Minimizing Carbon Footprint in Diet Plans

15.093 Optimization Methods

Tommaso Salvatori - salva358@mit.edu
Rory Wilson - roryw@mit.edu

December 8, 2023

Contents

1 Problem

Food systems are responsible for around 26% of global greenhouse gas emissions. A critical challenge in environmental sustainability is identifying a diet that satisfies nutritional needs while minimizing environmental impact. This project addresses this challenge by developing a daily dietary plan that minimizes the carbon footprint associated with the diet while adhering to FDA nutritional guidelines, thereby promoting environmental sustainability and nutritional adequacy.

The growing environmental awareness among consumers is leading to significant changes in spending and convenience preferences for more sustainable choices. For instance, the amount of U.S. consumers who say they are vegan has increased by 500% since 2014 (Bourassa, 2023). However, numerous challenges accompany these dietary changes (Vermeir et al., 2020). Key concerns include:

- What foods effectively reduce emissions?
- Is it financially viable for me to adopt these new dietary habits?
- Can I achieve low emissions while maintaining my specific dietary needs?
- Will I still meet nutritional requirements amidst these changes?

We aim to use optimization to address these questions.

2 Data

Our analysis utilizes data on the environmental impact of 43 foods, the nutritional values for 8.8k foods, the dietary constraints based on FDA guidelines, and the average U.S. food prices. We focused our analysis on minimizing the total carbon emissions of a daily diet, measured in kilograms of carbon dioxide (kg CO_2). We first obtained the emissions data for 43 foods that covered all of the major food groups that form the raw ingredients of a consumer's diet, ranging from potatoes and beef to beer and chocolate.

We matched foods to their corresponding nutritional profiles using the FuzzyWuzzy Python library - including both macro and micronutrients, serving size, and caloric information - and normalized the data per gram. This approach allowed us to apply FDA guidelines as model constraints, ensuring dietary variety. We also incorporated price data, providing insight into the trade-offs between emissions and financial costs.

Initial exploratory analysis revealed insights into the foods that produced the most emissions per kilogram of production, as seen in Figure 1. These are the foods that we expect to see minimized in the optimal diet. Additionally, we identified that Melons, Peas, and Cheese were the foods with the highest nutrient density (see Appendix). These foods will most likely be used by the model to meet the FDA's nutritional constraints.

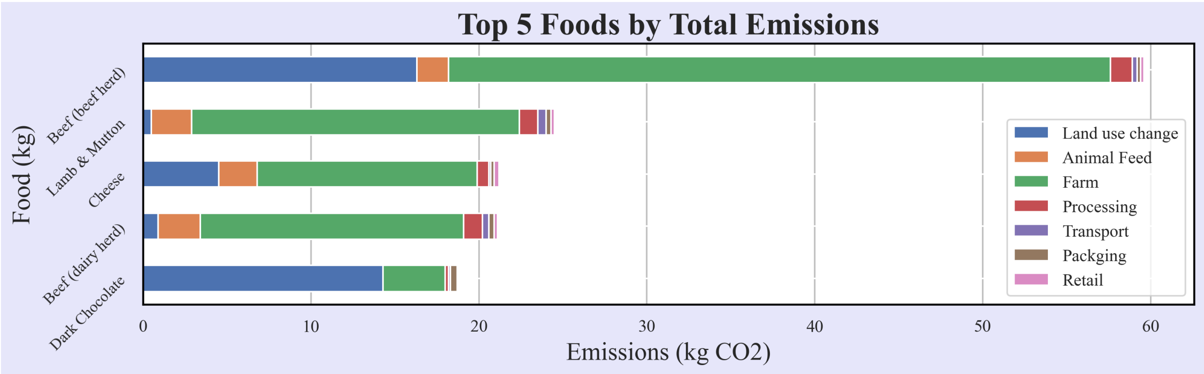

Figure 1: Investigating the highest-emissions foods

3 Formulation

3.1 Modelling the Problem

To tackle this problem, we expressed our aim and restrictions as an objective function and constraints in a linear optimization problem. The goal is to minimize total diet-related carbon emissions, denoted by $c^T x$. Here, c represents the emissions from producing a gram of each food, and x is the consumed quantity in grams. The objective function is constrained by $\sum_{i=1}^{n} x_i y_j \geq R_j$, ensuring that nutrient intake (y_j for nutrient j from food i) meets or exceeds FDA's daily recommendations (R_j). The decision variable, x, quantifies the daily consumption of each of the 43 foods in grams.

To ensure practical applicability, we introduce quantity constraints for each food item. A universal constraint $x_i \leq 500$ limits any food item to a maximum of 500 grams per day. Additionally, we define a 'capacity' constraint C_i for each food, reflecting recommended daily intake levels. For instance, no more than 100 grams of nuts can be included in the diet.

3.2 Incorporating Cost

The model also accounts for cost considerations using a dual objective. Users can adjust their cost sensitivity through a hyperparameter λ. By modifying λ, the model can prioritize minimizing cost, emissions, or a balance of both. The trade-off is visualized in Figure 2, showcasing the impact of different λ values on the total cost and emissions.

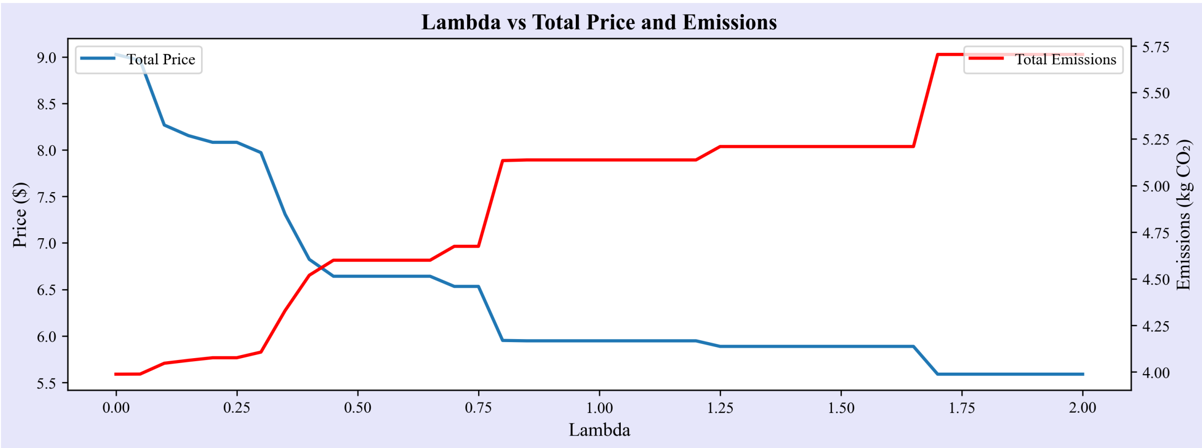

Figure 2: Tuning the hyperparameter λ

3.3 Allowing for Dietary Preference

Recognizing the diversity in dietary preferences, we designed the model to adapt to various dietary requirements. Thirteen profiles were created, ranging from common diets to specific allergy or lifestyle-based restrictions. We grouped foods into categories G_k (e.g., 'meat', 'dairy', 'gluten') and used binary variables z_d to represent dietary preferences. This approach allows the model to include or exclude entire food categories based on the user's dietary restrictions, using big-M constraints: $x_i \leq M \cdot (1 - z_d), \forall i \in G_k, \forall d \in D, \forall k \in K$, where D is the set of all diet preferences and K the set of all food groups.

Users can also specify essential ingredients through another set of binary variables w_l and minimum quantities Q_l, ensuring these ingredients are included in the recommended diet. For instance, a caffeine-head may demand that coffee be a part of his diet, or a pub-lover his beer, or a carnivore his meat. Lastly, the model supports customization for different body types and activity levels by allowing users to specify macronutrient goals. This introduces additional constraints $\sum_{i=1}^{n} x_i y_j \geq N_j$, which become active only if the user's macronutrient targets exceed FDA recommendations.

3.4 Final Model

Our final mixed-integer optimization model minimizes carbon emissions and price, controlled by a hyperparameter λ, subject to nutrient requirements, dietary preferences, and macronutrient needs.

$$\min c^T x + \lambda \cdot p^T x$$

$$\begin{aligned}
&\text{s.t.} && \\
&\sum_{i=1}^{n} x_i y_j \geq R_j, && \forall j \in N && (1)\\
&\sum_{i=1}^{n} x_i y_j \geq N_j, && \forall j \in N && (2)\\
&x_i \leq 500, && && (3)\\
&x_i \leq C_i, && \forall i \in F && (4)\\
&x_i \leq M \cdot (1 - z_d), && \forall i \in G_k, \forall d \in D, \forall k \in K && (5)\\
&x_i \geq Q_l \cdot w_l, && \forall i \in G_k, \forall l \in L, \forall k \in K && (6)\\
&x_i, y_j \geq 0, z_d, w_l \in \{0,1\}, && \forall i \in F, j \in N, d \in D, l \in L && (7)
\end{aligned}$$

4 Results

4.1 The Optimal Diet

Implementing our formulation in Julia with Gurobi optimizer, we first targeted a diet with minimized emissions and no cost consideration. This yielded a balanced diet of 2,800 calories at an affordable cost of \$4.8. Remarkably, the diet's total carbon emissions stood at 1.96 kg CO_2 per day, a stark contrast to the estimated 4.72 kg CO_2 for an average American diet, signifying a 58% reduction in emissions. The foods and corresponding quantities included in the diet can be visualized below.

Optimal Diet for Minimized Emissions (grams)							
Bread	373.7	Peanuts	94.0	Rapeed Oil	7.0	Eggs	54.2
Beans	113.6	Soymilk	273.9	Turnips	200.0		
Peas	135.3	Soybean Oil	32.9	Mandarins	400.0		

Figure 3: Food items and quantities in optimized diet

This solution yielded a significant result. The total emissions resulting from the diet were 1.96 kg CO_2. Rose et al. estimate the diet of the average US consumer causes roughly 4.72 kg CO_2 per day in emissions. Our optimized solution therefore represents a 58% decrease in daily emissions.

4.2 Dietary Profiles

To extend our model to diverse dietary preferences, we examined six distinct profiles: Vegetarian, Pescatarian, No Nuts, No Gluten, No Lactose, and Keto. Vegetarian and Pescatarian diets, unsurprisingly, showed a 47% decrease in emissions compared to the national average. However, the No Gluten and No Lactose diets presented a 1% increase in emissions and higher costs (over \$13 per day). The Keto diet demonstrated the most significant environmental impact, doubling the emissions due to high cheese, chicken, and tofu content. This is an indicator of how heavily constrained diets can have damaging effects on the environment.

4.3 Individualized Diets

In further exploration, we personalized diets for specific profiles. As the authors of the study, we humbly decided to be the first testers. The 'Tommy' diet, with a medium level of meat consumption and a caffeine and alcohol requirement - I love my dinner wine - was well below the national average (-25%). Surprisingly, the 'Rory' diet, even though it required a high level of meat, emits almost exactly as much as the benchmark. This shows how even heavy meat consumers can optimize their ingredient selection to reduce their carbon footprint significantly.

To test the limits of the calorie requirement, who better to pick than the 7'1" behemoth, four-time NBA champion, Shaquille O'Neal? Using figures on his dietary intake, we estimated his daily diet produced around 13.26 kg CO_2 daily. Our optimization model returned an equivalent 8,600 calorie diet that met his nutritional requirements but produced just 3.99 kg CO_2 per day, representing a 70% reduction. If Shaq wants to go green, we suggest a lot of oats...

Diet	Emissions	Emissions vs Average	Price ($)	Calories	Protein	Carbohydrates	Fats
Optimal	1.96	-58%	4.81	2800	116	367	109
Vegetarian	1.96	-58%	4.81	2800	116	367	109
Pescatarian	2.34	-50%	5.78	2800	128	351	111
No Nuts	2.52	-47%	6.06	2800	117	421	78
Tommy	3.60	-24%	4.95	2800	145	328	109
Shaq O'Neal	3.99	-16%	9.03	8609	294	1470	194
Cheap	4.61	-2%	2.78	2800	130	275	143
Rory	4.70	0%	5.28	2800	175	278	120
No Gluten	4.76	1%	13.13	2800	132	339	118
No Lactose	4.76	1%	13.13	2800	132	339	118
Keto	9.33	98%	8.73	2687	250	50	173

Figure 4: Components for each analyzed diet

4.4 Price-Emissions Tradeoff

Investigating the price-emissions interplay, we formulated a cost-minimizing diet by raising λ to a very large number. Surprisingly, this 'budget-friendly' diet still achieved a 2% reduction in emissions compared to the national average, debunking the myth that eco-friendly eating is prohibitively expensive.

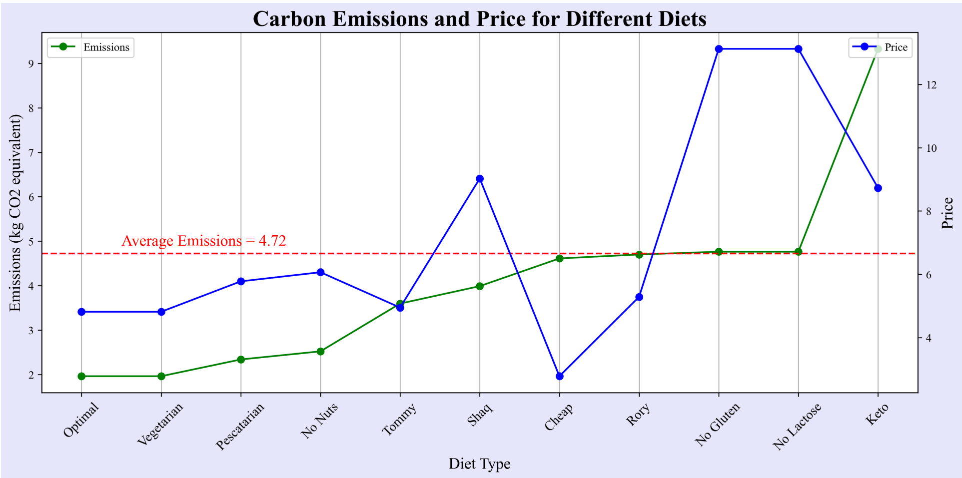

Figure 5: Comparing the price-emissions trade off for different diets

5 Impact

This study offers valuable insights into sustainable dietary practices. It demonstrates that an environmentally friendly diet is not only nutritionally adequate but also financially feasible, catering to a variety of dietary preferences.

If our class of 93 students adopted our optimized diet, we could save 93,688 kg CO_2 on an annual basis. That is equivalent to 20 cars a year in emissions. Extrapolating further, if the entire US population were to adopt this meal plan, the potential reduction in emissions could be equivalent to those from over 71.1 million cars, or about 25% of all US vehicles.

We appreciate that not everyone wants to eat the recommended vegetarian diet. However, our experiments have outlined that, with the data at hand, we can all make more environmentally conscious decisions around food while still allowing for a gluten-free diet, a glass of wine, or even the 8,600 calories and 294g of protein required to keep Shaq delivering his best performances on the court!

5.1 Practical Applications

The potential applications of our model extend to both academic and commercial settings. A primary application could be the development of a user interface for personalized dietary planning. This interface would consider individual parameters such as height, weight, sex, age, activity level, and dietary restrictions, and calculate the user's basal metabolic rate (BMR). Users could adjust their caloric intake based on their weight management goals, and the system could factor in financial considerations through a price sensitivity feature. Such a tool would enable users to receive customized diet plans that are both carbon-efficient and tailored to their personal needs.

Secondly, the model results could be integrated into a recipe generator for practical diet planning. This study could also enhance existing diet apps with emissions data, providing users with immediate feedback on the environmental impact of their dietary choices. When selecting foods to include in their diet, the user would be made aware of the relative carbon emissions of that food, via a color-coded scheme. After inputting a meal, the user would be shown a bar that indicates how the meal compares to the optimum diet on an emissions basis.

Finally, the model could be used to inform policy decisions to promote lower-emission diets and encourage the consumption of specific nutrient-rich, low-emission foods.

5.2 Future Directions

Our future efforts will focus on expanding our food and emission datasets to refine our analysis further. Additional research into the specific environmental impacts of various foods will not only enhance our model but also empower consumers to make more informed decisions. This study lays a solid foundation for raising awareness about the environmental implications of food consumption, paving the way for individuals to contribute meaningfully to global sustainability efforts.

6 References

1. Rose, Donald et al. "Carbon footprint of self-selected US diets: nutritional, demographic, and behavioral correlates." The American journal of clinical nutrition vol. 109,3 (2019): 526-534. doi:10.1093/ajcn/nqy327

2. Vermeir, I. et al. (2020) 'Environmentally Sustainable Food Consumption: A review and Research Agenda from a goal-directed perspective', Frontiers in Psychology, 11. doi:10.3389/fpsyg.2020.01603.

3. Bourassa, Lacey. "Vegan and Plant-Based Diet Statistics for 2023." PlantProteins.co, 2023, www.plantproteins.co/vegan-plant-based-diet-statistics/.

7 Appendix

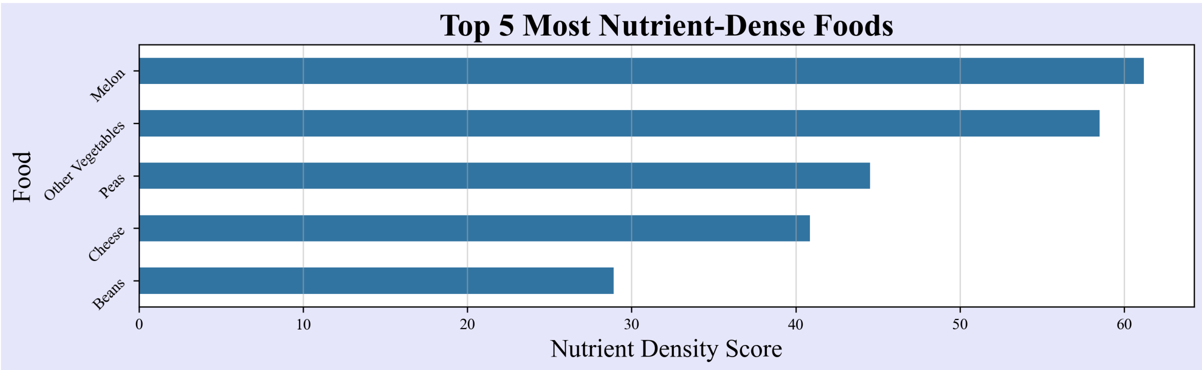

Figure 6: Investigating the most nutrient-dense foods

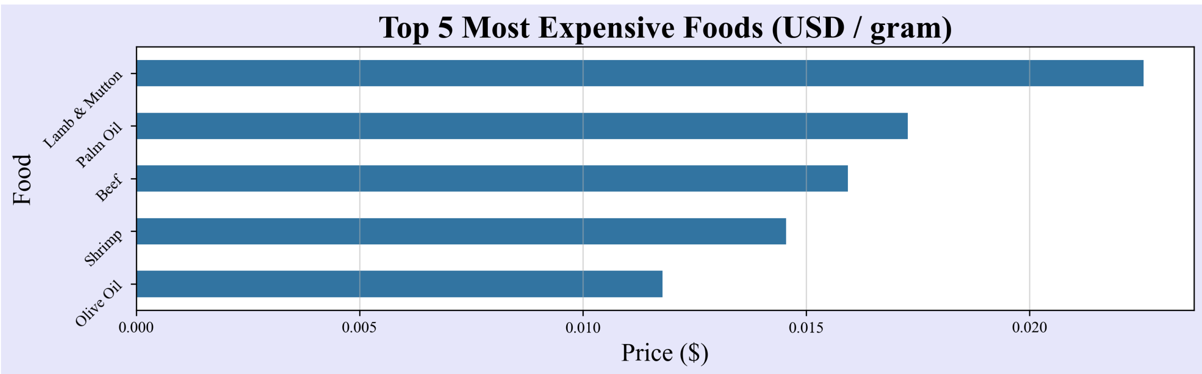

Figure 7: Investigating the most expensive foods