Article

Optimizing school food supply: integrating environmental, health, economic, and cultural dimensions of diet sustainability with linear programming

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Abstract: Minimizing greenhouse gas emissions (GHGE) from public sector meals bears considerable potential to reduce climate impact. This paper aimed at finding an appropriate strategy for reducing GHGE in the Swedish school food supply without compromising its nutritional adequacy, affordability, and cultural acceptability. Prices, amounts, and GHGE of all foods and drinks supplied to three schools over one year were optimized by linear programming. Three models were developed: Model 1 minimized GHGE while constraining relative deviation (RD) from observed food supply; Model 2 minimized total RD while imposing stepwise GHGE reductions; Model 3 additionally constrained RD for individual foods to -75% and +200% of observed values.

Model 1 reduced GHGE by 89-95% with an average RD (ARD) from observed food supply of 480-887%. In Model 2, comparable GHGE reductions (80%-95%) at lower ARD (78%-459%) were achieved but with high RDs for individual foods. Model 3 excluded no foods, avoided high RDs, and reduced GHGE by 40% in all schools with ARDs of 7.2-8.1% at 12-15% lower cost. An omnivorous, nutritionally adequate, and affordable school food supply, with considerably lower GHGE is achievable with moderate changes to the observed food supply. This method could also be applied in other settings and countries.

Keywords: nutrition; children; greenhouse gas emissions; school meals; sustainability

1. Introduction

The emission of anthropogenic (human-induced) greenhouse gases has been established as a driver of climate change being one of three earth system processes that has reached critical levels [1], and is therefore a major threat to the health of humans, animals, natural habitats [2,3]. Today's food production systems account for about 25% of the world's anthropogenic greenhouse gas emissions (GHGE), and contribute substantially to deforestation, the exploitation of land and freshwater, nitrogen cycle disruption, and the loss of biodiversity [4]. Moreover, suboptimal diets have been shown to have negative impacts on both mortality and morbidity from non-communicable diseases such as cardiovascular diseases, cancer and type-2 diabetes [5]. Increasing wealth and urbanization often result in a dietary shift towards increased consumption of resource-demanding and greenhouse gas-intensive foods, frequently of animal origin, and a reduced consumption of e.g. whole foods such as legumes, vegetables and fruits [6–8]. Hence, in order to improve health, reduce anthropogenic GHGE, and further contribute towards reaching several of the 2015 Sustainable Development Goals [9] and the Paris Agreement [10], fundamental changes of our diets are needed, as also emphasised by the 2019 EAT Lancet Commission [11].

In 2012, the Food and Agriculture Organization (FAO) of the United Nations (re-)established the concept of sustainable diets and described them as: "[…] *protective and respectful of biodiversity and ecosystems, culturally acceptable, accessible, economically fair and affordable; nutritionally adequate, safe and healthy; while optimising natural and human resources*" [11]. These dimensions of diet sustainability are not always compatible or synergistic, and often trade-offs have to be made between different demands such as nutritional adequacy, environmental impact, and affordability [12].

One method suitable for optimizing diets and identifying mathematically the best trade-offs is linear and non-linear programming. Few studies in the area of diet sustainability optimisation have used this method; more common are studies that explore the concept by assessing health and/or environmental aspects of self-selected diets [13–19]. However, optimization has been used to minimize the cost of nutritionally adequate diets [20–22], as well as to identify diets with reduced GHGE [23–28]. To the best of the knowledge of the authors, no study has so far applied the method to public meal planning.

Many countries provide meals in the public sector, which are a substantial source of diet-related GHGE. In Sweden, meals produced and served in the public sector such as in schools, hospitals, and care homes are provided to up to one third of the population (three million) daily. Fully subsidized lunches are served daily in primary schools to all 1.3 million children aged 6 to 15 [30]. Due to their reach and scale (approximately 230 million meals/year), school meals have substantial potential to shape children's diets and impact on GHGE—in both the short and long term. The total GHGE coming from food consumption has been estimated to be about two tons of carbon dioxide equivalents per Swedish person and year [31]. Given the demanded 30% coverage of calories per meal, the total GHGE associated with school meal serving can be estimated to be approximately 780,000 tons per year.

The aim of this study was to find an appropriate strategy of reducing GHGE in the Swedish school food supply using linear programming, without compromising its nutritional adequacy, affordability, and cultural acceptability.

2. Materials and Methods

2.1 DATA ACQUISITION

Annual observed school food supply

Three municipalities in Sweden provided data on school food purchases for one of their primary schools. Information on all foods and drinks purchased during the school year of 2015/2016 was obtained through the municipality's procurement system [30]. This system provides data on amounts of each food bought in kilograms (kg) and its price (total cost and price per kg). The weight of nutritionally identical food items, bought on several occasions over the school year, was aggregated to a total weight for each school separately. Foods bought as organic and non-organic variants, as well as frozen and fresh, were not aggregated, but instead treated as separate foods items due to differences in price. The price of each food was calculated based on the average price paid for all deliveries of that food weighted by the amount ordered. Very expensive foods and drinks contributing only marginally to nutrient supply such as spices, foods for special needs (e.g. gluten-free bread), bottled water, baking powder, or items considered to have been bought for canteen staff such as coffee and tea were excluded from the list. In the end, the observed food supply was based on 499 food items in School 1, 539 items in School 2, and 367 items in School 3.

The National Food Agency's guidelines for "Good school meals" recommends that the school lunch should cover 30% of the daily dietary reference values on average [31]. Assuming a school with 50% girls, 50% boys, and equal numbers of pupils in each of the 10 primary school age categories (6–15 years), a reference lunch for a reference pupil should provide 604 kilocalories (kcal) according to these recommendations [32]. This value, together with the total amount of kcal for all foods purchased by each school for the entire school year, was used to calculate an energy-standardized food supply for one reference pupil and lunch, i.e. the energy-proportional shares of each food item adjusted for the estimated energy requirement. The energy-proportional shares of each food for one pupil and lunch were calculated for modelling purposes and represent the observed food supply for the entire school year. For example, all foods purchased for the entire school year in School 1 contained approximately 46 million kcal. The total amount of salmon purchased was 99 kg, with an energy content of approximately 99000 kcal. As the energy content for a lunch for a reference pupil should be 604 kcal, the energy-proportional share of salmon for one pupil and lunch was about 1.3 g (i.e. the average intake per day over the school year). This approach was applied to all foods, which all together constituted the observed food supply per pupil and lunch.

Nutritional composition of foods

Data on nutritional composition of foods as eaten (e.g. cooked rice) were extracted from the Swedish National Food Agency's food database containing 2088 food items [33]. For foods not appearing in this database, data from the Norwegian Food Composition Table [34] and the USDA food composition databases [35] were consulted, respectively. Yield factors and edible proportions, as provided by the food composition databases, were applied to convert weights of purchased raw foods into weights of edible food. Foods delivered in units (e.g. limes) were converted to weights [36]. All calculations on nutritional adequacy referred to the nutrient content of the edible shares of prepared (cooked, simmered, fried, baked etc.) foods (see below). Hence, unavoidable kitchen food waste is considered in all calculations. Although nutritional adequacy was calculated on the basis of the composition of edible shares, the results (cost, weight, greenhouse gas emissions) refer to the amount of raw food as purchased. These values were, adjusted to reflect the amounts as raw. The salt intake was estimated to be 20% of the purchased amount based on the estimation that only a part of the salt applied to cooking water ends up in consumed food such as pasta [33,34].

Greenhouse gas emissions (GHGE) of foods

The GHGE of the foods were expressed as carbon dioxide equivalents (CO_2eq) of food products, weighted for typical Swedish consumption patterns [39] The weighting accounts for the differences according to production systems, origin and consumption. For example, the GHGE emission for the average tomato consumed in Sweden is the average GHGE for tomatoes grown in Sweden, the Netherlands and Spain, weighted by share of total consumption. These data were extracted from the Climate Database from the Research Institutes of Sweden, RISE, which builds on results from life cycle analyses [38,39] and Swedish food supply/purchasing patterns [39]. The climate database contains values for several GHGE (carbon dioxide, CO_2; methane, CH_4; and nitrous oxide, N_2O) that are weighted in line with their respective global warming potential over a 100 year period, using factors recommended by the Intergovernmental Panel on Climate Change [40]. This yields a single value for the combined GHGE, measured as kg of CO_2eq per kg of food item (kg CO_2eq/kg), also known as "carbon footprint". The system boundaries for calculating the CO_2eq values are from primary production until the factory gate (packaging, further distribution to shops and homes, meal preparation after delivery and waste management are not included). The CO_2eq calculations include contributions from imported products where the climate impact for a standard assumed transport to Sweden is included [38,39]. As the nutritional value of the supply was calculated on the basis of edible shares but the CO_2eq value was based on the weight of the raw food, CO_2eq losses from unavoidable food waste are considered. The Climate Database contains 2078 foods commonly consumed in Sweden as well as foods of particular interest from a nutritional and/or environmental point of view and is linked to the Swedish National Food Agency's food database with information on nutritional content. For analytical and descriptive purposes, foods were grouped in 12 food categories, as defined in the climate database (Eggs; Drinks (w/o milk); Fats and oils; Seafood; Fruits and berries; Vegetables and roots; Meat; Cereals; Dairy; Nuts and seeds; Seasoning and sauces; Sugar and sweets).

2.2 OPTIMIZATION

Linear optimization

Linear programming (LP) is the application of an algorithm for maximizing or minimizing a given (linear) objective function subjected to a set of (linear) constraints on a list of decision variables [41]. It consists of three major elements: (i) the objective function (a loss function or its negative of the goal variable), (ii) the decision variables (the variables to be changed by the model), and (iii) a set of constraints (criteria to be met). If all conditions can be met, then a solution is said to be found. In LP models, constraints that determine the degree to which the objective function can be minimized or maximized are called "active constraints" [42]. Nutrients that met exactly 100% of their reference values in the solution were identified as active constraints. Non-active constraints are per definition above the minimum or below the maximum limit, once the active constraints have determined the solution of the model. Linear optimization was performed with the COIN Cut and Branch Solver algorithm, which is part of the Excel® 2016 software add-in OpenSolver, V. 2.8.6 [43].

Nutritional adequacy of optimized food supply

Based on the Nordic Nutrition Recommendations 2012, dietary reference values (DRVs) for planning school meals in Sweden were implemented as obligatory constraints in the optimizations [32,44]. The DRVs used were the equivalents (30%) of the estimated energy requirements (EER), recommended intake ranges for macronutrients, the recommended intakes (RIs) and estimated upper intake levels (ULs) of micronutrients [44]. The nutritional constraints for a reference pupil were set by averaging the DRVs over ten ages and both sexes (Table S1). All optimized food supply solutions met the DRVs for a Swedish school lunch.

After optimization, amounts of the optimised food category supply was compared to the recommended intake in this food category. For this comparison, the Swedish food-based dietary guidelines (FBDGs) were used [45].

Total GHGE of observed and optimized food supply

The GHGE of the observed and optimized food supply were calculated as the sum of the corresponding raw food weights multiplied with their specific CO_2eq value in the Climate Database.

Total cost of observed and optimized food supply

The total weight of each food product was calculated and multiplied by the specific cost of the product as purchased by the schools to obtain the cost of the observed and optimized food supply, respectively.

Deviation from observed food supply

To assess the similarity of the optimized food supply with the observed list of food items, the relative (= percentual) deviation (RD) was calculated. For example, if 100 kg of potatoes were used in the previous school year in one of the school canteens and 120 kg of potatoes were included in the optimized solution, the relative deviation would be +20%. Hence, the absolute relative deviation [abs(RD)] of the amounts suggested by the linear programming algorithm from observed supply of each food item the is the non-negative value of the relative deviation and was calculated for each food item according to Formula 1:

$$\boldsymbol{abs}(\boldsymbol{RD_i}) = \frac{abs(M_i - m_i)}{m_i} \qquad \text{(Formula 1)},$$

where m stands for the observed supply of the i-th food item in grams provided to the reference pupil and M_i is the weight of the i-th food item after optimisation. The absolute value of RD for each individual food item [abs(RD_i)] was used as a constraint in Models 1 and 3. In order to achieve the least deviation from (or the highest similarity to) the observed food supply, the total sum of the absolute values of RDs (=TRD) from all N food items in the model was calculated and used as the objective function in Models 2 and 3 (Formula 2):

$$\boldsymbol{TRD} = \sum_{i=1}^{N} \boldsymbol{abs}(\mathbf{RD}_i) \qquad \text{(Formula 2)}.$$

The average relative deviation (ARD) from the observed food supply was used as a proxy of similarity between the observed and the optimized food supply and was calculated by dividing the TRD by the model's total number of food items (N), as given in Formula 3:

$$\boldsymbol{ARD} = \boldsymbol{TRD}/\boldsymbol{N} \qquad \text{(Formula 3)}.$$

Models

In this study, three different models were developed for the LP analyses. An overview of the applied models and their corresponding objective functions, constraints and calculated outputs is given in Table 1.

Model 1—Minimizing GHGE of observed food supply ($GHGE_{min}$), while meeting nutritional constraints

In Model 1, the objective function of the linear programming model was the minimization of the total GHGE (calculated as CO_2eq) of the observed food supply. The decision variables were the amounts of edible foods that were eligible to be included into the optimized food supply for a pupil and one lunch. The only set of constraints initially applied was to meet the DRVs of energy and nutrients to explore how much GHGE could be reduced maximally without compromising nutritional adequacy. Each food item was allowed to increase or decrease unconditionally in weight from the observed food supply. Subsequently, the RD of each food item was constrained in a step-wise process in order to limit the deviation from the observed food supply. Each food was allowed to increase/decrease first by +1000/-100%, then by +500/ 100%, +300/-100%, ±100%, ±99%, ±90%, ±80%, ±70%, ±60%, ±50%, ±45%, and ±40% or until the model did not provide any solution. This was done to explore how the school food supply changed compared to baseline for each step of restriction as well as to explore the changes occurring between the different steps. The computed outputs of the model were the TRD, the ARD, the cost and the total daily GHGE. As the TRD depended on the original number of foods

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in the school's observed food supply, the TRD was not comparable across the schools. Therefore, only the ARD value is reported.

Model 2—Minimizing the total absolute relative deviation (TRD_{min}) from observed food supply with stepwise reduction of GHGE

Model 2 was established to explore the possibility to attain a higher degree of similarity to the observed food supply (i.e. less deviation) than achieved in Model 1 but at comparable GHGE reductions. In Model 2, the objective function of the LP model was the minimization of the TRD from the observed food supply while still ensuring nutritional adequacy and imposing stepwise reductions of GHGE by relative values (until a feasible solution that satisfied all constraints could not be found). As TRD is not a linear function and therefore cannot be part of the linear equation system used by LP, new decision variables Z_i: $Z_1 \rightarrow Z_n$ were created according to Darmon et al. [46]. The new decision variables were submitted to the following constraints (Formula 4):

$$Z_i \geq (m_i - M_i)/m_i \text{ and } Z_i \geq -(m_i - M_i)/m_i \qquad \text{(Formula 4).}$$

Thus, for each standardized difference, its absolute (positive) value was selected because Z_i by definition has to be greater than or equal to both the relative difference and its inverse value. The TRD_{min} model allowed for a minimization of the sum of the absolute values of all relative deviations from the observed food supply [46]. In the TRD_{min} model, no limits were set to the RDs of the individual food items supplied. The computed outputs of the model were the ARD, the cost and the total daily GHGE.

Model 3—Minimizing the total absolute relative deviation (ARD) from observed food supply with stepwise reduction of GHGE while constraining the RD (CRD_{min}) of individual food items range between -75% and +200%

In Model 3, (CRD_{min}), we limited the RD of individual food items to decrease by a maximum of 75% and increase by a maximum of 200% in order to increase food variability and avoid the extreme deviations for individual food items that Model 2 still resulted in. The outputs of the model were the ARD, the cost and the total daily GHGE. Additional outputs of all models were the type and number of foods removed, reduced or increased from the observed food supply. The total food category deviation (TFCD) was calculated as the sum of shares of optimized weights in each main food category that were replaced by other food items belonging to the same category [37].

Table 1. Characteristics of the three linear programming models applied to optimize the food supply. All models used the amounts of foods supplied as decision variables. All solutions provided by the models fulfilled the imposed set of nutritional constraints as provided in Supplemental Table 1.

Acronyms of models	Objective function (minimum)	Climate impact (CO_2eq)	Affordability (cost in SEK)	Cultural acceptability	Mathematical feasibility criterion
Model 1: $GHGE_{min}$[a]	GHGE[b]	Minimized	Calculated output	ARD calculated output, RD constrained	Individual food items' RD progressively reduced, from 1000% until not feasible
Model 2: TRD_{min}[c]	TRD	Progressively constrained by steps of 10% until feasibility stopped	Calculated output	TRD minimized, ARD calculated output	Individual food items' RDs unconstrained (all food items can deviate unconditionally)
Model 3: CRD_{min}[d]	TRD	Progressively constrained by steps of 10% until feasibility stopped	Calculated output	TRD minimized, ARD and TFCD calculated outputs	Single food items' RDs constrained to interval between -75% and +200%

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[a] $GHGE_{min}$, optimized for lowest achievable GHGE.
[b] As total sum of CO_2eq.
[c] TRD_{min}, optimized for minimum total relative deviation with unconstrained relative deviation for individual food items.
[d] CRD_{min}, optimized for minimum total relative deviation with RD constrained for individual food items to range between -75% and +200%
RD, relative deviation from observed food supply; SEK, Swedish krona, (1 SEK ≈ 0.106 United States dollar); TRD, total relative deviation; ARD, average relative deviation; TFCD, total food category deviation

3. Results

The observed food supplies for the three schools in 2015/16, when standardized to an energy requirement of 604 kcal per pupil and lunch, were associated with GHGE of 810g, 1022g, and 967g CO_2eq, at a cost of 9.1, 10.6, and 11.2 Swedish krona (SEK), respectively (1 SEK ≈ 0.104 United States dollar or 0.092 €). The observed food supply did not meet the requirements for vitamin D (nutrient supply was 61-97% of RI), iron (82-88% of RI), and saturated fatty acids (135-140% of %E targets). Minimizing GHGE while constraining for nutritional adequacy only ($GHGE_{min}$, Model 1) resulted in a solution containing 7-9 foods only, out of the 367 to 539 original foods that were purchased during the school year 2015/16 (Table S2). The GHGE values of the optimized food supply were 89-95 % lower than the observed supply (51-86 g/meal), at a cost ranging between SEK 3.9 and 6.5 (Table S2). Model 1 suggested radical changes, containing considerably higher amounts of a few single foods such as potatoes, herring and chickpeas as compared to observed quantities. Entire food categories such as Meat, Eggs, and Dairy comprising the majority of foods were omitted completely.

When progressively limiting the maximum relative deviation (*abs(RD)*) in Model 1, the number of foods in the optimized supply increased but so did the GHGE (Table 2). The lowest ARD achieved in Model 1 was 39.8% in School 1, 44.7% in School 2 and 69.6% in School 3. At these ARDs, the GHGE were reduced by 16%, 5.6% and 38% respectively, compared to the observed levels. Most of the optimized food assortments costed less than the observed supplies. The active constraints in this model were saturated fatty acids (upper limit), vitamin D (lower limit), iron (lower limit), and salt (upper limit) in all schools and polyunsaturated fatty acids (lower limit) in School 2. Hence, these five nutrients were active constraints, controlling how much it was possible to reduce the GHGE of the optimized food supply.

When minimizing the TRD from observed food supply (TRD_{min}, Model 2) and applying step-wise reductions of GHGE, both the ARD and the number of foods removed increased gradually (Table 3). Going for the least GHGE, CO_2eq values could be reduced by as much as 80%, 90%, and 95% for Schools 1, 2, and 3, respectively, with ARD values ranging between 78% and 459%. Model 2 delivered a solution that reduced GHGE by 40% while keeping the ARD within a range of 4.3 to 4.9% (Table 3). In contrast, to achieve GHGE reductions by 40% in Model 2, Model 1 required ARD values ranging between approximately 60% and 70% (Table 2).

In Model 2, foods excluded or reduced relatively to the observed food supply were primarily items from the food categories Meat, Eggs, and Fats and oils (Figure S2) as well as items from the subcategories Cheese, Cream, and Rice. The types of foods that increased were mainly items from the food category Vegetables and roots, and items from the subcategories Bread, Fish, Margarine, Milk, and Offal. Although the ARD values in Model 2 were low compared to Model 1 (at comparable GHGE reductions), the relative increase in the supply of some individual foods turned out to be high (e.g. at 40% lower GHGE, Bread in Schools 1 and 2 and Offal in School 2 increased more than 8-fold). In Model 2, only a few food subcategories of animal origin were included at greater amounts compared to the observed supply (Salmon; Milk; and Offal, typically blood sausage/black pudding), while most of the changes resulted in an increased supply of plant-based foods.

In Model 3, limiting the RD of individual food items to a more acceptable range between -75% and +200% (CRD_{min}) from the observed food supply, resulted in more foods being reduced or increased (Table 4), as compared to Model 2 where foods were allowed to be excluded entirely and/or to increase unconditionally (Table 3). At 40% lower GHGE, the ARD was slightly higher in Model 3 (7.2-8.1%) as compared to Model 2 (4.3-4.9%) (Tables 3 and 4). However, the high relative increase in the supply of some food subcategories in Model 2 (Figure S1) was avoided in Model 3 (Figure S2). Moreover, no foods were excluded entirely in Model 3, thus increasing the food variability of the optimized solutions. Offal (i.e. blood products) and milk remained in the optimized supplies while the amount of meat was reduced (Figures S1 and S2).

As shown in Figure 1, the ARD in Model 3 did not increase markedly until a GHGE reduction of 30-40% was reached. Figure 2 further illustrates the absolute changes by main food category and the total food category deviation (TFCD) for Model 3 when GHGE were decreased by 40% for the three schools. While the absolute amount of the food category Meat was reduced in the optimizations for all three schools, solutions for Schools 1 and 2 differed in the main food categories Dairy; Vegetables and roots; and Cereals. For example, optimizing the food supply resulted in lower quantities of Milk in Schools 1 and 2, but greater quantities in School 3. The main changes in Model 3 occurred rather between than within the food categories (Figure 2).

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Table 2. ARD, cost, and associated GHGE (CO_2eq) when minimizing GHGE while applying constraints on nutritional adequacy and maximum allowed RD from observed food supply (Model 1, $GHGE_{min}$).

	ARD (%)			Cost[a] (SEK)			CO_2eq[b] (g)			# of food items Removed[c]			# of food items Reduced[c]			# of food items Increased[c]		
School #	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**
Observed value				**9.07**	**10.63**	**11.22**	**810**	**1022**	**967**	**499**	**539**	**367**	**499**	**539**	**367**	**499**	**539**	**367**
Max. RD per food (%)[d]																		
Unconstrained[e]	887	293	480	6.50	5.54	3.88	86	72	51	492	532	358	0	1	0	7	6	9
1000	229	235	203	9.16	8.63	4.11	174	127	126	423	453	317	2	1	4	74	85	46
500	166	178	164	8.47	8.75	5.57	201	180	192	410	427	300	2	3	2	87	109	65
300	145	150	137	8.03	8.17	5.85	224	212	223	379	399	292	1	1	1	119	139	74
100	99.5	99.2	99.0	7.27	7.71	6.66	277	295	293	301	261	254	3	3	2	195	275	111
99	98.5	98.2	98.1	7.28	7.70	6.72	282	302	300	0	0	0	302	262	251	197	277	116
90	89.6	89.4	88.9	7.41	8.11	7.58	325	361	373	0	0	0	301	247	253	198	292	114
80	79.5	79.6	79.7	7.56	8.73	8.14	373	445	463	0	0	0	301	240	246	198	299	121
70	69.3	69.7	69.6	7.77	9.31	10.14	423	540	600	0	0	0	281	228	203	218	311	164
60	59.6	59.8	—	7.97	9.73	—	477	653	—	0	0	—	265	219	—	234	320	—
50	49.6	49.7	—	8.28	10.44	—	549	829	—	0	0	—	253	207	—	246	332	—
45	44.7	44.7	—	8.73	10.92	—	605	965	—	0	0	—	237	206	—	262	333	—
40	39.8	—	—	9.20	—	—	680	—	—	0	—	—	207	—	—	292	—	—

[a]Cost of food supply per reference portion after optimization
[b]Amount of carbon dioxide equivalents (CO_2eq) of food supply per reference portion after optimization.
[c]Number of foods removed, reduced or increased after optimization.
[d]Maximum allowed (negative or positive) relative deviation for individual food items from observed food supply during the school year 2015/2016.
[e]No constraint on maximum allowed (negative or positive) relative deviation individual food items from observed food supply during the school year 2015/2016.
ARD, Average relative deviation from observed food supply during the school year 2015/2016 after optimization.
GHGE, Greenhouse gas emissions.
GHGE*min*, optimized for lowest achievable GHGE.
RD, relative deviation from observed food supply during the school year 2015/2016.
SEK, Swedish Krona.
—, No achievable solution.

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Table 3. ARD, cost, and associated GHGE (CO_2eq) when minimizing TRD from observed food supply while applying constraints on nutritional adequacy and relative GHGE reductions (Model 2, TRD_{min}). As the TRD values were not comparable across the schools, the ARD values are reported.

	ARD (%)			Cost[a] (SEK)			CO_2eq[b] (g)			# of food items removed[c]			# of food items reduced[c]			# of food items increased[c]		
School #	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**
Observed value				**9.07**	**10.63**	**11.22**	**810**	**1022**	**967**	**499**	**539**	**367**	**499**	**539**	**367**	**499**	**539**	**367**
CO_2eq constraint[d] (% reduction)																		
Unconstrained[e]	1.5	2.6	3.1	9.26	10.68	11.59	796	1013	998	4	7	4	2	1	4	3	4	2
10	1.7	2.8	3.1	9.20	10.51	11.26	729	920	870	3	6	5	3	3	3	3	3	3
20	2.0	3.1	3.5	8.89	10.44	11.03	648	818	774	5	7	4	3	3	4	3	3	2
30	2.7	3.5	4.0	8.67	10.14	10.91	567	715	677	8	9	6	3	2	4	3	3	2
40	4.5	4.3	4.9	8.22	9.60	10.30	486	613	580	13	11	8	5	2	4	3	3	3
50	8.4	5.9	7.2	7.91	8.79	9.57	405	511	484	30	18	15	3	2	2	4	4	5
60	15.4	9.1	11.4	7.66	8.36	8.76	324	409	387	58	30	24	3	3	1	4	4	5
70	31.9	15.3	19.9	10.15	7.18	7.38	243	307	290	111	39	43	2	2	4	6	5	3
80	78.1	24.5	34.3	10.11	6.62	6.28	162	204	193	176	77	59	1	3	4	8	6	4
90	—	63.2	69.6	—	4.18	4.27	—	102	97	—	210	143	—	2	2	—	6	6
95	—	—	458.8	—	—	3.87	—	—	51	—	—	328	—	—	1	—	—	8

[a]Cost of food supply per reference portion after optimization.
[b]Amount of carbon dioxide equivalents (CO_2eq) of food supply per reference portion after optimization.
[c]Number of foods removed, reduced or increased after optimization.
[d]Maximum allowed amount of carbon dioxide equivalents (CO_2eq) per optimized food supply.
[e]No constraint on maximum allowed amount of carbon dioxide equivalents (CO_2eq) per optimized food supply.
ARD, Average relative deviation from observed food supply during the school year 2015/2016 after optimization.
GHGE, Greenhouse gas emissions.
RD, relative deviation from observed food supply during the school year 2015/2016.
SEK, Swedish Krona.
TRD, Total relative deviation.
TRD_{min}, optimized for minimum total relative deviation from observed food supply with unconstrained RD for individual food items.
—, No achievable solution.

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Table 4. ARD, cost, and associated GHGE (CO_2eq) when minimizing TRD while applying constraints on nutritional adequacy, relative GHGE reductions, and additional constraints on the RD of individual food items from observed food supply when the maximum RD for each food item is delimited to -75% and +200% (Model 3, CRD_{min}).

	ARD (%)			Cost[a] (SEK)			CO_2eq[b] (g)			# of food items reduced[c]			# of food items increased[c]		
School #	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**
Observed value				**9.07**	**10.63**	**11.22**	**810**	**1022**	**967**	**499**	**539**	**367**	**499**	**539**	**367**
CO_2eq constraint[d] (% reduction)															
Unconstrained[e]	1.9	3.7	4.2	9.14	10.70	11.36	781	1094	977	10	13	11	3	11	7
10	2.0	4.1	4.2	9.07	10.41	11.09	729	920	870	10	13	11	3	11	7
20	2.4	4.6	4.4	8.87	9.89	10.89	648	818	774	13	13	12	3	13	9
30	3.8	5.3	5.1	8.42	9.51	10.64	567	715	677	21	14	15	4	14	9
40	7.8	7.2	8.1	7.97	9.04	9.65	486	613	580	41	24	27	7	15	8
50	19.8	11.6	19.0	7.80	8.68	8.34	405	511	484	98	48	74	16	19	11
60	—	62.0	—	—	8.47	—	—	409	—	—	278	—	—	69	—

[a]Cost of food supply per reference portion after optimization.
[b]Amount of carbon dioxide equivalents (CO_2eq) of food supply per reference portion after optimization.
[c]Number of foods removed, reduced or increased after optimization.
[d]Maximum allowed amount of carbon dioxide equivalents (CO_2eq) per optimized food supply.
[e]No constraint on maximum allowed amount of carbon dioxide equivalents (CO_2eq) per optimized food supply.
ARD, Average relative deviation from observed food supply during the school year 2015/2016 after optimization.
CRD_{min}, optimized for minimum total relative deviation while constraining the relative deviation of individual food items to a range between -75% and +200%.
GHGE, Greenhouse gas emissions.
RD, relative deviation from observed food supply during the school year 2015/2016 after optimization.
SEK, Swedish Krona.
TRD, Total relative deviation.
—, No achievable solution.

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A comparison based on data for Figure 2 showed that, the optimized food amounts from Model 3, being 40% lower in total GHGE, met the Swedish FBDGs for fish, red and processed meat, and fruits/vegetables. The solutions provided at least 30% of the recommended 2 portions of 130g of fish/week, and no more than 30% of the maximum 600g recommended red and processed meat per week in all schools. The fruit and vegetable recommendation (30% of 500g/week) was covered in School 1 and almost met by Schools 2 and 3 (68% and 91%, respectively).

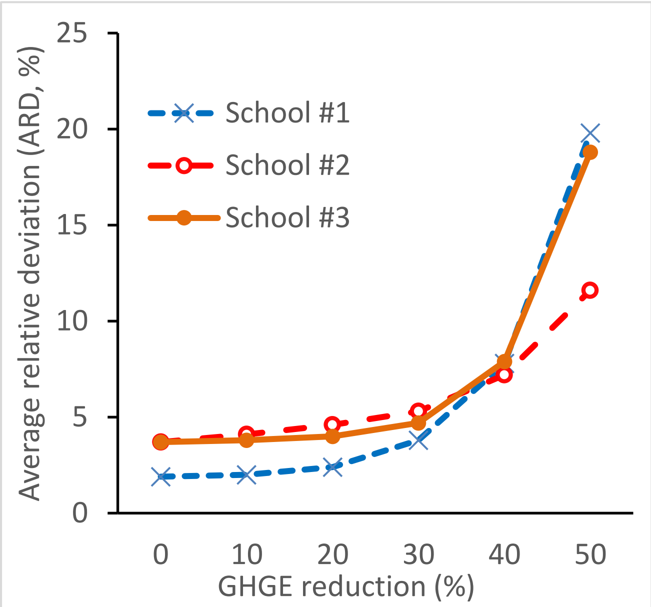

Figure 1. Average relative deviation (ARD) in relation to GHGE reduction (by steps of 10%) when minimizing total relative deviation (TRD) and applying constraints on nutritional adequacy, relative GHGE reductions, and additionally constraining the relative deviation (RD) of individual food items from observed food supply to a range between -75% and +200%; (Model 3, CRD_{min}). The ARD from the observed supply, without constraining the GHGE (X-axis value "0"), was due to nutritional constraints only. GHGE, Greenhouse gas emissions; The RD of the optimized solutions refers to the observed food supply during the school year 2015/2016.

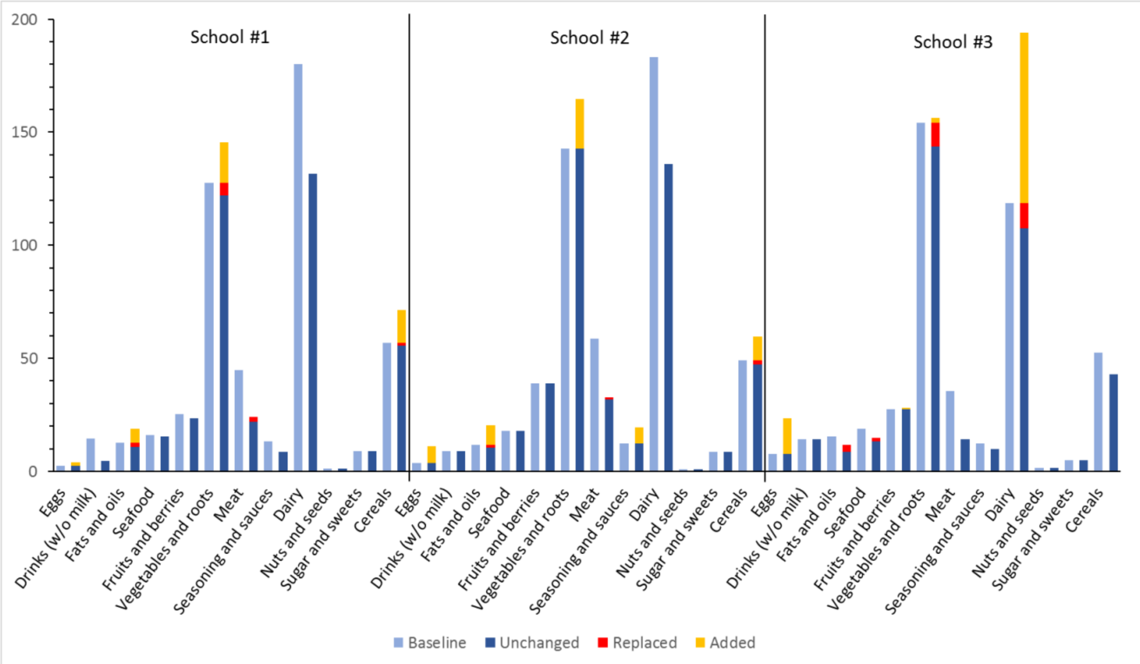

Figure 2. Food category quantities (g/optimized food supply) before (bright blue columns) and after (dark blue columns) optimizing for minimum TRD from observed food supply, when applying constraints on nutritional adequacy, a GHGE reduction of 40% from observed emissions, and additional constraints on the RD of individual food items (Model 3, CRD_{min}). The yellow parts of the column show the main food category amount of the optimized supply and indicate the amount added to this category. The red parts of the column indicate the amount that was replaced by foods from the same category. CRD_{min}, optimized for minimum total relative deviation while constraining the relative deviation of individual food items to a range between -75% and +200%; GHGE, Greenhouse gas emissions; RD, relative deviation from observed food supply during the school year 2015/2016 after optimization; TRD, Total relative deviation.

4. Discussion

In the study at hand, we have shown that considerable reductions in GHGE from school food supply can be achieved even by small changes from the baseline food supply. Seemingly, the best possible optimization strategy is to minimize the deviation from the baseline supply instead of minimizing GHGE. Constraints to be applied during optimization are nutritional adequacy and a maximum decrease of 75% and maximum increase by 200% from the baseline food supply in order to approach cultural acceptability (Model 3). This strategy resulted in a 40% reduction in GHGE. This approach could be applied not only for school settings but also for other sectors for attaining a more sustainable procurement and planning of public meals. Solutions that used GHGE as goal function (Model 1) or minimized the total relative deviation of the food supply without further limiting the deviation of individual foods (Model 2) can barely be considered as realistic solutions due to extreme changes of single foods (Figure S1). In Model 3, the cost for the optimized food supply increased only moderately or in many cases decreased. The proposed changes affected predominantly a limited range of foods; the foods reduced or removed were mainly from the food categories Meat and Dairy whilst those which increased came mainly from the categories Cereals as well as Vegetables and roots. However, all optimized solutions included animal products such as eggs, milk and fish and were therefore omnivorous. Our findings prove that only moderate (≈8%) average deviations from the observed food supply are needed to comply with the 2030 Climate and Energy Framework of the European Commission and its goal of reducing the GHGEs in the Region by 40% by 2030 [47]. A similar conclusion was reached by Milner et al. [50] who modelled a 40% decrease in GHGE of the average UK diet. A high likelihood of acceptability was achieved by Model 3, which also comprised the potential of health gain by being nutritionally adequate.

In a recent review of studies assessing the sustainability of self-selected diets, several incompatibilities between health, affordability, and environmental dimensions of the concept were identified [12]. For example, in studies from France, diets with a higher nutritional quality were associated with higher GHGE [14,15] and higher cost [48]. Similarly, implementing food-based standards for English school meals aiming at improving nutritional quality was shown to result in increased GHGE [49]. Such findings suggest the need for a holistic approach where nutritional adequacy, affordability and acceptability are considered simultaneously [12]. We therefore adopted a comprehensive strategy for Swedish school food supply where GHGE was first mathematically minimized while simultaneously integrating aspects of health, affordability and acceptability, in line with what others have done [23–25,50]. In addition, we showed that by also focusing on minimizing the deviation from the observed supply (as opposed to minimizing GHGE), and additionally constraining the relative deviation of foods to range between pre-determined limits (here we applied a -75%/+200% range), GHGE could still be reduced considerably but with less average deviation from the usual food supply and with no extreme deviations for individual food items that some of our initial models resulted in. Similar to with previous findings [23,26,27], our results suggest that this approach can achieve food supply patterns with low GHGE that are nutritionally adequate and that deviate only moderately from the current supply.

Other researchers aiming to align health and environmental priorities have recommended dietary approaches that exclude entire food categories, such as vegetarianism [16,51,52]. Such approaches are based on the high contribution of livestock to the overall GHGE burden [56]. For health reasons, switching to a vegetarian or vegan diet is not necessarily an advantage. Although overall mortality and incidence of non-communicable diseases decreases with an elevated intake of fruits and vegetables [53], vegetarian or vegan diets do not inevitably result in health improvement [54] and diets with appropriate ratios of vegetables, fruits, pulses, meat and fish are also health-promoting [55,56]. Furthermore, the exclusion of an entire food category such as red meat could compromise iron status in vulnerable populations. Meat has a high bioavailability of iron and also enhances absorption of iron from other foods [57]. Reducing the intake of meat and meat products and substituting it with cereals, pulses, and tubers may negatively affect iron status [57]. The uptake of iron is highly dependent on individual factors (e.g. iron status) combined with the effects of a multitude of dietary inhibitors and enhancers [58] and current recommendations emphasize diversified diets as the most important strategy for achieving an adequate iron status [59]. Moreover, diets excluding meat and meat products may not be culturally acceptable in Sweden where the majority of the population consumes omnivorous diets [60]. Our study shows that considerable GHGE reductions can be achieved by diets without omitting entire food categories.

Limitations

The applied models did not take into account linkages between the production lines of foods, for example, the fact that beef and offal can be consumed as by-products of dairy farming. Offal and milk remained in the optimized supplies while meat was reduced. If these changes would occur at larger scale, the associated changes in consumer patterns may lead to a potential re-allocation of foods with high GHGE away from school canteens to other consumer groups. On a larger scale, particularly after taking market dynamics into consideration, this can lead to inadequate usage of the entire animal and may therefore not result in the desired effect of a reduction in the environmental impact. Therefore, future studies should take the proportionalities among the parts of the slaughtered animals into consideration, along with the implementation of the share of beef that results from milk production, as done e.g. by Barré et al. [27].

Fish, often recommended as an environmentally friendly alternative to red meat [61], was one of the foods which increased considerably in the optimized food supply. Models 2 and 3 suggested increasing the supply of specific fish species (herring). Here, too, it is important to consider external linkages, such as what other fish species are likely to be caught in the same net. Moreover, fish production from wild stocks cannot increase much, as 96% of the world's fish stocks are already either moderately or fully exploited or over-fished [62]. Fish from even the lowest-impact aquaculture systems accounts for GHGE comparable to or even higher than that of poultry, pork and dairy and can be a source of eutrophication [63].

Other relevant aspects of food sustainability such as eco-toxicity, land use change, water use, eutrophication, acidification, animal welfare and biodiversity loss were not considered in the current study. However, data for these parameters are currently much more limited than those for GHGE, which can be used as a proxy for other environmental impact metrics [64].

The modelling of the optimized diets did not consider seasonality, although food purchases covered the whole school year. However, none of the foods reduced or increased after optimization is subjected to limited availability depending on the season (Figure S2). Moreover, buying locally produced foods according to season does not automatically imply lower GHGE as these depend more on production systems (e.g. types of inputs used and characteristics of production processes) rather than on country of origin [65]. The considerable variability in environmental impact of different production systems was not covered in the current study. The use of GHGE-data with improved accuracy for different ways of producing a food item would have given preference to the most climate efficient production systems in the present models. However, that would have required more specific data from life cycle analyses, which to date are not available for the Swedish context.

Finally, although the number of schools was low, they came from different regions of Sweden (the east and south-west). The observed food supply of these schools was comparable to the nutritional quality of school meals today [66] and the solutions for each school were comparable. Our approaches did not include foods that were not already present in the buying lists as they could potentially compromise acceptability (foods that pupils or school canteens are not familiar with). Future optimization studies might explore the inclusion of some of the many new foods emerging on the market with low GHGE in the model, such as oat- or algae-based products, or even include products fortified with important nutrients (i.e. those nutrients constraining the current solutions).

5. Conclusions

In conclusion, the present study shows that a school food supply can be defined, which has considerably lower GHGE, is omnivorous, nutritionally adequate and affordable, by making only moderate changes to what schools are buying today. Linear programming using dietary reference values, cost, the climate impact of foods, and previous food supply patterns can together provide solutions tailored to individual schools in heterogeneous settings. With this method, considerable savings in GHGE, at a minimally modified food supply pattern, can be achieved. These savings may become part of multi-lateral frameworks on effective GHGE reductions [70]. Given the high number of schools and other public sector meals provided daily in Sweden and other countries, the methodology developed could be of great use in future meal planning and procurement. The next challenge will be to translate these new food lists into acceptable school meals in collaboration with professionals from the public meal sector. These aspects will be investigated in a forthcoming intervention study to prove the potential of nutritionally adequate and sustainable school meals in terms of both human and planetary health.

Supplementary Materials: The following are available online at www.mdpi.com/xxx/s1, Table S1: Nutrient constraints applied; Table S2: Amounts, cost, RDs, and GHGE of individual food items in observed and optimized supply, $GHGE_{min}$ Model 1; Figure S1: RD changes of individual food items when minimizing TRD (unconstrained), constraining GHGE (Model 2); Figure S2: RD changes of individual food items when minimizing TRD (constrained to -75%/+200%), constraining GHGE (Model 3). A list of all foods used in the schools can be obtained from the corresponding author upon request. The CO_2eq data can be obtained from RISE, Borås, Sweden (US), upon individual agreement.

Author Contributions: LSE conceived the idea for this project; PEC, EP, LSE, AKL and AP developed the overall research plan and maintained study oversight; The data collection was done by PEC and EP; data analysis was conducted by AP and PEC in collaboration with ND and US; PEC and AP wrote the first draft of the paper, which was commented on by all authors and revised accordingly; PEC and AP had the primary responsibility for the final content. All authors read and approved the final manuscript.

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