studies, the required shifts in the use of animal-based products might not be homogeneous across countries or gender (35).

Summarizing, our results suggest that modeling acceptable country-level diets, that consider both health and sustainability parameters (45), is challenging. However, using country-level data might lead to more acceptable diets than using a global approach. It is possible to meet nutritional requirements and a strict GHGE target, but it is difficult to achieve diverse and acceptable diets with current food product availability. Strong product and process innovation, improving nutritional profiles (e.g., reformulation, fortification, supplementation) and environmental performance is needed to meet the 2050 GHGE target in terms of healthy and acceptable diets, taking into account price, texture, and taste. Current dietary patterns in the Netherlands are not consistent with the required GHGE targets, and specific policies may be needed to help people shift to diets with lower environmental impacts (46).

In conclusion, we used newly calculated per capita food system GHGE targets for 2030 and 2050 designed to limit global average temperature rise to 1.5°C. Forecasting GHGE factors for food products, we optimized diets to comply to different sets of constraints, studying how FBDGs and eating patterns of flexitarians, pescatarians, (lacto-ovo) vegetarians, and vegans affect the results. We have found multiple solutions for future diets and for different eating patterns, meeting food system GHGE targets and nutritional needs. We have shown that more stringent GHGE targets and more stringent eating patterns reduce the diversity of possible diets, potentially limiting their acceptability and increasing the risk of inadequate vitamin B-12 and calcium intake. Taken together, the scenarios considered here suggest some clear shifts will be needed to meet food system

GHGE targets and comply to nutritional constraints: less meat (especially beef), cheese, butter and snacks, and more fish and shellfish and plant-based products.

More research is needed, considering a wider range of environmental indicators; additional aspects such as price, taste, and texture; product reformulation; fortification; and supplementation. Shedding more light on these aspects will enable policy makers and advisory associations to decide on ways to identify acceptable changes and guide the necessary dietary shifts. Changes should focus not only on various food consumption patterns, but also on food production.

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