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Protein for a Healthy Future: How to Increase Protein Intake in an Environmentally Sustainable Way in Older Adults in the Netherlands

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ABSTRACT

Background: Protein intake greater than the currently recommended amount is suggested to improve physical functioning and well-being in older adults, yet it is likely to increase diet-associated greenhouse gas emissions (GHGEs) if environmental sustainability is not considered.

Objectives: We aimed to identify dietary changes needed to increase protein intake while improving diet environmental sustainability in older adults.

Methods: Starting from the habitual diet of 1,354 Dutch older adults (aged 56–101 y) from the Longitudinal Aging Study Amsterdam cohort, mathematical diet optimization was used to model high-protein diets with minimized departure from habitual intake in cumulative steps. First, a high-protein diet defined as that providing ≥1.2 g protein · kg body weight^{-1} · d^{-1} was developed isocalorically while maintaining or improving nutritional adequacy of the diet. Second, adherence to the Dutch food-based dietary guidelines (FBDG) was imposed. Third, a stepwise 10% GHGE reduction was applied.

Results: Achieving a high-protein diet aligned with the FBDG without considering GHGEs required an increase in vegetables, legumes, nuts, whole grains, meat/dairy alternatives, dairy, and eggs and a reduction in total meat (for men only) and discretionary products, but it resulted in a 5% increase in GHGEs in men and 9% increase in women. When a stepwise GHGE reduction was additionally applied, increases in poultry and pork (mainly for women) and decreases in beef/lamb and processed meat were accrued, with total meat staying constant until a 50–60% GHGE reduction. Increases in whole grains, nuts, and meat/dairy alternatives and decreases in discretionary products were needed to lower GHGEs.

Conclusions: A high-protein diet aligned with FBDG can be achieved in concert with reductions in GHGEs in Dutch older adults by consuming no more than the recommended 500 g meat per week while replacing beef and lamb and processed meat with poultry and pork and increasing intake of diverse plant-protein sources. *J Nutr* 2021;151:109–119.

Keywords: diet optimization, protein, environmental impact, community-dwelling older adults, greenhouse gas emissions

Introduction

Adequate protein intake is a fundamental prerequisite for muscle protein synthesis and maintenance of skeletal muscle mass and physical function (1, 2), and it has been shown to be especially important for healthy aging (3). Several metabolic and observational studies indicate that older adults require a greater protein intake than younger adults for adequate muscle synthesis and for maintaining physical function (4–7). Age-related changes in physiological, psychological, and social factors may upset the balance between dietary consumption and nutritional requirements, making adults aged ≥65 y in particular vulnerable to inadequate protein intake (8). Inadequate protein intake is one of several determinants of malnutrition and frailty in older adults, increasing the risk of mortality and comorbidities (8, 9). Currently, the RDA for protein established by the Health Council of the Netherlands (HCN), the European Food Safety Authority (EFSA), and WHO is 0.8 g protein · kg body weight (BW)$^{-1}$ · d^{-1} for adults, including older adults (10–12). However, because protein intake

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above this amount is suggested to better maintain physical functioning and well-being in adults aged ≥65 y, a higher RDA of 1.0–1.2 g protein · kg BW^{-1} · d^{-1} has been proposed by expert groups (2, 5, 13).

Although an increase in protein intake could potentially support better health in older adults (14), it presents an environmental concern. The current protein demand and supply places a substantial burden on the environment, playing a paramount role in anthropogenic climate change and biodiversity loss, among other negative environmental effects (15–17). Animal-based protein in particular plays a pivotal role in the diet's overall environmental impact (18). In Europe, ∼25% of all greenhouse gas emissions (GHGEs) are due to food consumption, with animal-based food consumption contributing to more than half of the diet's overall impact (19). In the Netherlands, 60% of total protein consumed by community-dwelling older adults is derived from animal-based sources, of which ∼50% comes from meat and dairy (20, 21). In addition to having a large environmental impact, red and processed meat has been associated with chronic diseases and overall mortality when consumed in high quantities (22–24). Shifting toward a more plant-based diet (i.e., shifting the direction of the animal- to plant-protein ratio from 60:40 toward 50:50 or 40:60) has thus been recommended by the HCN in its 2015 guidelines for a healthy diet (22, 25) and by the Agriculture and Land Use sector in the 2019 Dutch Climate Agreement (26, 27). The need for a more plant-based diet is also addressed in the Farm to Fork Strategy of the European Green Deal, which aims to achieve a 50% GHGE reduction by 2030 compared with 1990 levels and climate neutrality by 2050 (28, 29). Not meeting this target risks increasing global warming to 1.5°C above pre-industrial levels sometime between 2030 and 2052, which is predicted to have significant impacts on ecosystems, oceans, biodiversity, and human health (30).

To meet the suggested higher protein requirement of the aging population and at the same time improve the environmental sustainability of the diet, it is essential to customize protein advice for this population (31). The current modeling study aimed to identify dietary changes that deviate least from habitual intake and increase protein intake in the context of the 2015 Dutch food-based dietary guidelines (FBDG) while reducing diet-associated GHGEs in Dutch community-dwelling older adults.

Methods

Study population and sample

The 2014–2015 Nutrition and Food-Related Behavior ancillary study from the Longitudinal Aging Study Amsterdam (LASA) provided the study population for this analysis. LASA is an ongoing cohort study in a representative sample of Dutch community-dwelling adults aged ≥55 y living in 3 geographical regions in the Netherlands (32, 33). The sample and data collection procedures for the LASA cohort (34, 35) and the Nutrition and Food-Related Behavior ancillary study (36, 37) have been described in detail and are summarized here. Dietary intake data were collected during the Nutrition and Food-Related Behavior ancillary study from 1439 participants (684 men and 755 women) by means of an FFQ (36–38). Of the 1439 participants, 85 participants in total were excluded in this study due to not fully completing the FFQ ($n = 19$), overreporting energy intake according to Willett's cutoff values (>4000 kcal/d for men and >3500 kcal/d for women; $n = 23$), and not having a valid measured BW ($n = 43$) (37, 38). BW was measured during the LASA medical interviews in 2011–2012, 2012–2013, and 2015–2016 and was averaged across the different measurement periods for each participant (37). Data on comorbidity, measured as self-reports of the number of chronic diseases from a list of 7 health conditions (35), and physical activity, measured using the validated LASA Physical Activity Questionnaire (34), were obtained during the main interview of the regular LASA waves.

The analytical sample of 1354 participants (644 men and 710 women) had a mean age of 69 y, a mean BMI (in kg/m^2) of 27, and a mean physical activity level of 62 metabolic equivalent h/wk. Comorbidities present in the sample include osteoarthritis (48.3%), hypertension (39.4%), incontinence (25.4%), cardiac disease (21.3%), cancer (15.1%), chronic nonspecific lung disease (12.8%), diabetes mellitus (11.8%), rheumatoid arthritis (9.9%), peripheral arterial disease (6.3%), and cerebrovascular accident or stroke (5.7%). Ethical approval for the LASA study and ancillary study was given by the Medical Ethics Committee of the Amsterdam University Medical Center, and all participants provided written informed consent.

Dietary data

Dietary intake data were collected by means of an adapted validated semiquantitative FFQ that asked participants how often they consumed various food items in the past 4 wk, as well as how much of the food they normally consumed per occasion (38, 39). In total, 254 food items were included in this analysis, and each food item was linked to the Dutch Food Composition Table 2011 to calculate nutrient intakes (40). Furthermore, estimates of 9 essential amino acids (EAAs)—that is, lysine, methionine, leucine, isoleucine, threonine, valine, histidine, tryptophan, and phenylalanine—were obtained for each food item from the USDA's food composition database (41), which is to our knowledge the most comprehensive EAA database available. When estimates were not available in the USDA database, they were retrieved from the Danish Frida Food Data database (42). The food items were aggregated into 25 food groups adapted from the food group classification used for the Dutch Food Consumption Surveys originally based on EPIC-Soft classification (43). Food items comprising ≥2 ingredients were classified into respective food groups based on the recipe calculations used in the FFQ (**Supplemental Table 1**) (39).

Environmental data

The environmental impact of the diet is measured using life cycle assessments (LCAs) of 3 environmental impact indicators, namely GHGE, land use (LU), and fossil energy use (FEU). LCAs were performed over the entire life cycle of the product, from cultivation and processing to packing, consumption, and final disposal using the ReCiPe 2016 Midpoint v1.00 method by Blonk Consultants (44, 45). Environmental impact estimates were largely obtained from 2 life cycle inventory databases from Blonk Consultants. The FFQ food items were first linked with environmental data from the Optimeal database, which contains environmental data of 208 commonly eaten food products in the Netherlands (46). Food items were matched based on similarities of foods in their nutritional composition and function

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Supplemental Figures 1–3 and Supplemental Tables 1 and 2 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/jn/.

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Abbreviations used: BW, body weight; EAA, essential amino acid; EFSA, European Food Safety Authority; FBDG, food-based dietary guidelines; FEU, fossil energy use; GHGE, greenhouse gas emission; HAB, habitual diet; HCN, Health Council of the Netherlands; LASA, Longitudinal Aging Study Amsterdam; LCA, life cycle assessment; LU, land use; PROT, high-protein diet; +PROT, high-protein diet aligned with the Dutch food-based dietary guidelines; +PROT-GHGE, high-protein diet aligned with the Dutch food-based dietary guidelines accounting for greenhouse gas emissions; QP, quadratic programming.

TABLE 1 Nutritional, environmental, and acceptability constraints applied during diet optimizations for Dutch older adults[1]

	Lower constraint	Upper constraint	References
Step 1: PROT			
Nutritional constraints[2]			
Energy, kcal/d	Mean HAB	Mean HAB	—
Protein, g·kg body weight^{-1}·d^{-1}	1.2	—	(2, 47)
SFA, g/d	—	Mean HAB	(48)
MUFA, g/d	Mean HAB	—	(48)
PUFA, g/d	Mean HAB	—	(48)
Fiber, g/d	Mean HAB or 25	—	(48)
DHA + EPA, mg	Mean HAB or 250	—	(48)
Folate equivalents, μg/d	Mean HAB or 300	1000	(49)
Vitamin C, mg/d	Mean HAB or 75	—	(49)
Calcium, mg/d	Mean HAB or 1200	2500	(49)
Iron, mg/d	Mean HAB or 11	25	(49)
Acceptability constraint			
Food items, g/d	—	95th percentile[3]	(50)
Step 2: Step 1 + +PROT			
Food groups			
Vegetables, g/d	200	—	(22)
Fruit, g/d	200	—	(22)
Whole grains, g/d	90	—	(22)
Nuts, g/d	14.3	—	(22)
Fish, g/d	—	14.3[4]	(22)
Meat, g/d	—	71.4[5]	(51)
Red meat, g/d	—	42.9[6]	(51)
Processed meat, g/d	—	Mean HAB	(22)
Warm savory snacks, g/d	—	Mean HAB	—
Sweets, g/d	—	Mean HAB	(22)
Sugar-sweetened beverages, g/d	—	Mean HAB	(22)
Step 3: Step 2 + +PROT-GHGE			
Environmental constraint			
GHGE, kg CO$_2$-eq/d	Stepwise 10% reduction from level in mean HAB	—	—

[1] Mean habitual intakes of the respective nutrients, food items, and food groups are calculated for men and women separately. The constraints applied in each step are in addition to the constraints applied in the prior step(s). HAB, habitual diet; HCN, Health Council of the Netherlands; PROT, high-protein diet; +PROT, high-protein diet aligned with the Dutch food-based dietary guidelines; +PROT-GHGE, high-protein diet aligned with the Dutch food-based dietary guidelines accounting for greenhouse gas emissions.

[2] When the mean habitual intake of a nutrient was above the DRI of that nutrient, the DRI defined by the HCN (49) or the European Food Safety Authority (48) (if not defined by the HCN) was used.

[3] Nonconsumers excluded.

[4] Equivalent to ~1 serving (100 g) of fish per week.

[5] Equivalent to the recommended maximum 500 g meat per week.

[6] Equivalent to the recommended maximum 300 g red meat per week.

as well as production methods as determined by an LCA expert. Food items that did not have a match in the Optimeal database were then matched to food products in a life cycle inventory database developed by Blonk Consultants in the context of the European Union-funded project PROMISS (Prevention of Malnutrition in Senior Subjects in the EU), which contains environmental data of 94 commonly eaten food products by European older adults. Furthermore, environmental data for 3 food items were obtained from the life cycle inventory database from the Netherlands National Institute for Public Health and Environment (52). GHGEs expressed in kilograms of carbon dioxide equivalents, LU in square meters per year, and FEU in mega joules were calculated per 100 g food.

Diet optimization with quadratic programming

To investigate possible directions for change on the food group level to achieve a high-protein diet in the context of the Dutch FBDG while improving the environmental impact of the diet in older adults, quadratic programming (QP) was conducted. QP is a mathematical optimization technique that finds a unique combination of variables (e.g., quantities of food in a diet) to optimize a quadratic objective function, while subject to a number of linear constraints (e.g., protein requirement) (53). Whereas most previous research has approached the challenge of simultaneously meeting nutritional and environmental goals by using linear programming, which produces large changes in a limited number of food products, we chose QP because it leads to a wider range of small changes, making it a more favorable approach to identify realistic changes on the population level, especially for a vulnerable population such as older adults. The modeling exercise was carried out in several cumulative steps involving the application of nutritional, acceptability, and progressively stringent environmental constraints. The steps and constraints are described in the following sections and shown in **Table 1**. Optimizations were performed using diet optimization software Optimeal 3.0 (Blonk Consultants) (54) and were done for men and women separately because men and women have been found to have different eating patterns (55, 56), which may lead to different dietary changes to reach the modeling objectives described later.

Nutritional constraints.

Starting from the mean habitual diet (HAB) of older men and women, high-protein diets (PROT), defined as providing ≥ 1.2 g protein $\cdot$ kg $BW^{-1} \cdot d^{-1}$ (2, 47), were modeled isocalorically to identify compositional changes in the diet needed to achieve a higher protein intake. To ensure that the nutritional adequacy of the diet did not worsen and had room to improve, micronutrients, fiber, and fatty acids were minimally constrained and saturated fatty acid was maximally constrained to the mean habitual subpopulation intake. When the mean habitual intake of a nutrient was above the DRI of that nutrient, the recommended intake defined by the HCN (49) or EFSA (48) (if not defined by the HCN) was used as the lower constraint.

Building on the PROT of men and women separately, high-protein diets aligned with the 2015 Dutch FBDG (+PROT) were modeled (22, 51). A lower constraint was set for vegetables, fruit, whole grains, and nuts equal to the recommended daily intake while an upper constraint was set for meat and red meat equal to the respective recommended weekly intake. Whereas the Dutch FBDG advises to limit consumption of processed meat, sweets, savory snacks, and sugar-sweetened beverages, there is no maximum consumption boundary suggested for these food groups (22), and therefore an upper constraint equal to the respective mean habitual subpopulation intake was established to prevent increases in these food groups.

With regard to fish, the Dutch FBDG recommends eating 1 serving of fish, preferably oily, per week (22). Although consuming >1 weekly serving of fish may provide additional health benefits, it poses a threat to fish stocks and marine biodiversity (57). Therefore, we set an upper constraint to 1 serving of fish per week. Because other diet optimization studies often conclude that higher fish intake is needed to meet nutritional requirements as well as lower diet-associated GHGEs (56), we conducted a sensitivity analysis with a lower constraint applied to fish intake to ≥1 serving per week (results presented in **Supplemental Figure 1**).

Environmental constraints (+PROT-GHGE).

Building on +PROT, the diets were further modeled for increasingly stringent reductions of GHGEs (see Table 1). +PROT was first constrained to have the same GHGE value as HAB (+PROT-GHGE-0%) and then was subjected to a 10% stepwise decrease in GHGEs (i.e., +PROT-GHGE-10%, +PROT-GHGE-20%, +PROT-GHGE-30%, etc.) (56, 58). The maximum number of 10%-reduction steps was reached when no diet solution could be achieved with a further 10% GHGE reduction. In other words, a maximum GHGE reduction was reached when an additional 10% GHGE reduction was not feasible given the model parameters (i.e., food items, constraints, and objective function).

Acceptability constraints.

To attain realistic dietary changes, food item quantities were constrained to an upper limit equal to the 95th percentile of the habitual intakes of consumers, calculated for men and women separately (50). An upper limit for organ meat was set to the mean habitual intake per sex because only a small percentage of the sample consumed organ meat (23% of men and 17% of women older adults). In addition, a lower limit for the food group fats/oils was set to the 5th percentile of the habitual intakes of consumers. In preliminary analyses, fats/oils were removed from the diet with GHGE reductions ≥50%, which we deemed culturally unacceptable.

Objective function.

The objective function of the model ensured that the modeled diet stayed closest to HAB when subjected to the aforementioned nutritional, environmental, and acceptability constraints. The objective function f was minimized:

$$f = \sum_{i=1}^{n} \left(x_i^* - x_i\right)^2 \tag{1}$$

where i is a food item, n is the number of available food items, x_i is the value in grams of food item i in the reference diet of the subpopulations, and x_i^* is the value in grams of the same food item in the modeled diet.

Data analysis

Descriptive statistics were conducted to describe the content of nutrients, environmental impact, and quantities of food groups of the mean HAB and modeled diets (PROT, +PROT, and +PROT-GHGE diets) for older men and women separately. To assess the acceptability of the modeled diets, departure from the mean HAB in terms of absolute change in mean intake of food groups ($abs\Delta_{food\ groups}$; $n = 25$) and food items ($abs\Delta_{food\ items}$; $n = 254$) (in %) was calculated. Diets similar to the mean HAB in terms of diet composition (i.e., diets with minimal departure) were considered culturally acceptable and feasible, whereas diets with larger departure from the mean HAB were considered to have greater risk of lower acceptability (58). Based on the formula used by Perignon et al. (58), we calculated the absolute departure from mean habitual intake by

$$abs\ \Delta_{food\ groups} = \frac{1}{25} \sum_{j=1}^{25} ABS\left(\frac{x_j^* - x_j}{x_j^*}\right) \tag{2}$$

$$abs\ \Delta_{food\ items} = \frac{1}{254} \sum_{i=1}^{254} ABS\left(\frac{x_i^* - x_i}{x_i^*}\right) \tag{3}$$

where j is the 25 food groups, and i is the 254 food items, abs is the absolute value, x is the observed quantity in the reference diet, and x^* is the quantity in the modeled diet. Taking into account the Dutch and European climate goals (26, 27), we described the dietary changes needed to achieve a 50% GHGE reduction. We then assessed whether these changes would be acceptable by discerning the diets' departure from the mean HAB as established by Equations 2 and 3 (58).

Results

Total protein content and GHGEs of habitual and modeled diets

HAB provided 1.02 g protein $\cdot$ kg $BW^{-1} \cdot d^{-1}$ for men and 1.00 g protein $\cdot$ kg $BW^{-1} \cdot d^{-1}$ for women. Protein content of the diet needed to increase by 16% for men and 20% for women to reach the 1.20 g protein $\cdot$ kg $BW^{-1} \cdot d^{-1}$ goal. The GHGE of HAB was 6.81 kg CO_2-eq/d for men and 5.68 kg CO_2-eq/d for women. Achieving a high-protein diet, whether aligned with the food-based dietary guidelines (+PROT) or not (PROT), implied higher diet-associated GHGEs. A change from HAB to PROT resulted in a 12% increase in GHGEs for men and 14% for women, whereas a change from HAB to the +PROT resulted in a 5% and 9% GHGE increase. For the +PROT-GHGE diets, the maximum attainable GHGE reduction in the diet modeling exercise was 80% GHGE reduction for both men and women.

Changes in food group quantities from HAB to modeled diets

The changes in food group quantities from HAB to PROT, +PROT, and +PROT-GHGE-50% are shown in **Figure 1**. The stepwise changes in food group quantities from HAB to modeled diets is similar for men and women (**Supplemental Figure 2**). For both sexes, achieving a high-protein diet without taking the guidelines or environmental impact into account (PROT) implied an increase in all meat products (besides organ meat), fish, cheese, eggs, legumes, nuts, meat/dairy alternatives, and savory snacks and a decrease in fats/oils and discretionary products, including dressings/sauces and sweets. Taking the food-based dietary guidelines into account (+PROT) resulted in increases from HAB in vegetables and fruit (men only) and stronger increases in cheese, eggs, nuts, and meat/dairy

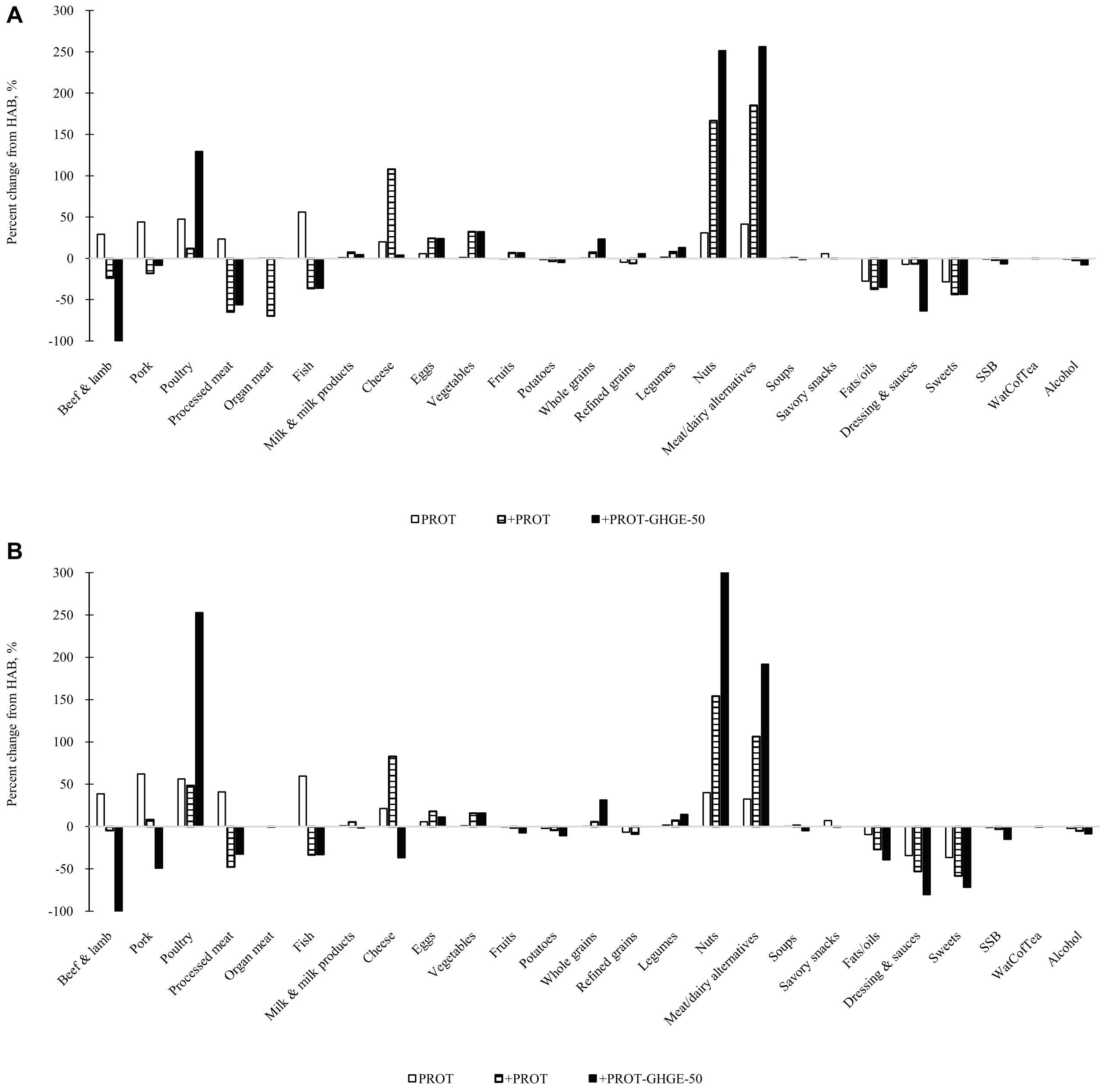

FIGURE 1 Percentage change in food group quantities from HAB to PROT, +PROT, and +PROT-GHGE-50 in Dutch men (A, *n* = 644) and women (B, *n* = 710) aged 56–101 y. GHGE, greenhouse gas emission; HAB, habitual diet; PROT, high-protein diet; +PROT, high-protein diet aligned with the Dutch food-based dietary guidelines; +PROT-GHGE-50, high-protein diet aligned with the Dutch food-based dietary guidelines with 50% GHGE reduction; SSB, sugar-sweetened beverages; WatCofTea, water, coffee, tea.

alternatives than from HAB to PROT. Because men had a habitually higher meat intake than what is recommended in the guidelines, total meat needed to decrease by 29% from HAB to +PROT. The habitual intake of meat among women, on the other hand, was already aligned with the food-based dietary guidelines. Fish was reduced from HAB to +PROT by 36% for men and 33% for women to the established upper constraint of 1 serving per week.

Achieving a high-protein diet aligned with the food-based dietary guidelines while meeting the Dutch and European GHGE reduction goal of 50% did not induce substantial changes in total meat from the recommended limit of 500 g/d (it reduced to 482 g/d for women) but required the removal of beef and lamb from the diet as well as a reduction of processed meat and pork and an increase in poultry for both sexes. Although total meat quantity remained relatively constant, the GHGE impact of meat reduced due to the partial substitution of beef and lamb and processed meat with poultry and pork (**Supplemental Figure 3**). While the quantity of cheese hardly changed for men (4% above habitual intake), it needed to be reduced by 36% below habitual intake for women. For both sexes, moderate increases in whole grains (20–30%) and legumes (14%) and substantial increases in nuts (250–310%) and meat/dairy alternatives (190–250%) were needed, as well as substantial reductions in fats/oils (70–80%), dressings/sauces (30–40%), and sweets (60–70%) for both sexes.

Diet properties and protein type and quality

The habitual intakes of dietary fiber, *ω*-3 fatty acids (DHA + EPA), folate, and calcium were below the DRI but the habitual intake of vitamin C exceeded the DRI in both men and women (**Supplemental Table 2**). Although the habitual intake of iron was above the DRI for men, it was below for women. For both sexes, achieving a high-protein diet with or without taking the food-based dietary guidelines into account resulted in increases in quantities of several nutrients. Although intake levels of DHA + EPA increased above the DRI from HAB to PROT, it remained at habitual intake levels for +PROT and subsequent +PROT-GHGE diets with an exceptional spike at 50% and 60% GHGE reduction levels due to high increases in poultry. Applying a progressive GHGE reduction led to nutrients fluctuating above and below the DRI, with fiber and calcium remaining below the DRI for women in most modeled diets. The diet weights in terms of dry matter in the modeled diets were higher relative to HAB except for PROT, and they subtly increased with greater GHGE reductions.

When increasing protein intake is the main goal and neither the food-based dietary guidelines nor GHGEs are considered, the ratio of animal- to plant-based protein increased from 60:40 (HAB) to 65:35 (PROT) in men and 61:39 (HAB) to 66:34 (PROT) in women (**Figure 2**). Taking the food-based dietary guidelines into account produced a trifling decrease in the animal- to plant-based protein ratio from the HAB. A progressive reduction in GHGEs resulted in small but cumulative reductions in the animal- to plant-based protein ratio. It was only with a ≥50% GHGE reduction when plant protein contributed to >50% of total protein intake for both sexes. The animal- to plant-based protein ratio of +PROT-GHGE-50% was 49:51 for both sexes, which is close to the 50:50 ratio recommended by the Netherlands Nutrition Center (25). The +PROT-GHGE-50% required an increase in the contribution to total protein from poultry, vegetables (only for men), whole grains, nuts, and meat/dairy alternatives and a decrease from beef and lamb, pork, processed meat, fish, milk and milk products, cheese (only for women), potatoes (only for men), and sweets (Supplemental Figure 3).

Using the quantity of 9 EAAs as a proxy for protein quality, the modeled diets generally led to improvements in protein quality relative to HAB (**Figure 3**). At a 50% GHGE reduction, only lysine slightly fell below habitual levels. Protein quality became compromised with a >50% GHGE reduction, when quantities of lysine, methionine, threonine, isoleucine, leucine, valine, and histidine fell below habitual intakes for both sexes. The reduction in quantities of 7 EAAs coincides with the dominance of plant-based protein sources in the diet, as illustrated in Figure 2.

Environmental impact of the habitual and modeled diets

PROT led to higher diet-associated LU and FEU compared with HAB, similar to its effect on GHGEs (**Figure 4**). Taking the FBDG into account resulted in LU and FEU levels similar to those in HAB for men and slightly higher levels than those in HAB for women. A progressive reduction in GHGEs resulted in a corresponding progressive reduction in LU and FEU of the diet. Whereas LU decreased in a linear-like manner similar to GHGEs, FEU decreased in a more geometric-like manner. FEU remained close to habitual levels up to and including a 40% GHGE reduction, and it substantially reduced with a ≥50% GHGE reduction.

Acceptability of the modeled diets

PROT was most similar to HAB in terms of diet composition—that is, it resulted in the smallest departure from HAB on the food group and food item levels (**Figure 5**). +PROT resulted in a greater departure from HAB, ~2 times greater than that of PROT. Imposing an additional constraint for GHGE did not induce substantial changes in absolute departure compared with that of +PROT until >50% GHGE reduction. A GHGE reduction >50% resulted in a considerably larger departure from HAB in food quantities on both the food group and food item levels, having a higher risk of lower cultural acceptability.

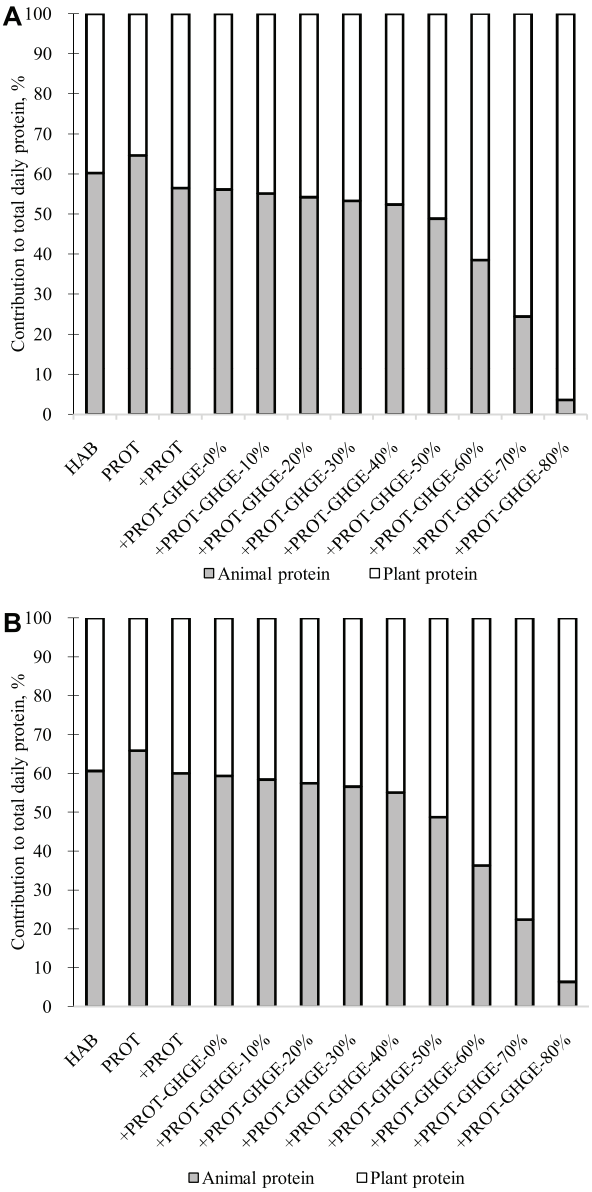

FIGURE 2 Contribution of animal protein and plant protein to total daily protein intake in HAB, PROT, +PROT, and +PROT-GHGE in Dutch men (A, *n* = 644) and women (B, *n* = 710) aged 56–101 y. The percentage on the +PROT-GHGE diets is the percentage reduction in GHGEs applied to the diet. GHGE, greenhouse gas emission; HAB, habitual diet; PROT, high-protein diet; +PROT, high-protein diet aligned with the Dutch food-based dietary guidelines; +PROT-GHGE, high-protein diets aligned with the Dutch food-based dietary guidelines accounting for greenhouse gas emissions.

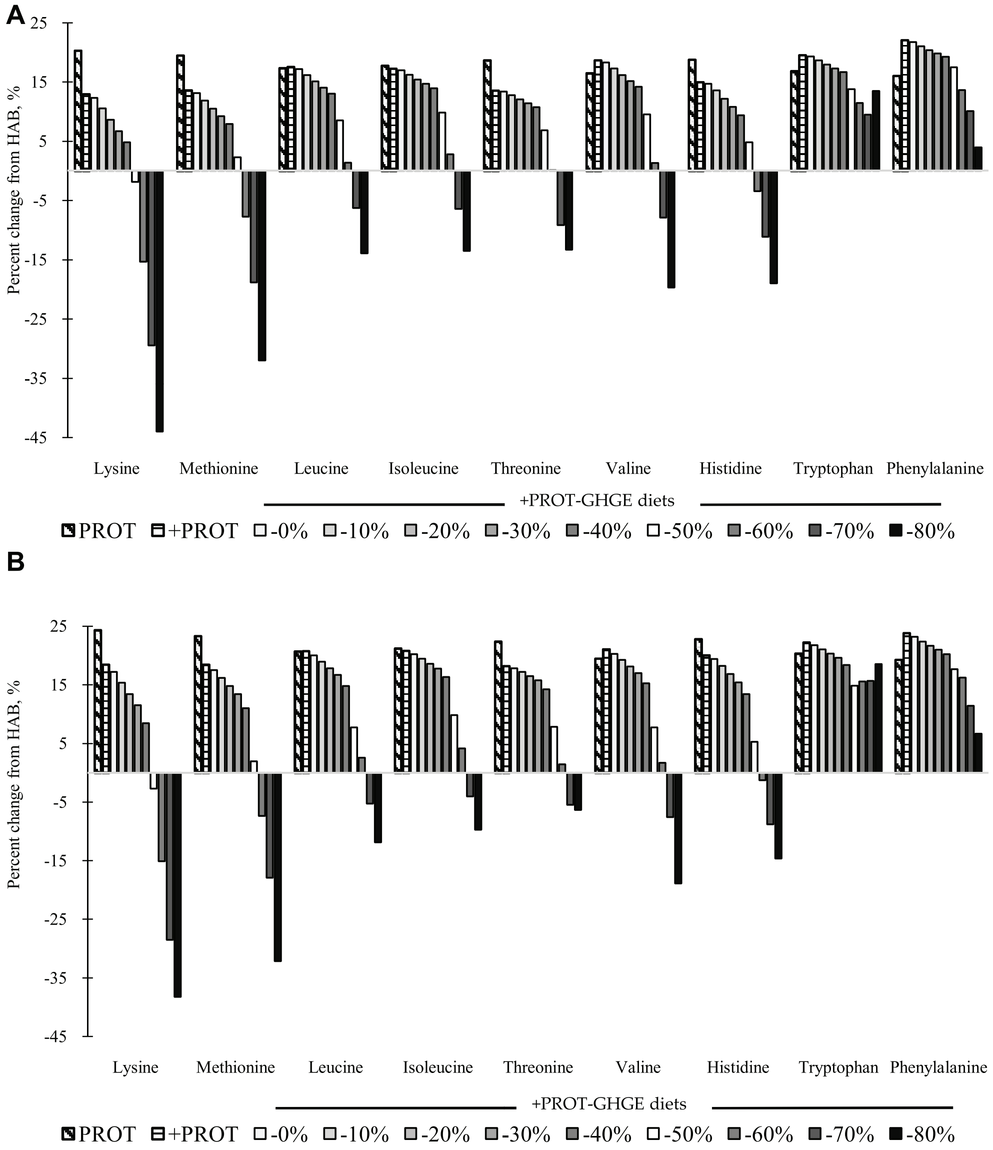

FIGURE 3 Percentage change in essential amino acids from HAB to PROT, +PROT, and +PROT-GHGE in Dutch men (A, $n = 644$) and women (B, $n = 710$) aged 56–101 y. The percentage on the +PROT-GHGE diets is the percentage reduction in GHGEs applied to the diet. GHGE, greenhouse gas emission; HAB, habitual diet; PROT, high-protein diet; +PROT, high-protein diet aligned with the Dutch food-based dietary guidelines; +PROT-GHGE, high-protein diets aligned with the Dutch food-based dietary guidelines accounting for greenhouse gas emissions.

Discussion

A potentially new RDA for healthy older adults of 1.2 g protein $\cdot$ kg BW^{-1} $\cdot$ d^{-1} could lead to net increases (5–14%) in GHGEs of the diet if environmental sustainability is not taken into account. To meet a potential higher protein recommendation and simultaneously improve the environmental sustainability of the diet in older adults, it is essential to pay particular attention to the origin of protein when customizing protein advice for this population. This diet optimization study shows that a high-protein diet aligned with the Dutch FBDG and with a 50% GHGE reduction can be achieved while still eating an ample amount of meat (500 g/wk), mainly by replacing beef and lamb and processed meat with mostly poultry and some pork. An increase in the contribution of plant protein from whole grains, legumes, nuts, and meat/dairy alternatives to total protein is needed to meet older adults' high protein demand in the context of the FBDG and environmental constraints. The results suggest that reductions in diet-associated GHGEs $\leq$50% are potentially feasible and culturally acceptable, yet changes needed to meet more stringent GHGE reductions (>50%) risk being unacceptable due to the substantially higher departures from food quantities in the habitual diet as well as due to compromised protein quality.

The findings of the current study are consistent with those of previous modeling studies that addressed the underlying challenge of simultaneously achieving a healthy and sustainable diet, supporting the need to shift away from environmentally intensive meats and energy-dense, nutrient-poor foods toward less environmentally intensive meats and more nutrient-rich plant foods (56, 58, 59). Our results show that when the ratio of animal- to plant protein becomes equal or flips to one favoring plant protein sources, lysine, methionine, leucine, and several other EAAs become compromised, which is due to the lower content of these EAAs in plant-based sources compared with animal protein sources (60, 61). Findings from a recent trial in

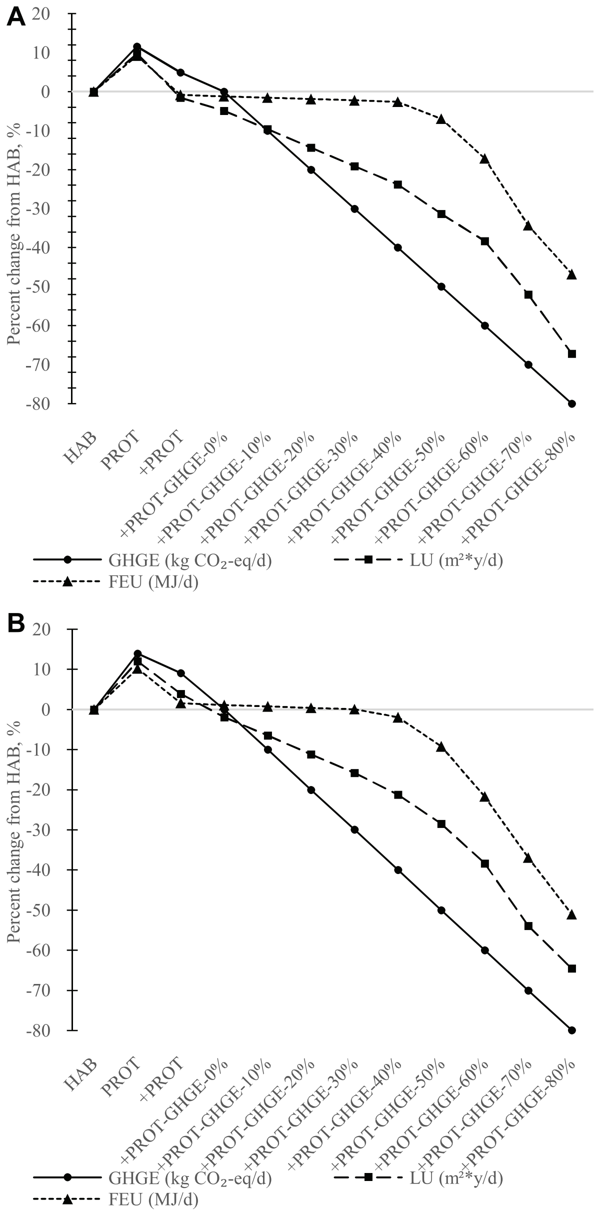

FIGURE 4 Percentage change in GHGEs, land use, and fossil energy use from HAB to PROT, +PROT, and +PROT-GHGE in Dutch men (A, *n* = 644) and women (B, *n* = 710) aged 56–101 y. The percentage on the +PROT-GHGE diets is the percentage reduction in GHGE applied to the diet. FEU, fossil energy use; GHGE, greenhouse gas emission; HAB, habitual diet; LU, land use; PROT, high-prtoein diet; +PROT, high-protein diet aligned with the Dutch food-based dietary guidelines; +PROT-GHGE, high-protein diets aligned with the Dutch food-based dietary guidelines accounting for greenhouse gas emissions.

healthy older women suggest that adequate intake of particular amino acids, rather than total protein, may be important for the maintenance of skeletal muscle mass and function, pointing to the importance of leucine (62). Although bioavailability of protein and other nutrients was outside the scope of this study, it is a concern for shifting toward a more sustainable plant-based diet. However, it was previously shown in a French modeling study that there is enough diversity in the diet to ensure the quality of protein and other key nutrients despite smaller quantities of animal products in the diet (63).

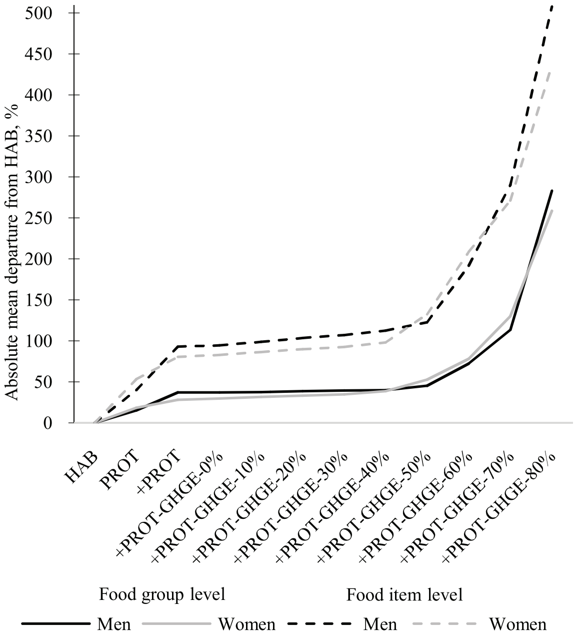

FIGURE 5 Absolute mean departure on food group level and food item level from HAB to PROT, +PROT, and +PROT-GHGE in Dutch men (*n* = 644) and women (*n* = 710) aged 56–101 y. The percentage on the +PROT-GHGE diets is the percentage reduction in GHGEs applied to the diet. GHGE, greenhouse gas emission; HAB, habitual diet; PROT, high-protein diet; +PROT, high-protein diet aligned with the Dutch food-based dietary guidelines; +PROT-GHGE, high-protein diets aligned with the Dutch food-based dietary guidelines accounting for greenhouse gas emissions.

Despite slight nutritional improvements after imposing constraints on food groups aligned with the FBDG, the food group constraints did not necessarily lead to a nutritionally adequate diet, with most of the modeled diets being compromised in DHA + EPA for both sexes and in fiber and calcium for women. However, given that the nutrient profiles of the modeled diets were maintained or improved relative to that of the habitual diet, the dietary changes found in this study indeed deliver a nutritional advantage. Similar to our findings, Salomé et al. (64) found that a higher consumption of diverse plant protein sources, including whole grains, legumes, nuts, and vegetables, was associated with higher probabilities of adequacy of vitamin C and folate but lower probabilities of adequacy for DHA + EPA, calcium, and iron, underscoring the importance of animal-based protein sources for adequate intake of these nutrients.

The results of our sensitivity analysis support previous linear programming studies, which have found that fish consumption needed to be increased to make the diet nutritionally adequate and more environmentally sustainable (55, 56, 58, 59). When a minimum rather than a maximum constraint on fish was placed, adequate levels of DHA + EPA were met in the modeled diets (results not shown). Particularly fatty wild-caught fish types are favored because their high content of ω-3 fatty acids and protein makes them a desirable component of a healthy diet, and their relatively low impact on GHGEs make them favorable in GHGE-restricted diets (65). Nevertheless, there is a need to consider a maximum consumption of fish beyond which there are few health gains. Eating more fish than what is needed for health could have unintended consequences on the environment beyond climate change, such as overfishing and aquatic biodiversity loss, that are not captured by GHGEs or in LCAs in general (66). To meet the HCN recommendation on DHA + EPA consumption with limited negative environmental effects, Hollander et al. (67) found that consumption of fish bycatch and discards is needed (bycatch is unwanted fish caught with the primary target species of a fishery and discards are unwanted fish caught with the primary target species of a fishery but are usually discarded due to having little economic value). Plant-based sources of DHA + EPA, such as seaweed and algae, may be another solution for a sustainable source of DHA + EPA as well as protein, yet such innovative products are not part of the current habitual Dutch diet and thus were not included in this modeling study.

This study found that synergies exist between GHGEs and other environmental impacts, namely LU and FEU, yet a ≥50% GHGE reduction was needed to bring FEU below the habitual FEU level. An explanation for the delayed decline of FEU of the high-protein diets aligned with the FBDG and with <50% GHGE reduction is the relative high quantities of poultry and persistence of milk and milk products, cheese, and eggs in the diet, which all experienced a reduction with ≥50% GHGE reduction.

This study has some strengths and limitations. Compared with other modeling studies (56, 58, 59), we used 3 markers of diet sustainability—namely GHGE, LU, and FEU—and used environmental impact data that were consistently calculated over the entire life cycle of the product. Although this study used only GHGEs as an environmental constraint to have a clear environmental target aligned with Dutch and European climate goals, it showed that synergies exist between GHGEs and the other environmental indicators. Despite this strength, there are many more markers of environmental sustainability (e.g., water footprint and eutrophication), as well as nonenvironmental sustainability dimensions including animal welfare and diet affordability (68), which were outside the scope of this study. A limitation of this study is that the modeled diets were not nutritionally adequate for 3 nutrients that were considered in the study, suggesting further improvements could be achieved by taking nutritional quality into account. Not applying constraints for nutritional adequacy may have influenced the modeling exercise to undervalue animal protein sources as they supply essential fatty acids and nutrients and perhaps to overvalue food products that may contain significant amount of sodium, such as cheese and meat/dairy alternatives. Generalizability of results to older adults in other countries is limited because cultural differences are likely to produce different starting diets, and variations in production systems or regions can lead to different environmental estimates of the food products (69).

This study addresses 2 societal challenges confronting many areas of the world: meeting the protein requirement of a growing older population and meeting this need within environmental limits. The dietary changes identified in this study can start the discussion on how to increase protein intake in an environmentally sustainable way in older adults. We showed that a 50% GHGE reduction is possible with meat and other animal-based protein sources remaining in the diet but that a change in meat type is needed to keep the diet within sound environmental limits. Increasing plant protein from whole grains, legumes, nuts, and meat/dairy alternatives also contributed to improved protein quantity and quality for Dutch community-dwelling older adults within environmental limits.

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