1. **Introduction**

* Introduce previous optimization research, importance of cultural acceptability

Though the majority of previous studies have attempted to maximize acceptability of optimized diets by employing optimization models that minimize distance from the current diet, and/or imposing acceptability constraints, few studies have imposed constraints based on specific ‘culturally valued’ food groups. One study from China (1) aimed to improve the acceptability of sustainable dietary patterns in a region of China characterized by high consumption of mutton. In this study, Yin et al. (1) argue that respect for food culture should go beyond minimizing changes in amount of all foods. Instead, more tailored approaches to optimization should be used, where food groups with less consumption elasticity are identified, e.g., including an additional objective function to minimize departure from food groups with high cultural value (in their study: mutton, beef, pork, and cereals/potatoes).

* Introduce Norwegian setting
* Introduce NNR

**AIMS**

The 2023 Nordic Nutrition Recommendations (NNR) combine nutritional and environmental considerations into streamlined nutritional guidelines. Further knowledge of potential benefits and challenges linked to diet following the new NNR guidelines is critical to the development of revised FBDGs for Norway. In this paper, we aimed to examine the NNR guidelines from a Norwegian context by: 1) investigating the environmental impacts of nutritionally optimized diets following the new NNR guidelines, 2) measuring differences in potential for environmental impact reduction across scenarios of meat consumption, and 3) identifying limiting nutrients and other notable challenges.

In this study, we aim to demonstrate how quadratic programming can be applied to develop nutritionally adequate, healthy, and more environmentally sustainable diets for the adult Norwegian population.

1. **Methods**

**2.1 Dietary intake data**

Dietary information data was derived from Norkost 3, a Norwegian national dietary survey among adults conducted in 2010-2011 (2). Dietary information was collected from a nationally representative sample of men (n=862) and women (n= 925) aged 18 to 70 years (mean age 46 years). Participants completed two randomly distributed 24-hour dietary recalls. Interviewers coded and entered all foods and beverages consumed directly into the in-house food and nutrient composition database and calculation system “KostBeregningsSystem” KBS (Department of Nutrition, University of Oslo). Daily means over two consumption days were calculated for each participant. The survey is described in more detail elsewhere (2).

Mean daily energy intake in the Norkost 3 survey was 10.9 megajoules (MJ) for men and 8.0 MJ for women (2). In the present study, energy intake was standardized to 10 MJ to enable comparability of the observed diet in Norkost 3 with the optimized diet. Individual food intakes were thus proportionally adjusted to meet an energy intake of 10 MJ, corresponding to the approximate daily reference energy requirement of an average adult (across sex and age at a moderate physical activity level) (3).

A total of 1,507 foods were included in the average observed diet, including products in both raw/uncooked (e.g., carrots and eggs) and cooked/processed form (e.g., bread and cold cuts). Food items were aggregated into 53 food sub-groups based on nutritional, culinary, and environmental characteristics. Food sub-groups were further aggregated into main groups for the reporting of results. Food sub-groups and main groups are described in Supplementary Table 1.

Data on the nutritional content of foods was sourced from the nutrition calculation system KBS. The nutrient content in each food sub-group was weighted based on the average consumption of its associated single food items in the population, as described previously by Gazan et al. (4).

where Aij the content of nutrient i per gram of food sub-group j; nj is the number of food items belonging to food sub-group j; xkj is the quantity of food item k of food sub-group j consumed in the population and aik is the content of nutrient i in food item k.

**2.2 Environmental impact data**

Environmental impact information for the food items was sourced from a newly developed database of environmental information representative of the Norwegian context. The database compilation is described in detail elsewhere (REF methods paper). The data are based on published Life Cycle Assessment (LCA) studies and include system boundaries from farm-to-retail, thereby including primary production, processing and packaging, international (if relevant) and domestic distribution/transportation, and energy use for storage in wholesale and retail. If the original sourced LCA data did not include waste these data gaps were not filled. Values were included for six environmental impact categories: the global warming potential of greenhouse gases on a 100-year timescale (kg CO2-eq); acidification of soils (kg SO2-eq); eutrophication of freshwater (kg P-eq) and marine waters (kg N-eq); water use, specifically the consumption of *extracted water* (5)(m3); and transformation and use of land (m2a).

As with nutritional content, the weighted environmental impact values for each of the sub-groups were calculated based on the single food items they include. However, to account for uncertainties in the environmental data, foods were aggregated into 38 food sub-groups prior to calculation of environmental impacts (see Supplementary Table 2). The estimated environmental impacts of these 38 food sub-groups were then assigned to the 53 food sub-groups mentioned above. For example, white bread and wholegrain bread form two separate food sub-groups, due to important nutritional differences. However, as the difference in environmental impacts between these two sub-groups of bread is uncertain, they were aggregated into one group for calculation of environmental impact. The two groups are thus distinct in terms of nutritional value, but share the same environmental impact values in this analysis. All environmental impacts associated with food sub-groups were expressed as impact category (IC) values per g of edible food item (i.e., excluding peel, bones).

**2.3 Diet optimization**

***2.3.1 Optimization model***

Quadratic optimization models were used to search for nutritionally adequate, healthy diets that departed as little as possible from the observed population average diet, and met increasingly stringent environmental constraints. The decision variables were the 53 food sub-groups consumed by the population. For each model, the objective function to be minimized was the quadratic deviation (D) from the mean observed intake of each food sub-group, as follows:

where Obsi and Opti denote the daily consumption of food sub-group (i) in the observed and optimized diets, respectively. This method penalizes large variations in diet composition, assuming that deviation from the observed diet is a reasonable proxy for diet acceptability.

The optimizations were performed using the IBM CPLEX solver run through the Rcplex package version 0.3-5 of the R statistical software version 4.1.3.

***2.3.2 Model constraints***

An overview of the nutrient constraints applied in the models is presented in Table 1. In order to ensure nutritional adequacy of the optimized diets, lower and upper limits for macro- and micronutrients were enforced. These constraints were based on the new Nordic Nutrition Recommendations published 2023 (NNR2023). Macronutrient recommendations for fat, protein, and carbohydrates were based on targets for dietary planning purposes. Fatty acid quality was ensured by constraining saturated and n-3 fatty acids, and measuring the content of α-Linolenic acid (ALA), mono-unsaturated fatty acids (MUFA), and poly-unsaturated fatty acids (PUFA). Micronutrient limits were based on recommended intake (RI) values when available; if RI was not available, adequate intake (AI) was used. The RI represents the average daily nutrient intake level that is sufficient to meet the nutritional requirements of nearly all (usually 97.5%) individuals in a particular life-stage group in the general population; the AI has larger uncertainty than RI, but is expected to meet or exceed the needs of most individuals in the life-stage group (3). Constraints were not set for Tolerable Upper Intake Level (UL); nutrient amounts in the final optimized diets were later checked to ensure they did not surpass available ULs. For nutrients with differing recommendations for females and males, an average was taken of the two values, assuming equal sex distribution in the population. Exceptions were made for Vitamin D and selenium. Vitamin D adequacy is difficult to achieve through dietary intake alone, and suboptimal vitamin D-status is common among population groups in Norway that are less exposed to sunlight and do not take vitamin D supplements (6). Constraining vitamin D may have led to unrealistic optimized diets; therefore, as in previous studies, vitamin D content in the diets was measured rather than constrained (7, 8). Preliminary analyses indicated a difficulty in fulfilling the selenium recommendation provided by NNR2023 (AI, average males and females: 82.5 μg/d) without imposing large changes in the diet. The provisional average requirement (AR) of 65 μg/d (average males and females) was thus used instead; this is still higher than the RI given in the previous Nordic Nutrient recommendations from 2012 (NNR2012)(55 μg/d) and twice that of the AR given in NNR2012 (32.5 μg/d)(9). To demonstrate the impact of a higher selenium recommendation on the optimization outcome, a sensitivity analysis was run with selenium set to the AI from NNR2023; more information follows in section 2.5 Sensitivity analysis.

The health-based constraints on food amounts included upper or lower boundaries based on NNR2023: whole grains ≥ 90 g per day, fruit and vegetables ≥ 250 g each per day, juice ≤ 100 g per day, nuts ≥ 20 g per day, vegetable oils and margarine ≥ 25 g per day, milk and dairy products 350-500 g milk-equivalents per day, total fish 300-450 g cooked fish per week (of which ≥ 200 g fatty fish), white meat ≤ current intake, and cooked red meat ≤ 350 g per week. Though NNR2023 only stipulates a “moderate intake” of egg, preliminary analyses with no constraint on egg intake showed a large increase in the content of egg, corresponding to up to 14 eggs per week. A constraint was thus set for egg content in the optimized diets, ≤ 1 egg per day. Since recommendations for meat and fish are provided in cooked weight, these were converted to raw weight using weight change factors (1.45 and 1.21, respectively)(10, 11).

Conversion factors of 1:10 and 1:1 were used for cheese and yoghurt, such that 10 g of cheese corresponded to 100 g milk-equivalents. This is based on recent data from Norwegian dairy production, and is in line with the range proposed by NNR2023 (10-20 g cheese per 100 g milk) (3, 12). In addition, a co-production factor of 40:1 for milk-equivalents and ruminant products was included in the model. The production of milk and beef are closely linked. In Norway, approximately 95% of dairy cattle are so-called “hybrid cattle” that produce both milk throughout their lives and meat after slaughter, as well as give birth to offspring (13). In 2030, it is predicted that Norwegian dairy production will include 182,313 cattle and that each cow will produce 8,982 kg of energy-corrected milk (ECM) and 285 kg of meat (12, 14). We considered a conversion factor of 93% for ECM and a meat to carcass weight ratio of 73% (15). This corresponds to a ratio of 40 kg of milk per kg of beef, when applying Eq.:

8,982 kg ECM x 93% (conversion factor) x = 285 kg beef x 73% (carcass yield)

To prevent the optimization models from including unreasonably high amounts of any single food sub-group, or completely eliminating others, realism constraints were applied to all models. An upper limit was set for food sub-groups corresponding to the 95th percentile of the intake distribution in the observed diet and a lower limit of 0.1 times the average observed intake. Further, water, coffee, tea, and spices were fixed to observed level due to their secondary role in the diet and in order to maintain acceptability of the diet. As a consequence of spices being fixed to observed level, the sodium constraint in the model was increased to 2400 mg/d (based on NNR2012, compared to 2300 mg/d as given in NNR2023).

The observed diet was first optimized in terms of nutrition and health, with no environmental constraints. Then, step-wise constraints were applied for global warming potential (GWP) in 5% increments, until results indicated that no solution was feasible. Limiting nutrients were identified as those nutrients whose values were very close to reaching, or exactly at either lower or upper constraint limits. These nutrients still fulfill imposed constraints, but were active constraints in the optimization (i.e., difficult to meet, such that fulfillment of the constraint influenced the optimization outcome).

***2.3.3 Model scenarios***

To examine the impact of meat distribution on the optimization outcome, optimization models both with and without GWP constraints were run for two scenarios (Table 2): Basis and Ruminant. Basis includes all constraints, as detailed above, with no adjustments. Ruminant includes the same constraints as Basis, but imposes a lower limit for intake of ruminant meat, such that content of ruminant meat in the optimized diet may not be lower than observed intake. Stepwise GWP constraints were then imposed separately for each scenario. The models with GWP constraints will henceforth be referred to as Basis+ and Ruminant+.

**2.4 Diet acceptability**

As a proxy for acceptability, a diet departure score (Δdiet) was used to estimate similarity between the average observed diet and optimized diets. Similarity between optimized diets without GWP constraints and at the maximum feasible GWP reduction were also compared, to adjust for the inevitable departure from the observed diet imposed by changes to meet nutritional and health recommendations. The diet departure score was represented by the average relative deviation from the observed diet (across food sub-groups), and was calculated by

where xj is the amount of food sub-group in the optimized diet and xobs,j is the amount of food sub-group in the average observed diet (or in the optimized diet chosen for comparison).

**2.5 Sensitivity analysis**

Four independent sensitivity analyses were performed. The first sensitivity analysis aimed to assess the impact of a higher selenium recommendation on the optimization outcome. In this scenario, the models were run with the selenium constraint increased from the AR (65 μg/d) to the AI (82.5 μg/d). In the second sensitivity analysis, all nutrient constraints were lowered to the AR to explore further climate impact reduction potential. The AR represents the average daily nutrient intake level that is estimated to meet the requirements of half the individuals in a population, and can be used to assess adequacy of nutrient intake (3). In the third sensitivity analysis, the upper intake constraint for white meat (white meat ≤ observed intake) was removed. The overall science advice provided by NNR2023 is to limit white meat intake to current level or lower, and instead replace meat consumption with increased consumption of plant foods and fish from sustainably managed stocks. However, this advice is based on environmental factors alone. White meat is considered neutral when it comes to health outcomes; unprocessed white meat may thus be included in a healthy diet in any amount. In this scenario, we assess the impact of allowing higher quantities of white meat on the optimization outcomes. Finally, in the fourth sensitivity analysis, daily consumption of pulses and legumes (40 g/d) was imposed, along with elements from the Danish Food-Based Dietary Guidelines (FBDG) (2020)(16). Due to the nature of the objective function, foods that are consumed in very small amounts (e.g., legumes) in the observed diet are unlikely to be modified appreciably by the optimization model, limiting the opportunities of change. Constraints on daily fruit and vegetable intake were increased to ≥300 g each, inclusion of pulses and legumes ≥40 g per day was forced, and an additional constraint on total meat intake ≤ 350 g per week was imposed.

1. **Results**

***3.1 Nutritional content, environmental impact, and food composition of the observed diet***

Values for all nutrients and environmental indicators in the observed diet are presented in Table 1, while the food composition is presented in Table 3. The average observed diet was lower than recommended in intake of dietary fiber, folate, vitamin D, and selenium, and contained too much saturated fat and sodium. The GWP of the average observed intake of Norwegian adults was 5.2 kg CO2-eq/10 MJ/day.

***3.2 Diets optimized to meet NNR2023 guidelines***

Optimization of the observed diet to follow NNR2023 guidelines (Basis scenario) resulted in an optimized diet with 9% lower GWP than the observed diet, and up to 14% reductions in other ICs (Table 3). Constraining ruminant meat intake to observed level in the Ruminant scenario led to an optimized diet with the same GWP as the observed diet, but with a 7% reduction in water use and 3% reductions in terrestrial acidification and land use. Marine eutrophication increased by 7% for the Basis scenario and 10% for the Ruminant scenario. Freshwater eutrophication also increased by 3% in the Ruminant scenario.

Content of main food groups (g/10 MJ) in the optimized diets is shown in Table 3. Detailed information on content of all 53 food groups in the optimized diets is available in Supplementary Table 3. Overall composition of the two optimized diets is similar. Content of bread is slightly lower than observed, and nearly all white bread is switched out with wholegrain bread. The amount of other grains, cakes and cookies, and potatoes is nearly doubled compared to observed. Content of vegetables, nuts, and plant-based fats is increased to meet NNR2023 guidelines, while the amount of fruit and berries is increased considerably above the guidelines. Dairy content (including cheese) is reduced by 37% from the observed diet, but at the upper limit of 500 g milk equivalents/day; further, dairy intake is re-distributed, with cheese decreasing by 88% and milk and other dairy increasing by 24% and 31%, respectively. Animal-based fats are decreased by 88%, but other discretionary foods (juice, beverages, sweets and snacks) remain in the diet in similar or lower amounts. The scenarios differ in regards to protein sources, though total content of main protein sources (g/day) is similar. Content of fish, eggs, and white meat is the same in both scenarios. In the Ruminant scenario, content of ruminant meat is maintained at observed level, while ruminant meat is decreased by 32% in the Basis scenario. Intake of pork is halved in the Basis scenario, but is reduced by 84% in the Ruminant scenario.

***3.3 Diets optimized to meet NNR2023 guidelines and GWP constraints***

When imposing stepwise GWP constraints to the Basis and Ruminant scenarios separately, the optimization model was able to produce feasible outcomes up until a 30% and 15% reduction in GWP, respectively, compared to the observed diet (Table 3). In both scenarios, reductions in GWP led to reduction in other ICs, except for marine eutrophication, which increased 2% in the Basis scenario and 8% in the Ruminant scenario. Overall reductions in IC categories were 2-4 times higher for the Basis+ scenario compared to the Ruminant+ scenario. Reductions were largest for terrestrial acidification, with a 36% reduction for Basis+ and a 13% reduction for Ruminant+. Land use also decreased by 31% in Basis+, but decreased by only 8% in Ruminant+. The decrease in water use was lesser, with a 10% reduction for Basis+ and 9% the Ruminant+.

Content of main food groups (g/10 MJ) in the Basis+ and Ruminant+ scenarios is shown in Table 3, and Figure 1 provides a visual illustration of the relative changes (%) in food group amounts compared to the observed diet. Content of other grains is increased by 185% in Basis+ and by 318% in Ruminant+. Basis+ includes a daily portion of cakes and cookies, while Ruminant+ includes less of these foods. The amount of potatoes is increased by 146% in Basis+, but by only 61% in Ruminant+. In both diet scenarios, fruits and vegetables are increased by 30% to meet health recommendations, and dairy intake is still high at about 500 g milk-equivalents. Cheese intake is decreased by 89% and redistributed to milk and other dairy sources. Content of animal-based fats, juice, beverages, and sweets and snacks is low in both diets.

The two scenarios show key differences in regards to protein sources. Content of fish and eggs are the same in both scenarios. White meat is reduced from the observed diet by 59% in Basis+, and by 89% in Ruminant+. Legumes are increased from the observed diet by 71% in Basis+ and 554% in Ruminant+. The relative changes are large due to low consumption of legumes in the observed diet; however, these changes represent increases of only 3 g in Basis+ and 24 g in Ruminant+. In Ruminant+, content of ruminant meat is maintained at observed level, while ruminant meat is decreased by 80% to the minimum possible given co-production constraints in Basis+. Intake of pork is similar to the observed diet in Basis+, at 56 g, but reduced by 84% in Ruminant+.

***3.4 Nutrient content of the optimized diets***

The nutritional contents of the optimized diets are provided in Supplementary Table 4. Limiting nutrients in the diet scenarios optimized to meet NNR2023 guidelines alone were similar and included saturated fat, sodium, vitamin A, folate, calcium, zinc, and selenium. Vitamin D was not constrained, but was above the AR (7.5 µg) and below the RI (10 µg) in both diets. Sodium, selenium (set to the AR, 65 µg) and zinc (set to the RI, 11.2 µg) were the strongest limiting constraints. Both optimized diets contained the highest amount of sodium allowed by the model constraints (2400mg); this is partly due to the decision to maintain spices (including discretionary salt) at the observed level.

Limiting nutrients in the diets optimized to meet GWP constraints in addition to NNR2023 guidelines were in line with those listed above. Saturated fat, folate, and zinc remained limiting nutrients in Basis+, but were not limiting in Ruminant+. Vitamin D was just above the AR in the Basis+ scenario, but below the AR in Ruminant+. Sodium and selenium were the strongest limiting constraint in both scenarios.

***3.5 Diet acceptability***

The diet departure scores for the Basis, Ruminant, Basis+, and Ruminant+ scenarios were 57%, 60%, 81%, and 120%, respectively (Table 3).

***3.6 Sensitivity analysis***

The first sensitivity analysis assessed the impact of applying a higher selenium recommendation on the optimization outcome (Supplementary Table 5). Setting the constraint to the RI led to an 18% reduction in GWP, which is nearly double the GWP reduction seen in the main analysis. Ruminant meat was immediately decreased to minimum allowable level and pork was increased until the upper limit for red meat was reached. Optimization results were feasible only up to a 20% reduction in GWP for the Basis+ scenario, and a 5% reduction in GWP for the Ruminant+ scenario.

In the second sensitivity analysis, constraints for all nutrients were lowered to the AR. GWP reductions up to 40% were feasible for the Basis+ scenario, but no further reductions were possible for the Ruminant+ scenario than in the main analysis. The amount of milk and dairy products in these diets is lower than in the main analysis, also allowing for a lower amount of ruminant meat.

In the third sensitivity analysis, the upper constraint on white meat was removed. In both the Basis and Ruminant scenarios, white meat was doubled from observed. GWP results were similar to the main analysis, with a 7% reduction in GWP in the Basis scenario and a slight increase of 1% in GWP in the Ruminant scenario. Results from the Basis+ and Ruminant+ scenarios were identical to results from the main analysis.

In the fourth sensitivity analysis, imposing a daily legume consumption of 40 g led to similar reductions as seen in the Basis scenario and similar diet structure. The optimization model was able to produce feasible outcomes up until a 35% reduction in GWP. All ICs were reduced, including a very small 1% reduction in marine eutrophication. Reductions were similar to the Basis+ scenario, but slightly greater, except for water use. The diet included 1700% more legumes than the observed diet (+68 g), 200% more potatoes, and 80% less meat.

***3.7 Summary of results***

Table 4 provides a general summary of content in the Basis+ and Ruminant+ scenarios, listed in the style of dietary recommendations. Results from the fourth sensitivity analysis (forced inclusion of legumes) are also included. As illustrated in this table, the diets retain many similarities, but differ importantly in regards to protein sources.

1. **Discussion**

To our knowledge, this is the first study to assess quantitatively the environmental impact of optimized diets following the NNR2023 guidelines. We found that nutritionally optimized diets following NNR2023 guidelines had generally lower environmental impacts than the observed diet, but that outcomes were dependent on the distribution of meat consumption in the diet. Further, we were able to identify diets following NNR2023 guidelines up until a 30% reduction in dietary GWP. Maintaining the observed level of ruminant meat limited the GWP reduction and required greater dietary changes.

***4.1 Optimized diets following NNR2023 guidelines***

We found that optimizing the average observed Norwegian diet to follow NNR2023 guidelines alone (Basis scenario) led to a diet with 9% lower GWP, decreased freshwater eutrophication, terrestrial acidification, water use, and land use, and increased marine eutrophication. Increasing intake of white meat and/or legumes did not have a notable impact on the environmental outcomes of following NNR2023 guidelines (sensitivity analysis 3 and 4). Further environmental optimization of the diet resulted in a nutritionally and environmentally optimized diet (Basis+ scenario) with 30% lower GWP than the observed diet, and 15-36% reductions across environmental indicators, with the exception of marine eutrophication, which increased 2%. The optimized diets contained more grains and potatoes, nuts, fruit and vegetables, plant-based fats, fatty fish, and eggs, and less meat, cheese, animal-based fats, and discretionary foods than the average observed Norwegian diet. The main dietary changes involved the substitution of meat with cereals and potatoes, and the intra-category substitution of foods, particularly beef with pork in the meat category and cheese with milk and other dairy products in the dairy category. Although decreased, a substantial amount of animal-based foods remained in the optimized diets (680-700g/d). Significant reductions in GWP can thus be achieved in a Norwegian setting by adopting diets that are healthy and do not require the exclusion of entire food categories from consumption.

These results suggest a synergy between health and environmental goals, in line with NNR2023’s mandate to integrate sustainability considerations into their health-based nutritional recommendations. However, although the majority of environmental measures improved after optimization to follow NNR2023 guidelines, marine eutrophication increased slightly, even after environmental optimization. This finding is in line with our previous research, where scenarios representing the Norwegian FBDG and the EAT-Lancet reference diet showed only minimal reductions in marine eutrophication compared to the observed Norwegian diet, while other impact categories were reduced dramatically (17). Previous evidence suggests that the high contribution of plant-based foods to levels of marine eutrophication necessitates substantial changes in dietary patterns in order to reach significant reductions, and indicates a need for concurrent improvements in production methods (18, 19). Moreover, though water use is often highlighted in the literature as a potential trade-off in ‘sustainable’ diets (20, 21), our results indicate a decrease in water use when switching to healthier and/or more sustainable dietary patterns in Norway. These findings highlight the importance of considering national context when investigating sustainability.

The optimization model was unable to identify feasible diets beyond a 35% reduction in GWP. Previous studies generally measure climate impact in terms of greenhouse gas emissions (GHGEs). A number of these studies have discovered feasible optimized diets at large GHGE reductions (>50%), with some identifying diets at over 70% reductions in GHGE (22-32). However, many of these studies focused on nutrient recommendations, and did not include epidemiology-based targets for food groups (24, 26-31). In addition, many of the optimized diets included increased amounts of fortified plant-based meat and dairy substitutes (23, 26, 28, 29, 33). These foods provide nutrients such as protein, vitamins B12 and D, calcium, iron, and selenium, at a lower environmental impact, and thus often replace animal-based foods in optimized diets (7). However, consumption of these foods is minimal in Norway, decreasing both the likelihood of the model adding these foods, and the acceptability of optimized diets containing these foods. Further, there is a general consensus that GHGE reductions beyond 30-40% may result in impaired nutritional adequacy or require large dietary shifts that may compromise acceptability (21, 31, 34, 35). A GHGE reduction of ~30% corresponds also to the GHGE level of the Danish plant-rich diet, which lays the foundation for the existing FBDG in Denmark, and to that of the optimized diet designed for Denmark by Nordman et al. (36).

The optimized diet for Denmark (36) had a similar but slightly lower content of animal-sourced products (~550g) than in the present study, but these foods were differently distributed. The diet included more total meat, chicken, cheese, and bread, but less beef, egg, milk, fish, grains, and potatoes than the Basis+ scenario diet proposed in the present study. These differences partially reflect cultural differences resulting from national agricultural strategies; however, the differences are likely also due to methodological variations such as source of nutritional and environmental data, and choice of constraints. For example, Nordman et al. (36) chose not to include a sodium constraint, due to their decision to maintain spices at observed level. As a result, the Danish optimized diets included high levels of sodium (>3600mg). The increase in grains and potatoes over bread seen in the present study was likely driven by trade-offs between acceptability of the optimized diet and the high sodium content in some store-bought breads, compared to grains for example, which contain similar nutrients but less sodium. Further, Nordman et al. (36) did not include a co-production factor linking milk and beef production, thus allowing for a lower level of beef in the diet, perhaps making room for higher amounts of cheese and other types of meat with lower environmental impact (poultry, pork). In this way, methodological decisions influence the structure of optimized diets.

Nonetheless, the dietary changes observed in the present study share a number of similarities with previous results from studies performed in other Nordic and European settings (21, 26, 27, 32, 34, 36). For example, we see in both the present study and the optimized diet for Denmark that the amount of red meat is close to the upper limit of 50g (cooked weight) per day, and that the ratio of pork to ruminant meat has increased substantially compared to the observed diet (36). Other optimization studies have also seen a redistribution between ruminant meat and pork and/or poultry (27, 29, 32, 37). Both Grasso et al. (37) and Kesse-Guyot et al. (32) found that total meat content of the optimized diets remained stable up even at a 50% reduction in GHGE, but that meat was strongly redistributed at the cost of ruminant meat. This redistribution is driven by e.g., the compromise between satisfying nutritional constraints for zinc, iron, and sodium, and the environmental constraints (32). In the present study, nutritional constraints for selenium, zinc, and sodium were drivers of the redistribution of meat sources and the maintenance of a considerable red meat intake. Furthermore, previous studies in Nordic countries have reported large increases in the amount of cereals and potatoes in optimized diets (26, 27, 36).

***4.2 The case of ruminant meat***

Another central aim of this analysis was to assess the possibility of maintaining ruminant meat consumption at the observed level in the Norwegian diet, while simultaneously reducing dietary environmental impact. We found that maintaining daily ruminant meat intake at 62 grams (equivalent to ~300 grams cooked meat per week) eliminated the reduction in GWP seen when adjusting the diet to follow NNR2023 guidelines, and increased both freshwater eutrophication and marine eutrophication. However, the adjustment still led to small reductions in terrestrial acidification, water use, and land use. If intake of white meat was simultaneously allowed to surpass the observed level (sensitivity analysis 3), environmental impact increased for all indicators except water use. When imposing stepwise GWP reductions, we found that the model could produce feasible diets at the observed level of ruminant meat consumption up until a 15% reduction in GWP. This diet also reduced freshwater eutrophication, terrestrial acidification, water use, and land use, but increased marine eutrophication by 8%, compared to the observed diet.

The dietary changes required to induce a 15% GWP reduction for the Ruminant+ scenario diet were similar to those seen for the Basis+ scenario at a 30% GWP reduction. However, due to the high contribution of ruminant meat in the Ruminant+ scenario to its overall environmental impact, extensive dietary changes were necessary to elicit even small reductions in GWP. These changes include large increases in the amount of grains while eliminating rice, increases in the amount of legumes and seeds, decreases in white meat, cheese, and discretionary foods, and differential distribution within the fruit and vegetables categories. Moreover, in the Ruminant+ scenario, both total meat and pork were substantially reduced, by 53% and 82%, respectively, in order to satisfy the upper limit for red meat consumption. Since pork is an important source of zinc and selenium in the optimized diets, legumes were increased by 600% to 28g/day to meet nutrient constraints. This is an example of an acceptability trade-off: low legume consumption in the observed diet indicates that large increases in legume content are less acceptable to consumers than increases in other more frequently consumed foods, and potentially unrealistic. However, for population groups intent on maintaining their consumption of ruminant meat, increasing legumes and decreasing intake of other meat types may be a more acceptable dietary change than decreasing ruminant meat. In line with our results, Yin et al. found that inclusion of additional cultural criteria impeded the environmental benefits, again highlighting the trade-offs between sustainability and context-driven acceptability.

***4.3 Strengths and limitations***

The results from the present study are sensitive to our interpretation of the written NNR2023 guidelines. For example, we have chosen a conversion factor of 1:10 for cheese to milk in this study, while the NNR2023 committee provide a range equivalent to 1-2 grams of cheese per 10 g of milk. If we had selected the more generous conversion factor, there would likely not have been as dramatic of a reduction in dairy products in the model, potentially limiting the environmental impact reductions seen in our results. Other examples include the exclusion of juice from the fruit recommendation, upper limit for egg intake, and vegetable oil recommendation. However, we believe that our interpretation is representative of the overall pattern of consumption recommended by NNR2023. Further, our comprehensive approach to the healthiness of the diet by inclusion of epidemiology-based targets for food groups, in addition to nutrient criteria, is a strength of the study.

Quadratic optimization is a data-driven method that is highly sensitive to methodological choices, as well as to the input data and its uncertainties. Methodological choices vary greatly across optimization studies (Gazan et al., 2018). In the present study, we chose a quadratic objective model with the goal of minimizing the departure from the observed diet. Quadratic models penalize large deviations and thereby tend to generate relatively small changes to many separate foods, while linear objective functions tend to generate larger changes to fewer foods. Still, foods that are consumed in very small amounts in the observed diet are less likely to be modified markedly by the optimization model. However, as shown in the study by Yin et al. (1), willingness to make changes in consumption of different foods is often dependent on cultural factors beyond current intake. We included the Ruminant diet scenario in order to highlight the cultural importance of ruminant meat in the Norwegian diet; nevertheless, future research should explore the use of weighting factors based on indicators of people’s readiness to make changes in intake of different food groups.

Using individual diets, rather than population averages (as used in the present study), as the optimization variables is another method of accounting for individual variability in dietary patterns, needs, and preferences. Building one optimization model per person, or per population subgroup, allows for more flexibility in the modelling process. For example, in the present study, we set nutrient constraints based on recommended intakes for the average adult population. For some nutrients (i.e., iron), this ‘combined’ requirement may not cover the needs of certain population groups (i.e., menstruating women). While individual-level optimization allows for preservation of inter-individual variability, its results can be more difficult to communicate due to the multitude of optimization results. As suggested by Gazan et al. (38), we used 53 food sub-groups rather than the original 1,507 food items as decision variables in the optimization models. Reducing the number of decision variables reduced the flexibility of the model, perhaps limiting the GWP reduction potential, but allowed for easier communication of results and guaranteed a variety in the underlying food items. This method is often preferred in studies intended for public health purposes (8, 38). Further, although the environmental database used in the present study contains values for all 53 food sub-groups, we assigned environmental values to 38 aggregated food groups in order to reduce uncertainty stemming from food sub-groups with environmental values based on lower quality input data. The grouping of foods (both nutritional and environmental) involved a series of decisions that were driven by knowledge of the Norwegian context, but ultimately subjective. These decisions likely impacted the optimization outcomes.

Moreover, the quality and uncertainties of the dietary intake, nutrient, and environmental impact data are limitations that may influence the reliability of the results. While the dietary data used in the present study are of a high quality and national representativeness, all dietary data is subject to a number of limitations, such as misreporting and selection bias. Moreover, the dietary data are approximately ten years old; however, the data are considered to represent the Norwegian current diet fairly well because dietary changes at the population level are generally slow [45]. While it is a strength of this study that six environmental indicators were included, environmental data based on life cycle analysis values involves a number of uncertainties (i.e., differences in the methods applied, year of data collection for primary production, standard factors used, etc.). Further, exclusion of avoidable food losses in the environmental database has most likely led to an underestimation of environmental impact for some foods. Inclusion of a co-production factor, often overlooked in similar studies, increased the representativeness of results on a food system level. However, the co-production factor was linked to the food sub-group ruminant meat (e.g., including beef/veal and lamb/mutton), as opposed to beef specifically. This affected environmental values for the sub-group and eliminated in practice content of lamb/mutton in the optimized diets. Further, we recognize that there exist several other dimensions of sustainability that were excluded from this study, including biodiversity and social, economic, and animal welfare concerns such as cultural landscape values and self-sufficiency.

1. **Conclusion**

Our findings indicate that the NNR2023 guidelines outline diets that have generally lower environmental impacts than current average Norwegian diets, though outcomes depend on meat consumption in the diet. Diets that are nutritionally adequate with considerably reduced GWP can be achieved for Norwegian adults, but will require a considerable reduction in the consumption of red/processed meat, poultry, and solid dairy (cheese), along with an increase in intake of grains, potatoes, fruits and vegetables, and plant oils. Moreover, we conclude that it is possible to reduce environmental impact of the diet while retaining a substantial intake of ruminant meat, but that the reduction is smaller and will necessitate substantial dietary changes. However, given the resistance to decreased production and consumption of ruminant meat in Norway (39, 40), communicating alternative pathways to reduced dietary impacts may prove more successful among some population groups. This advice could follow that of NNR2023, emphasizing an increase in whole grains, legumes, and potatoes, and a decrease in total meat quantity (including white meat), cheese and animal-based fats, and discretionary foods.

Our findings contribute to the ongoing work of defining sustainable dietary patterns for Nordic countries. Future research should focus on expanding optimization models to include other aspects of sustainability to better capture the complexity of food systems. This research may consider the use of individual optimization models that account for the needs and preferences of different population groups.

**Tables**

**Table 1.** Overview of variables applied as nutrient and environmental constraints in the optimization models (C) or measured (but not constrained) in optimized diets (m) and nutritional composition of the average observed daily diet (per 10 MJ).

|  |  |  |  |
| --- | --- | --- | --- |
|  | **Constraint limit**✝ | **Observed diet\*** | **Optimized diet** |
| Energy, MJ | 10 | 10 | C |
| Protein, E% | 10-20 E% | 19 | C |
| Carbohydrates, E% | 45-60 E% | 46 | m |
| Added sugar, E% | <10 E% | 8 | C |
| Dietary fiber, g | ≥30 | **28** | C |
| Fat, E% | 25-40 E% | 37 | C |
| Saturated fatty acids, E% | <10 E% | **13** | C |
| Trans fatty acids, E% | ≤1 E% | 0.4 | m |
| n-3 fatty acids, E% | ≥1 E% | 1.2 | C |
| ALA, E% | ≥0.5 E% | 0.9 | m |
| MUFA, E% | 10-20 E% | 14 | m |
| PUFA, E% | 5-10 E% | 6 | m |
| Vitamin A, RE μg | ≥750 | 816 | C |
| Vitamin E, alfa-TE | ≥10.5 | 15 | C |
| Thiamin (Vitamin B1), mg | ≥1 | 2 | C |
| Riboflavin (Vitamin B2), mg | ≥1.6 | 2.3 | C |
| Niacin, NE | ≥16 | 23.2 | C |
| Vitamin B6, mg | ≥1.7 | 1.9 | C |
| Folate, μg | ≥330 | **287** | C |
| Vitamin B12, μg | ≥4 | 8 | C |
| Vitamin C, mg | ≥102.5 | 118.1 | C |
| Vitamin D, μg\*\* | ≥10 | **6.7** | m |
| Sodium, mg | ≤2400\*\*\* | **3248** | C |
| Potassium, mg | ≥3500 | 4510 | C |
| Calcium, mg | ≥967 | 1108 | C |
| Magnesium, mg | ≥325 | 387 | C |
| Phosphorus, mg | ≥520 | 1950 | C |
| Iron, mg | ≥10.8 | 11.3 | C |
| Zinc, mg | ≥11.2 | 12.5 | C |
| Iodine, μg | ≥150 | 220 | C |
| Selenium, μg | ≥65\*\*\*\* | **61.2** | C |
| Copper, μg | ≥0.9 | 1.4 | C |
| Alcohol, g\*\*\*\*\*\* | 0 | **9.3** | C |
| **Environmental constraints** | | | |
| Global warming potential, kg COe-eq | \_ | 5,2 | m/C\*\*\*\*\*\* |
| Freshwater eutrophication, g P-eq | \_ | 1,2 | m |
| Marine eutrophication, g N-eq | \_ | 4,9 | m |
| Terrestrial acidification, g SO2-eq | \_ | 55 | m |
| Water use, m2 | \_ | 0,6 | m |
| Land use, m3a | \_ | 5,8 | m |

Bold numbers indicate suboptimal amounts in the observed diet.

✝ Micro- and macronutrient limits based on nutrient recommendations from the Nordic Nutrition Recommendations 2023 (NNR2023). Micronutrient limits are recommended intake (RI) or adequate intake (AI) values, unless otherwise specified (3).

\* Based on daily dietary intake data for adults 18-70 years from the Norkost 3 national dietary surveillance survey 2010-2011 (2).

\*\* Vitamin D was not constrained.

\*\*\* The sodium limit recommended by NNR2023 is 2300mg. As spices (including salt) have been fixed to observed level in this study, the sodium constraint has been slightly relaxed to the level recommended in The Nordic Nutrition Recommendations 2012 (NNR 2012)(9).

\*\*\*\* The average requirement (AR, average for males and females) for selenium has been used in this study. The RI of selenium is 82.5 μg.

\*\*\*\*\* NNR2023 recommend abstinence from alcohol consumption. NNR2012 recommend consumption <10 g/d for women and < 20 g/d for men. The observed consumption is thus below this recommendation, but above the recommendation given in NNR2023 (abstain).

\*\*\*\*\*\* The observed diet was first optimized according to nutrient, health, and realism constraints alone. In this model, global warming potential was measured, not constrained. In the follow models, global warming potential was constrained in 5% reduction increments (-5%, -10%, -15% …).

**Table 2.** Overview of health-based constraints for food amounts in the Basis and Ruminant scenarios, compared to amounts in the average observed daily diet (g/10 MJ). Detailed information on content of all 53 food groups in the optimized diets is available in Supplementary Table 3.

|  |  |  |  |
| --- | --- | --- | --- |
|  | **Consumed amount** | **Constraint limit** | |
|  | **Observed diet\*** | **Basis** | **Ruminant** |
| Whole grains, g | 70 | ≥90 | ≥90 |
| Fruit, g | 200 | ≥250 | ≥250 |
| Juice, g | 120 | ≤100 | ≤100 |
| Vegetables, g | 180 | ≥250 | ≥250 |
| Pulses and legumes, g | 4 | - | - |
| Nuts, g | 4 | ≥20 | ≥20 |
| Vegetable oils and margarine, g | 16 | ≥25 | ≥25 |
| Milk and dairy products, g \*\* | 790 | 350-500 | 350-500 |
| Total fish, g | 80 | 52-78 | 52-78 |
| Fatty fish, g | 28 | ≥35 | ≥35 |
| Eggs, g | 27 | ≤55 | ≤55 |
| Total meat, g | 165 | - | - |
| White meat, g | 39 | ≤39 | ≤39 |
| Red meat, g | 122 | ≤73 | ≤73 |
| Ruminant meat, g | 62 | - | ≥62 |

Food amounts in raw weight. Optimization scenarios: (1) Basis, health constraints based on NNR2023 with no adjustments; (2) Ruminant, additional lower limit for intake of ruminant meat (≥ observed intake).

\* Based on dietary intake data for adults 18-70 years from the Norkost 3 survey 2010-2011 (2).

\*\* Milk-equivalents, using a conversion factor of 1:10 (10 grams of cheese per 100g of milk) (3, 12). Does not include dairy fats (e.g., butter).

|  |
| --- |
|  |

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
|  | **Observed diet**✝ | **Basis** | **Ruminant** | **Basis+** | **Ruminant+** |
| Bread | 192 | 185 | 161 | 204 | 203 |
| Other grains | 40 | 77 | 73 | 114 | 167 |
| Cakes, cookies | 41 | 71 | 82 | 73 | 28 |
| Potatoes | 76 | 139 | 137 | 187 | 122 |
| Vegetables | 165 | 270 | 269 | 250 | 250 |
| Fruit and berries | 200 | 313 | 343 | 250 | 250 |
| Milk | 278 | 345 | 344 | 412 | 411 |
| Other dairy | 80 | 108 | 102 | 45 | 47 |
| Cheese | 43 | 5 | 5 | 4 | 4 |
| Nuts and seeds | 4 | 21 | 21 | 21 | 24 |
| Legumes | 4 | 6 | 6 | 7 | 28 |
| Eggs | 27 | 55 | 55 | 55 | 55 |
| Fish | 80 | 78 | 78 | 78 | 78 |
| Ruminant meat | 62 | 42 | 62 | 13 | 62 |
| Pork | 60 | 30 | 10 | 56 | 11 |
| White meat | 38 | 38 | 38 | 16 | 4 |
| Other meat | 5 | 2 | 2 | 2 | 1 |
| Fats, plant-based | 16 | 25 | 25 | 25 | 25 |
| Fats, animal-based | 16 | 2 | 2 | 2 | 2 |
| Juice | 120 | 100 | 100 | 12 | 12 |
| Other beverages | 397 | 223 | 255 | 26 | 26 |
| Sweets, snacks | 23 | 25 | 27 | 7 | 2 |
| Water, coffee, tea | 2236 | 2236 | 2236 | 2236 | 2236 |
| Other | 32 | 5 | 5 | 5 | 5 |
| **Environmental measures** |  |  |  |  |  |
| Global warming potential,  kg COe-eq | 5.2 | 4.7 **(-9%)\*** | 5.1 **(0%)** | 3.6 **(-30%)** | 4.4 **(-15%)** |
| Freshwater eutrophication,  g P-eq | 1.15 | 1.1 (-4%) | 1.2 (+3%) | 0.9 (-22%) | 1.0 (-13%) |
| Marine eutrophication, g N-eq | 4.90 | 5.3 (+7%) | 5.4 (+10%) | 5.0 (+2%) | 5.3 (+8%) |
| Terrestrial acidification,  g SO2-eq | 55.00 | 47.1 (-14%) | 53.5 (-3%) | 35.0 (-36%) | 48.1 (-13%) |
| Water use, m2 | 0.59 | 0.5 (-10%) | 0.5 (-7%) | 0.5 (-15%) | 0.5 (-9%) |
| Land use, m3a | 5.82 | 5.1 (-13%) | 5.7 (-3%) | 4.0 (-31%) | 5.4 (-8%) |
| **Acceptability** |  |  |  |  |  |
| ∆diet (%)\*\* | - | 57 | 60 | 81 | 120 |

**Table 3**. Content of main food groups (g) and environmental impacts (…) per 10 MJ in the average observed Norwegian diet and diet scenarios optimized to meet NNR2023 (3) health and nutrient guidelines, and stepwise global warming potential constraints.

Food amounts in raw weight. Optimization models: Basis, health constraints based on NNR2023 with no adjustments; Ruminant, additional lower limit for intake of ruminant meat (≥ observed intake); Basis+, Basis scenario but with added stepwise GWP constraints; Ruminant+, Ruminant scenario but with added stepwise GWP constraints.

✝ Based on dietary intake data for adults 18-70 years from the Norkost 3 national dietary surveillance survey 2010-2011 (2).

\* Percent change compared to the average observed diet.

\*\* Total departure from observed diet (%).

**Table 4.** Quantities of food groups for a healthy diet with 10 MJ (2390 kcal), generating approximately 3.6/4.4/3.4 kg CO2-equivalents per day (30/15/35/% less than the average observed Norwegian diet✝). Given in raw weight, unless noted otherwise.

|  |  |
| --- | --- |
| **Common to all scenarios:** | * About 200 g of (whole grain) bread and approximately 150 g of other cereals (oats, breakfast cereals, pasta, etc.) per day |
| * At least 180 g of potatoes per day |
| * Up to one portion of baked goods (cake, waffles, buns, crackers, etc.) per day |
| * At least 500 g of fruits and vegetables per day |
| * Between 20-30 g of nuts per day * About one egg per day * Not more than 450 g of milk and dairy products per day, and about two slices of cheese per week (30 g) * About three portions of fish and other seafood per week (450g\*), where at least one is fatty fish (200g\*) * Around 25 of vegetable oils and margarine per day, and little to no butter and animal fats |
| **Choose one:** | Basis+ (-30% GWP) |
| * Not more than one small portion (60 g\*) of beef per week * Around 2 portions (270 g\*) of pork per week * One small portion (80 g\*) of poultry per week * At least one small portion (50 g) of legumes per week |
| Ruminant+ (-15% GWP) |
| * Not more than two portions (300 g\*) of beef per week |
| * One small portion (50 g\*) of pork per week * One very small portion (20 g\*) of poultry per week |
| * At least 2.5 portions (200 g) of legumes per week |
| Legumes+ (-35% GWP) |
| * Not more than one small portion (60 g\*) of beef per week * One very small portion (30 g\*) of pork per week * One very small portion (20 g\*) of poultry per week * One portion of legumes (70 g) per day |

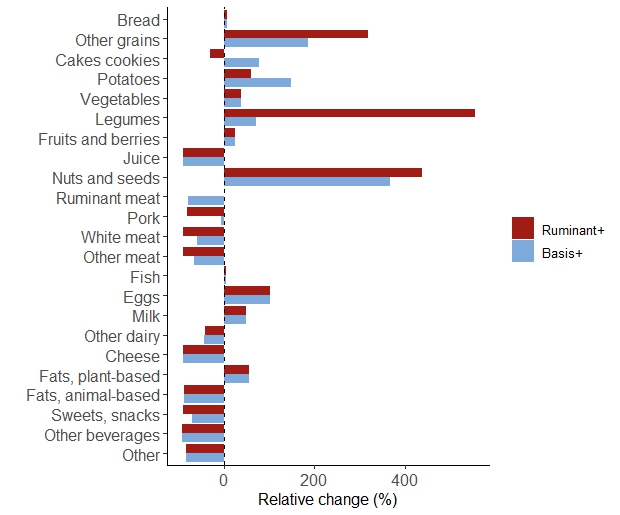
Optimization models: Basis+, NNR2023 guidelines with no adjustments (3); Ruminant+, additional lower limit for intake of ruminant meat (≥ observed intake); Legumes+, lower limit for intake of pulses and legumes (≥40 g) and includes elements from the Danish FBDG (2020)(16) (fruit and vegetables ≥ 300g each; total meat ≤350 g/week)(Fourth sensitivity analysis – See Supplementary Table 5).

✝ Based on dietary intake data for adults 18-70 years from the Norkost 3 national dietary surveillance survey 2010-2011 (2).

\* Cooked weight.

**Figures**

**Figure 1.** Relative changes (%) in food groups compared to the average observed Norwegian diet✝, after optimization of different dietary models to meet NNR2023(3) health and nutrient guidelines, and GWP constraints.



Optimization models: Basis+, NNR2023 guidelines with no adjustments (3); Ruminant+, additional lower limit for intake of ruminant meat (≥ observed intake);

✝ Based on dietary intake data for adults 18-70 years from the Norkost 3 national dietary surveillance survey 2010-2011 (2).

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