Exploring the Environmental Impact of Replacing Animal-Based Food Items with Plant-Based Food Items in China using Linear Programming

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Introduction

Proteins are essential in the human diet, as they are the building blocks of the human body. However, the current global protein production and consumption is deemed unsustainable. Namely, the growing demand for animal-based products negatively impacts the environment. Also, the availability of proteins is unevenly distributed across the globe; ranging from underconsumption to overconsumption [1]. Therefore, to sustainably nourish nearly 10 billion people by 2050, it is crucial to adopt diets that emphasize plant-based foods and limit animal-based foods, which offer significant health and environmental benefits [2].

The OECD-FAO Agricultural Outlook 2023-2032 projects that the global average per capita meat demand will increase by 2% from the base period 2020-2022 to 2032 [3]. The most significant increase in meat consumption will occur in middle-income countries, being driven by economic growth and urbanization. In contrast, consumers in high-income countries become increasingly concerned about issues such as animal welfare and the impact of animal-based foods on the environmental footprint, while those in low-income countries, despite a growing population, continue to be constrained by their income levels [4, 3].

China, being a middle-income country, is highlighted by the aforementioned report as country that will experience a rebound in meat consumption (after a downward trend due to the African Swine Fever outbreak in 2018). Supply chain advancements and investments in large-scale production units are mentioned as key drivers [3]. Especially beef consumption will increase, although it remains low in per capita quantity [3]. In contrast, it is projected that pork consumption will grow slower than the consumption of other meats, although it remains the dominating meat product [5]. Because of these developments, China is used as a case study to demonstrate the environmental impact of substituting these animal-based foods.

The question of how to deal with the rising demand for animal-based products is commonly being addressed from either a production or consumption perspective [6]. On one hand, the production pathway focuses on reducing the environmental impact per kilogram of animal-based product. On the other hand, the consumption pathway encourages consumers to reduce their intake of animal-based products [6]. This factsheet explores the consumption side, examining how a dietary shift towards plant-based foods can significantly reduce the environmental footprint.

Therefore, the aim of this factsheet is: *"To understand the impact of a more plant-based diet on environmental indicators (GHG emission, land use, and water footprint) in China by using a linear programming model."*

Methodology

Diet optimization is an often used method to explore relationships between the different dimensions of a sustainable diet. It aims to find an optimal diet for a population or individual that maximizes a certain objective function (e.g. environmental footprint) whilst satisfying several constraints (e.g. nutritional adequacy and consumer acceptability) [7]. This factsheet will showcase such a linear optimization model.

Data

For the diet optimization model, several data sources are consulted. First, for the dietary profile of China the Supply Utilization Accounts (SUA) from FAO are used [8]. The 'Food supply quantity (tonnes)' data for the latest available year (2021) will act as the reference diet. To be able to link the dietary profile to nutritional adequacy, this database is linked to the Global Nutrient Conversion Table For FAO Supply Utilization Accounts [9]. For the environmental footprints of Chinese foods, the Chinese Food Life Cycle Assessment database is used [10].

Product selection

For the animal-based products, the three dominant meat products are selected, being 'Meat of pig with the bone, fresh or chilled', 'Meat of chickens, fresh or chilled' and 'Meat of cattle with the bone, fresh or chilled'. Also, 'Raw milk of cattle' is included in the scope. For the plant-based substitutes, protein-rich food items are selected that comprise more than 0.1% of the total consumption in 2021. The selection consists of three items, being 'Soya beans', 'Groundnuts, shelled' and 'Broad beans and horse beans, dry'. Note that these are raw product equivalents, meaning that it comprises both the raw product as well as all derived products as a result of processing. In the case of 'Soyabeans', this means also tofu is included.

Following the previous step, environmental footprints of the selected food products are obtained from the Chinese Food Life Cycle Assessment database [10] (Table 1). Exact matches were not possible due to the granularity of this dataset, which covers more specific food items. For the majority of the data, provided food item averages (e.g. pork) are obtained. Where appropriate, a separate average over all products within a food (sub)group was taken (indicated by *). Data on land-use of groundnuts were not available (indicated by **), and therefore set to the same value as the other substitutes. Note that the same values apply for both soybeans and broad beans and horse beans, as they are both legumes.

Nutrient selection

For this study, only two nutrients will be considered: protein and calcium. As indicated, the nutrient content of the selected products are calculated using the Global Nutrient Conversion Table For FAO Supply Utilization Accounts [9]. Meat is a source of high-quality protein, and its substitution with plant-based substitutes should ensure that adequately levels of protein are retained. Calcium was chosen because previous research identified it as a critical nutrient in China, as there is a risk of potential deficiency [11].

Table 1 Environmental indicators of in-scope products (per kg food as consumed)

Food item	GHG (kg CO_2-eq/kg)	Water Use (m^3/kg)	Land Use (m^2/kg)
Beef	15.66	20.40*	29.05
Pork	9.52	12.40	9.36
Chicken	6.84	5.05	3.63
Milk	1.51	1.72	1.83
Soybean	1.15*	2.96	0.95
Groundnuts	1.42*	2.62*	0.95**
Broad beans and horse beans	1.15*	2.96	0.95

Model formulation

Our model is a substitution model where there is a one-way substitution of animal-based product with plant-based substitutes. The mathematical formulation (A) and notations (B) are presented in Figure 1. The objective function minimizes the GHG emission of the product mix (in-scope animal- and plant-based products). Constraint 1 makes sure that each animal-based product is maximally reduced with 20%. Constraint 2 ensures that each plant-based product is maximally increased with 50%. Constraint 3 makes sure that the intake of nutrient *k* from the product mix remains the same after substitution. Constraint 4 prescribes that the protein intake from the in-scope animal-based products should be reduced by exactly 10%. Constraint 5 is the non-negativity constraint. The model has been implemented in Python using the PuLP package.

Results

Optimal solution

The results of the optimization are presented in Table 2. It can be observed that in decreasing the animal-based protein with 10%, the most GHG-intensive products are decreased first; beef with a maximum of 20% and pork with 14%. To achieve the same quantity of protein, the substitute with the lowest GHG per gram of protein is selected. This is soyabean, followed by broad beans and horse beans.

Table 2 Optimal solution (volumes in tonnes edible product)

Food item	Actual volume (2021)	Optimal solution	Change (%)
Beef	6.14E+06	4.91E+06	-20.00
Pork	3.75E+07	3.23E+07	-14.00
Chicken	1.33E+07	1.33E+07	0
Milk	3.29E+07	3.29E+07	0
Soybean	6.47E+06	9.70E+06	+50.00
Groundnuts	2.70E+06	2.70E+06	0
Broad beans and horse beans	9.76E+05	1.04E+06	+6.84

A $\min\{((GHGMEAT_i \cdot 1000 \cdot X_i) + (GHGSUBS_j \cdot 1000 \cdot Z_j))\}$

Subject to:

$$meatbaselevel_i \cdot 0.8 \leq X_i \leq meatbaselevel_i \quad \forall i \qquad [1]$$

$$plantbaselevel_j \leq Z_j \leq 1.5 \cdot plantbaselevel_j \quad \forall j \qquad [2]$$

$$(((\textstyle\sum_i N\_MEAT_i^k \cdot 10^4 \cdot X_i) + (\sum_j N\_SUBS_j^k \cdot 10^4 \cdot Z_j)) / population / 365) + N\_Fixed_k \geq N\_Current_k \quad \forall k \qquad [3]$$

$$(\textstyle\sum_i N\_MEAT_i^{protein} \cdot 10^4 \cdot X_i) / population / 365 == 0.9 \cdot animal\_protein\_baselevel \qquad [4]$$

$$X_i, Z_j \geq 0 \qquad [5]$$

B

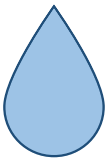
X_i, Z_j	Decision variables; Annual consumption of animal-based product i and substitute j (edible tonnes per year for the total population)
$GHGMEAT_i$, $GHGSUBS_j$	GHG emissions of animal-based product i and substitute j (per kg consumed unit)
$meatbaselevel_i$	Total consumption of animal-based product i in 2021 (edible tonnes per year for the total population)
$plantbaselevel_j$	Total consumption of substitute j in 2021 (edible tonnes per year for the total population)
$N\_MEAT_i^k$, $N\_SUBS_j^k$	Nutrient content of nutrient k in animal-based product i and substitute j (per 100 gram)
N_Fixed_k	Per capita daily intake of nutrient k from the fixed part of the diet in 2021 (excluding in-scope products)
$N\_Current_k$	Per capita daily intake of nutrient k in 2021
animal_protein_baselevel	Per capita daily protein content (g) of in-scope animal-based products in 2021
population	Population of China in 2021

Figure 1 Mathematical formulation (A) and notations (B)

Impact on environmental indicators

From calculations for minimizing the other indicators comparable results were obtained as for GHG emission, because the footprints strongly correlate (e.g. beef scores highest on all footprints). In Table 3, the environmental impact is shown. The absolute change refers to the change in footprint of the product mix *before* and *after* substitution.

Table 3 Environmental impact of optimal solution

INDICATOR	ABSOLUTE CHANGE IN FOOTPRINT*	EQUIVALENT
	-6.55E+10 kg CO_2-eq (-10.80%)	Yearly emission of 14 million passenger cars**
	-8.05E+10 m3 (-10.83%)	Yearly water use of 800 million households***
	-8.17E+10 m2 (-12.62%)	The size of 16 million football fields****

* Compared to the footprint of the product mix in the reference diet of 2021
** Based on a yearly emission of 4.6 tonnes of CO_2 per year for a typical passenger car [12]
*** Based on a yearly water consumption of 275 litres per day for an average household [13]
**** Based on a football pitch of 5000 m^2

Discussion

This study aimed to assess the environmental impact of shifting towards a more plant-based diet in China. The results show that a 10% decrease of protein from animal-based sources has a significant environmental impact. Especially the reduction in beef decreases the ecological footprint considerably. As indicated, the per capita consumption of beef is projected to increase in China. Although it is relatively low, it should be noted that China is the second largest beef consumer in the world [3]. So, in terms of environmental impact, only a slight increase can have a huge environmental impact.

However, some limitations of this study should be noted. First of all, the study focused more on impact quantification than on obtaining a diet with nutritional adequacy. Ideally more nutrients should be included, and each nutrient constraint should be formulated such that recommended intake levels are reached (instead of current intake levels). The reason that this study chose to use current intake level, is because China already shows a large per capita daily intake of protein (113 g, which is higher than the daily recommended value of 50 g [14]). Minimizing GHG emission would simply reduce the plant-based protein intake instead of showcasing the substitution mechanism.

Another limitation is that this study solely focused on protein quantity and not on protein quality. Proteins from animal-based sources are often called 'complete proteins', as they fulfil indispensable amino acid requirements [15]. Plant-based protein can have lower levels of these amino acids, meaning that a 1:1 substitution is overly simplified from a nutritional perspective. Furthermore, digestibility of plant-based proteins are generally lower than for animal-based proteins. Also, (other) health effects of substitutes should be taken into account. Therefore, these results are purely for illustrating the environmental impact, not to promote any nutritionally optimal substitution strategy.

Furthermore, we expect significant inaccuracy in the (assumed average) data. Most footprint data were derived from studies with limited system scope.

Future research should further explore possible substitution strategies in China by more comprehensively considering all aspects of a sustainable diet. These diets should be "*protective and respectful of biodiversity and ecosystems, culturally acceptable, accessible, economically fair and affordable; nutritionally adequate, safe and healthy; while optimizing natural and human resources*" [16]. Also, a broader variety of plant-based substitutes, such as meat replacers and lab-grown meat could be examined. In any case, attention should be given to the regional, social and economic differences that exist in China.

Given the growing global population and increasing pressure on planetary boundaries, future research should also focus on applying the developed model to other countries. These type of models can support policymakers in developing sustainable food security strategies for a growing population, while minimizing trade-offs and aligning with the goals of the Paris Agreement.

Conclusion

Meat consumption is expected to increase in China, leading to significant environmental impacts. This factsheet demonstrated that a more plant-based diet can significantly reduce greenhouse gas emissions, and save substantial amounts of land and water resources. Policy makers should further pursue actions to encourage consumers to adopt a more plant-based diet, for example through awareness campaigns that show the impact of food or by introducing taxes on meat and dairy. Despite the anticipated growth in meat consumption, effective policies and increased public awareness can still enable China, and other countries, to make strides in mitigating the environmental impact of its food system. Finally, the optimization model developed in this research offers a generic framework and tool that can be applied to other countries when relevant data are available. As a result, the impact of this study extends well beyond the specific case of China.

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To explore the potential of nature to improve the quality of life

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The mission of Wageningen University & Research is “To explore the potential of nature to improve the quality of life”. Under the banner Wageningen University & Research, Wageningen University and the specialised research institutes of the Wageningen Research Foundation have joined forces in contributing to finding solutions to important questions in the domain of healthy food and living environment. With its roughly 30 branches, 7,700 employees (7,000 fte), 2,500 PhD and EngD candidates, 13,100 students and over 150,000 participants to WUR’s Life Long Learning, Wageningen University & Research is one of the leading organisations in its domain. The unique Wageningen approach lies in its integrated approach to issues and the collaboration between different disciplines.