Environment–Equity–Economy Model for Food

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Summary

The current food system considers efficiency and profitability as priorities and ignores environmental sustainability and social equity. This has resulted in severe environmental damage and hunger.

We incorporate environmental, equity, and eonomic factors to build an **Environment-Equity-Economy Model (EEE Model)** to re-optimize the current food system. The EEE Model consists of three interlocking submodels: Environmental Sustainability Model, Equity of Food Distribution Model, and Economic Cost-Benefit Model. We upgrade sustainability and equity to priorities at the sacrifice of economic profit.

The first E: The Environment Model involves three environmental indicators: greenhouse gas (GHG) emission, eutrophication, and land use for food production. We find that **transforming the national citizens' diet composition** will significantly reduce all three indicators. We use a logistic model to predict the future situation, with a time parameter to measure the time needed to achieve environmental sustainability. An animal-product tax drives this transformation.

The second E: The Equity Model is based on the uneven food distribution. Our concept is to reduce the "hunger ratio," the proportion of food-insecure people. To achieve this goal, the government can deliver food to food-insecure people. An assistance factor measures the intensity of government assistance. To pay for this, the government can collect a food-equity tax from food producers and distributors.

The third E: The Economy Model considers the net profit of food producers and distributors. In our re-optimized food system model, the economic net profit is not just the difference between benefit and cost; it includes the animal-product tax and the food-equity tax.

We employ our model in case studies of **China** and **Finland**. We find that

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- China will have 26% less GHG emissions, 16% less eutrophication, and 33% more land spared. The hunger ratio will decline, with no food-insecure people by 2029. The cost is 5% less profit for food production.
- Finland will have 33% less GHG emissions, 32% less eutrophication, and 27% more spared land. The hunger ratio will decline, with no food-insecure people by the 2027. The cost is 10% less profit for food production.

We also discuss the scalability and profitability of our model, determine its strengths and weaknesses, and explore future work.

Introduction

Problem Background

The current food system has yielded many positive results over the last few decades. However, it has also resulted in increasingly severe problems, including many highly-processed high-calorie and low-nutritional-value food items, high levels of food loss and waste, the accompanying ecological footprint, and most importantly, the inequitable distribution of food.

Challenged by ICM, we build a model to modify the food system by considering the balance among **Environment**, **Equity**, and **Economy**.

Problem Restatement

- Develop a food system model that optimizes efficiency, profitability, sustainability, and equity. Then compare the optimized food system with the current one and predict the time needed to achieve the change.
- Find the benefits and costs of the changes of the optimized food system and predict when they'll happen.
- Specify the differences of the model for developed vs. developing countries, and apply the model to the actual situations.
- Explore the scalability and adaptability of the model in regions of different sizes.

Our Approach

Figure 1 illustrates our approach. We establish our modified food system model, the **Environment-Equity-Economy Model (EEE Model)**, which tries to balance environmental sustainability, social equity, and economic profit. The model consists of three submodels.

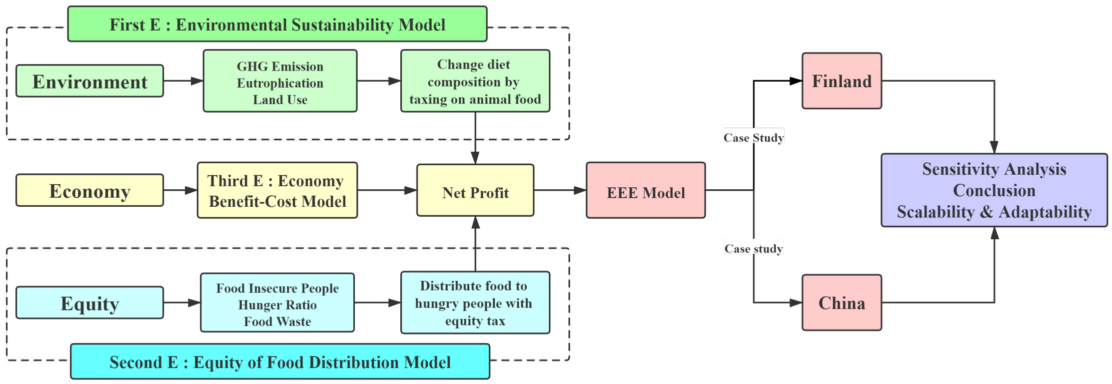


Figure 1. Our approach.

We choose **China** and **Finland** as target countries for case study of the model. We find that our model can achieve great progress on environmental recovery and social equity. Finally, we discuss scalability and adaptability of our model, do a sensitivity analysis, and prescribe future work.

Assumptions

1. **We consider only calories and protein as basic diet needs.**
   Justification: Calories provide the necessary energy, and protein maintains a healthy body. Thus, they're the most-needed nutrition. For simplicity, we neglect other nutrients, such as vitamins and minerals. Also for simplicity, we consider calories and protein independently, despite the fact that protein itself contains calories (4 kcal/g); calories from protein make up only a small proportion of total calories.

2. **The price of food is stable and constant.**
   Justification: As the problem statement says, there is enough food to feed everyone in the world; thus, the supply is more than the demand.

3. **Greenhouse gas emission from food transportation can be neglected.**
   Justification: According to Roser et al. [n.d.], greenhouse gas emission from food transportation is much smaller than from food production.

4. **We ignore extreme events.**
   Justification: The tendency of development of our modified food system will not change overall despite natural and other disasters. We assume that our target countries are stable.

5. **Other factors have negligible influence on the food system.**
   Justification: Other factors that can affect food system are too plentiful to be considered. This assumption avoids unnecessary complication of the model.

6. **The statistics that we gather from websites are accurate and reliable.** Justification: We collect most data from authoritative websites.

Table 1.

Notation.

Symbol	Meaning
T	Tax Rate on animal products
δ	Population growth rate
$N(t)$	Total population
$\mu(t)$	Percentage of calories provided from vegetal food
$\lambda(t)$	Percentage of protein provided from vegetal food
x	Daily need for protein
y	Daily need for calories
$\alpha,\ \beta$	Preference weights on vegetal and animal food
$H(t)$	Food-insecure people under the current system
$H^*(t)$	Food-insecure people under our modified system
A	Assistance factor
$R(t)$	People who receive help from government
$\mathrm{GA}(t)$	Government assistance investment
$h(t)$	Hunger ratio
m_{food}	Total food sales
p_{net}	Net profit of one unit of food
W_{net}	Total net profit of food system

Environment–Equity–Economy Model

The current food system considers **efficiency** and **profitability** as priorities, which can be seen as economic factors. The producers have the goal of maximizing economic profit, which ignores environmental sustainability and social equity. As time goes by, the natural environment becomes worse, and more people suffer from food scarcity, causing a larger wealth gap. To avoid further deterioration, we need to improve the current food system: We need to make changes to seek a balance among environment, equity, and economy.

Our **Environment-Equity-Economy Model (EEE Model)** is composed of three submodels:

- **First E : Environmental Sustainability Model**

  To decrease damage to the environment, we transform the composition of diet by taxing animal foods.

- **Second E : Equity of Food Distribution Model**

  To relieve the hunger problem, government should deliver food to people in need, with costs paid by food producers and distributors in the form of a food-equity tax.

- **Third E : Economy Benefit-Cost Analysis Model**
  We re-analyze costs and benefits in light of the animal-product tax and the food-equity tax.

Environmental Sustainability

Selection of Indicators

We select three major indicators to measure the environmental sustainability of a country's food system: annual **greenhouse gas emissions** from the food system, annual **eutrophication emissions** from the food system, and **land use** for the food system.

- **Greenhouse Gas (GHG) Emissions**
  Food is responsible for approximately 26% of global GHG emissions [Ritchie and Roser 2021], causing global warming, glacier melting, and sea level rise. Therefore, management and control of agricultural greenhouse gas emission by adjusting current food system is key to emission reduction. We express GHG emissions from the food system in kilograms of carbon dioxide equivalent, denoted as GHE.
  Production of animal food emits much more GHG than vegetal food. Thus, one of the useful methods of decreasing level of GHG emission is to change citizens' diet composition.
- **Eutrophication Emissions (EUE)**
  Eutrophication is the pollution of water bodies and ecosystems due to excess nutrients. Excess nitrogen and other nutrients from food production run into the surrounding environment. Eutrophication of water severely harms the balance of the freshwater ecosystem and has a detrimental effect on the supply of drinking water.
  We express the degree of eutrophication in units of grams of phosphate equivalent, since phosphate is the most important contaminant.
- **Land Use (LU)**
  Producing food requires farmland. The expansion of agriculture has great impacts on the environment, causing declines in forest area and biodiversity. We can take action by returning some farmland back to nature.

Adjustment of Food System

As the global population increases, more food must be produced to feed people. If nothing is done, what follows are more greenhouse gas emissions and eutrophicaction emissions, further deforestation, and loss of biodiversity.

For the same protein and calories, animal products generally emit more greenhouse gas, cause more eutrophication, and require more land than vegetal products.

So, to achieve environmental sustainability of the food system, we can **change the diet composition** of citizens by providing more vegetal products and less animal products. Government can be the driving force in this adjustment by **taxing animal products**. Doing so will raise costs for food producers, so they will produce less animal products, and gradually people's diet composition will change.

Environmental Sustainability Model

Model of Transformation of Diet Composition

We choose calories and protein as a person's basic nutrition needs. To simplify the problem, we neglect other nutrients such as vitamins and trace elements.

Assume that one person consumes x kcal (food calories) and y g of protein *per day*. Let $\mu(t)$ be the percentage of calories, and $\lambda(t)$ the percentage of protein, from vegetal products.

Thus, the annual food production of a country with N people must offer $365Nx$ kcal calories and $365Ny$ g of protein, of which $365\mu Nx$ kcal and $365\lambda Ny$ g of protein are provided by vegetal products.

We can increase μ and λ to **transform citizens' diet composition to a vegetal-preferred state**. The transformation takes time to accomplish: 30–50 years. We suppose that the increases in μ and λ over time t follow a logistic model:

$$\begin{cases} \dfrac{d\mu}{dt} = r\mu\left(1 - \dfrac{\mu}{\mu_{\max}}\right), \quad \mu(0) = \mu_0 \\[2ex] \dfrac{d\lambda}{dt} = r\lambda\left(1 - \dfrac{\lambda}{\lambda_{\max}}\right), \quad \lambda(0) = \lambda_0, \end{cases} \tag{1}$$

whose solution is

$$\begin{cases} \mu(t) = \dfrac{\mu_{\max}}{1 + \left(\dfrac{\mu_{\max}}{\mu(0)} - 1\right) e^{-rt}} \\[4ex] \lambda(t) = \dfrac{\lambda_{\max}}{1 + \left(d\frac{\lambda_{\max}}{\lambda(0)} - 1\right) e^{-rt}} \end{cases} \tag{2}$$

where $\mu_{\max}$ and $\lambda_{\max}$ are the final values of μ and λ after the complete transformation that we expect to achieve, while r is the time parameter that determines how long it will take to achieve total conversion of diet composition. The values of $\mu_{\max}$ and $\lambda_{\max}$ will differ depending on national conditions. Larger r translates to a shorter time needed to achieve the transformation.

Parameters

Parameters for Vegetal Products

We introduce the following parameters:

- $\mathrm{GHE}_{\mathrm{cal,veg}}$: GHG emission per 1000 kcal provided by vegetal products, with units kg CO_2 eq/1000 kcal;
- $\mathrm{EUE}_{\mathrm{cal,veg}}$: Eutrophication emission per 1000 kcal provided by vegetal products, with units g PO_4 eq/1000 kcal; and
- $\mathrm{LU}_{\mathrm{cal,veg}}$: Land use required to produce 1000 kcal calories provided by vegetal products, in units m^2/1000 kcal,

with analogous definitions for $\mathrm{GHE}_{\mathrm{pro,veg}}$, $\mathrm{EUE}_{\mathrm{pro,veg}}$, and $\mathrm{LU}_{\mathrm{pro,veg}}$ for protein.

Different countries prefer different mixes of vegetal and animal products. Therefore, in our case studies we use parameters specific to the target country, based on the eating habits of its people. The general form is

$$\mathrm{GHE}_{\mathrm{cal,veg}} = \sum_{i=1}^{n} \alpha_i \times \mathrm{GHE}_{\mathrm{cal,veg},i}, \tag{3}$$

with analogous equations for EUE and LU, where there are n typical vegetal foods, $\mathrm{GHE}_{\mathrm{cal},i}$ is greenhouse gas emissions per 1000 kcal provided by the ith vegetal food, and α_i is the proportion of the ith vegetal food. Other parameters are specified in the similar way.

Parameters for Animal Products

Animal products cause similar effects to the environment, the only difference being the amount. Hence we have analogous parameters to those above: $\mathrm{GHE}_{\mathrm{cal,ani}}$, $\mathrm{EUE}_{\mathrm{cal,ani}}$, $\mathrm{LU}_{\mathrm{cal,ani}}$ and $\mathrm{GHE}_{\mathrm{pro,ani}}$, $\mathrm{EUE}_{\mathrm{pro,ani}}$, and $\mathrm{LU}_{\mathrm{pro,ani}}$.

Also analogously, we have

$$\mathrm{GHE}_{\mathrm{cal,ani}} = \sum_{j=1}^{m} \beta_j \times \mathrm{GHE}_{\mathrm{cal,ani},j}$$

where there are m typical animal foods, and similar equations for EUE and LU.

Effect of Changing Diet Composition

Since producing vegetal food emits less greenhouse gas, produces less eutrophication, and requires less land, then as the proportion of vegetal food increases with time, environmental sustainability will be achieved through three significant effects:

- decrease of greenhouse gas emission per year,
- reduction of eutrophication emissions per year, and
- decline in land use for the food system.

Their functions with time are respectively

$$\begin{aligned}\mathrm{GHE}(t) = 365 \Bigg(&\frac{\mu N x}{1000}\,\mathrm{GHE}_{\text{cal,veg}} + \frac{\lambda N y}{100}\,\mathrm{GHE}_{\text{pro,veg}} \\ &+ \frac{(1-\mu) N x}{1000}\,\mathrm{GHE}_{\text{cal,ani}} + \frac{(1-\lambda) N y}{100}\,\mathrm{GHE}_{\text{pro,ani}} \Bigg),\end{aligned}$$

with analogous equations for $\mathrm{EUE}(t)$ and $\mathrm{LU}(t)$.

Equity of Food Distribution

Introduction

Since massive food producers and distributors prioritize efficiency and profitability (economic cost and benefit), they have no responsibility for aiding hungry people, causing uneven food distribution and negative consequences, such as redundance of food in some place and famine in others.

To achieve equity, government must take actions by **delivering redundant food to food-insecure people**. This would save wasted food and reduce the hunger ratio.

As for the cost of food delivery, government can collect a **food-equity tax** from the producers and distributors. This may raise the economic cost but could benefit equity.

Food-Equity Model

Current system

Let the population of a country in year t be

$$N(t) = N_0 (1+\delta)^t, \qquad \textbf{(4)}$$

where N_0 is population in 2020, δ is the population growth rate, and $t = 0$ in 2020.

If we do nothing, the hunger ratio $h(t) = H(t)/N(t)$—the proportion of food-insecure people—will stay constant, which means that the food-insecure population $H(t)$ will keep rising with the increase in population, causing more severe social inequality:

$$H(t) = H_0(1+\delta)^t,$$

We note that

$$\frac{H'(t)}{N'(t)} = \frac{H_0}{N_0},$$

where N_0 and H_0 are the initial values of $N(t)$ and $H(t)$ in 2020.

Modified System

To improve this situation, we need government to intervene to deliver food. Our ultimate aim is to decrease the hunger ratio $h(t)$ over time. We denote by H^* the modified food-insecure population. To reduce the hunger ratio, we need the rate of increase of the food-insecure population to be smaller than the rate of growth of population,

$$H^{*\prime}(t) < N'(t). \tag{5}$$

To be more specific, let A be an assistance factor that measures the degree of government assistance. A larger A means more intense government assistance and a faster decrease in the hunger ratio. In mathematical terms, we have the initial value problem.

$$\frac{H^{*\prime}(t)}{N'(t)} = \frac{H_0}{N_0} - At, \qquad H^*(0) = H_0. \tag{6}$$

We solve this problem with MATLAB and get

$$H^*(t) = (H_0 - A\,N_0\,t)\,(\delta+1)^t - \frac{A\,N_0}{\ln(\delta+1)} + \frac{A\,N_0\,(\delta+1)^t}{\ln(\delta+1)}, \tag{7}$$

for the food-insecure population under our modified system. We can determine the population $R(t)$ who receive assistance from government as

$$\begin{aligned} R(t) &= H(t) - H^*(t) \\ &= H_0(\delta+1)^t - \left[(H_0 - A\,N_0\,t)\,(\delta+1)^t + \frac{A\,N_0}{\ln(\delta+1)}[(\delta+1)^t - 1] \right] \\ &= A\,N_0 \left[t\,(\delta+1)^t - \frac{(\delta+1)^t - 1}{\ln(\delta+1)} \right]. \end{aligned}$$

The expense of government assistance would be borne by food producers and distributors in the form of a food-equity tax.

Economy Cost-Benefit Analysis

Economic Costs

We consider that there are three main economic costs in food system: material, land, and labor. We assume that these three costs are linear in the amount of food production, with corresponding slopes p. Thus we have the cost of material

$$C_{\text{mat}} = \sum_{i=1}^{k} m_i \times p_{\text{mat},i},$$

where m_i and p_i are the amount of and cost of material for producing the ith food, with analogous equations for the costs for labor and land. We sum over k types of foods.

Then the economic cost is

$$\text{Economic Costs} = C_{\text{mat}} + C_{\text{labor}} + C_{\text{land}}.$$

Economic Benefits

According to Assumption 2, the price of the food is stable, thus the economic benefit is

$$\text{Economic Benefit} = \sum_{i=1}^{k} m_{\text{food},i} \times p_{\text{food},i}$$

where p_i is the price of food i.

Profits

Thus the economic profit $W(t)$ is

$$\begin{aligned} W(t) &= \text{Economic Benefits} - \text{Economic Costs} \\ &= \sum_{i=1}^{k} m_{\text{food},i} \times \left(p_{\text{food},i} - p_{\text{mat},i} - p_{\text{labor},i} - p_{\text{land},i}\right) \\ &= \sum_{i=1}^{k} m_{\text{food},i} \times p_{\text{net},i}, \end{aligned}$$

where for convenience we let p_{net} denote the combination of four prices; it can also be seen as the net profit per one unit of food. Then m_{food} is the amount of food sold to (consumed by) the customer per year, where customers are people who are neither food insecure nor receiving assistance, that is,

$$m_{\text{food}}(t) = 365(x + y)[N(t) - H(t)].$$

The government will be charging an animal-product tax at rate T. Taking into account also the the food-equity tax, the net profit under our modified food system is

$$\begin{aligned} W_{\text{net}}(t) &= W_{\text{taxed}}(t) - \text{GA}(t) \\ &= W_{\text{veg}}(t) + (1 - T)W_{\text{ani}}(t) - \text{GA}(t), \end{aligned}$$

where GA is the cost of government assistance.

Difference from Current System

The biggest difference between our modified system and the current system is that we eliminate the priorities of efficiency and profitability and consider environmental and social factors in our model by transforming the diet composition and taxing for food equity.

The results will be:

- Greenhouse gas emissions will decrease. **(Benefit)**
- Eutrophication will decrease. **(Benefit)**
- More land will be released back to the nature for recovery of biodiversity. **(Benefit)**
- More food-insecure people will have food, and the hunger ratio will eventually fall to zero. **(Benefit)**
- The net economic profit of food producers and distributors will decrease to a certain extent. **(Costs)**

We now apply our model to analyze the food systems of the target countries **China** and **Finland**.

Case Study : China

China is a developing country with large-scale population, economy, and land area. China has the largest food system in the world, which has to feed nearly one-fifth of the world population. During the last few decades, Chinese food system development has considered efficiency and profitability as priorities, ignoring adverse environmental and social impact. Thus, China has severe environmental problems and hunger problems, which need to be mitigated by adjusting the current food system.

We apply our model to improve the Chinese food system and note the benefits and costs of our modification.

Environmental Benefit from First E

Considering that China has a huge population, the transformation of people's diet composition will take a relatively long time. We expect 30 years for the complete transformation, with corresponding time coefficient $r = 0.01$. Our plan is to

increase μ from 0.8 to 0.9 and increase λ from 0.6 to 0.8.

For the Chinese, we choose rice and wheat as representative vegetal products, and pork, poultry, beef, mutton, and eggs as representative animal products. Their weights are listed in in **Table 2**, together with parameter values for the Chinese food system.

Table 2.

Chinese parameter values.

Parameter	Value	Weight	Value
Calories(kcal) x	2500	α_{rice}	0.5
Protein(g) y	80	α_{wheat}	0.5
μ_0	0.8	β_{pork}	0.3
λ_0	0.6	β_{poultry}	0.2
$\mu_{\max}$	0.9	β_{beef}	0.1
$\lambda_{\max}$	0.8	β_{mutton}	0.1
Time coefficient r	0.1	β_{egg}	0.3

Using weights and environmental parameters $(\text{GHE}, \text{EUE}, \text{LU})$ of selected foods from Roser et al. [n.d.], we calculate the comparison of vegetal and animal products in **Figure 2**.

All parameter values for animal products are much larger than the corresponding parameter values for vegetal products. This means that in offering the same amount of calories and protein, animal products cause more severe consequences than vegetals. Thus, it can be reasonably expected that the transformation of diet composition will have a significant effect on the environmental protection.

We insert all parameter values into the functions $\text{GHE}(t)$, $\text{EUE}(t)$, and $\text{LU}(t)$ and plot the results in **Figure 3**.

In **Figure 3(a)** and **Figure 3(b)**, the blue dotted line represents the future situation when nothing is done, while the red solid curve means the future situation in our modified food system. In **Figure 3(c)**, the blue upper curve is the total area of farmland, and the red lower curve is land not used for agriculture.

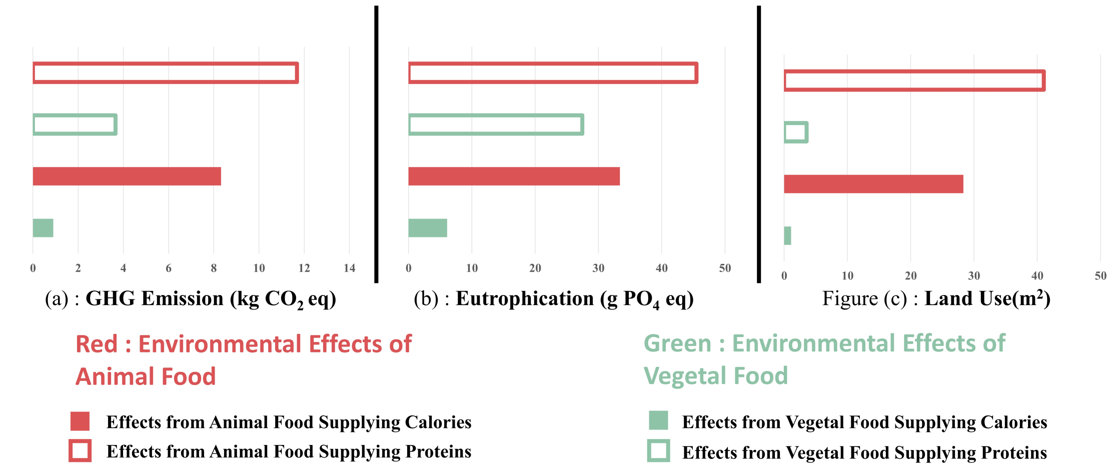


Figure 2. Comparison of vegetal and animal products.

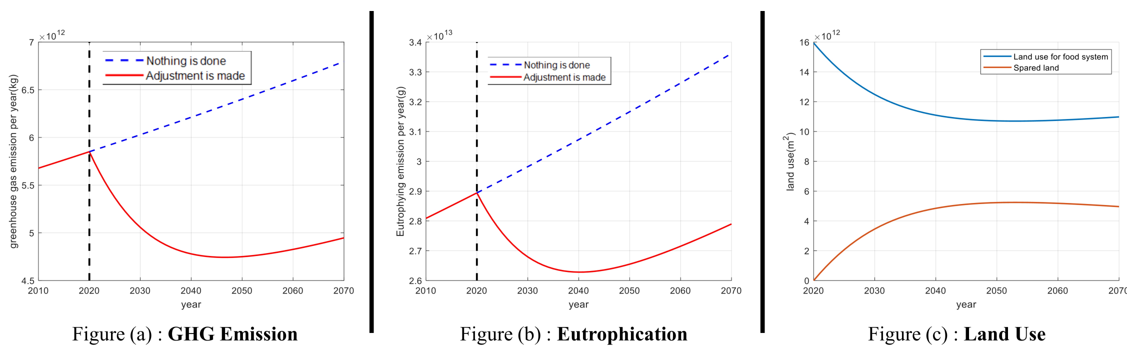


Figure 3. Future environmental effects in China.

From **Figure 3**, we can see that in our modified food system, all of GHE(t), EUE(t), and LU(t) immediately decline. After 30 years, in 2050, the environment will have made huge progress, including :

- Total GHG emissions per year will decrease 26% in 2050.
- To slow down the rate of eutrophication, the total amount of phosphate in the soil will decrease 16%.
- 33% of agricultural land can be given back to the environment.

Food Delivery and Net Profits from Second and Third E

The hunger ratio of China is 1% [Roser et al. n.d.]. To improve this situation, the government can intervene by delivering redundant food to food-insecure areas.

We set the assistance factor to be $A = 0.01$ and the animal-product tax rate to be $T = 0.05$. We obtain the $R(t)$ population which government must assist and the $W_{\text{net}}(t)$ net profit. We plot the results in **Figure 4**.

In **Figure 4(a)**, the red upper curve is the hunger population $H^*(t)$, the blue lower curve is the hunger ratio $h(t)$.

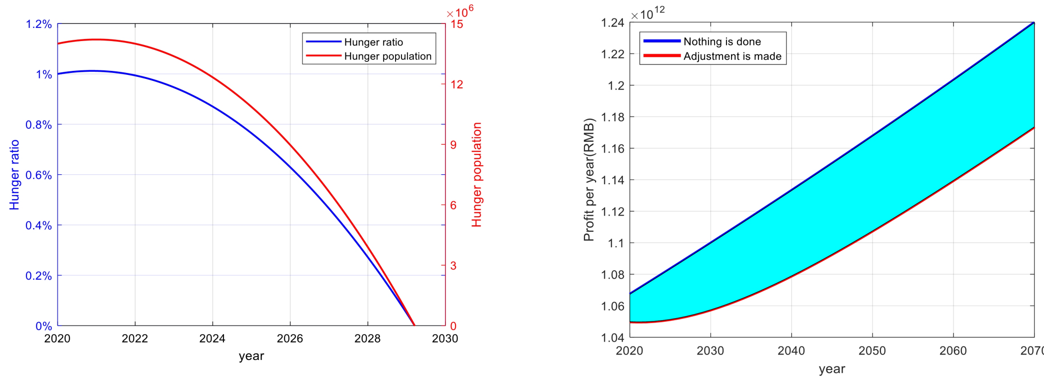


Figure (a) : **Hunger Ratio** Figure (b) : **Net Profit**

Figure 4. Hunger and net profit in China.

In **Figure 4(b)**, the blue upper line is the future profit per year if nothing is done, while the red lower curve is the future profit in our modified food system, and the cyan area between the curves is foregone net profit.

As we can see from **Figure 4(a)**, the hunger population decreases, and by 2029 there are no food-insecure people in China.

Such progress involves cost. We find that $W_{\text{net}}(t)$ would be about 5% lower each year under our modified food system. We consider that a reasonable sacrifice for sustainable development.

Conclusions for Chinese Food System

To summarize the effects of our re-optimizing the food system, we list all the consequences in **Table 3**

Table 3.
Effects of Chinese modified food system.

Aspect	Effect
Modification	Remove priorities of efficiency and profitability
Benefits:	26% less GHG emission in 2050
	16% less eutrophication in 2050
	33% more land back to the nature in 2050
	More people fed, lower hunger ratio
Costs:	5% less profit
Implementation time:	Hunger ratio begins to reduce by 2021
Accomplishment time:	No food-insecure people by 2029

To sum up, in our case study of Chinese food system, we sacrifice some economic profit, with the return of a better natural environment and a more equal country. We consider that our model meets the criterion of sustainable development.

Case Study : Finland

We choose as our second target country Finland, a developed country with relatively small population, economy, and land area. Although Finland has a highly-developed economy, the current hunger ratio of Finland is 2% [Roser et al. n.d.]—worse than in China.

Environmental Benefit from First E

Considering that Finland has a relatively small population, the transformation of people's diet composition should take less time than China. We expect 20 years for the complete transformation to achieve, with corresponding time coefficient $r = 0.2$. Our plan is to

increase μ from 0.5 to 0.7 and increase λ from 0.4 to 0.6.

For the Finns, we choose potato and wheat as representative vegetal products, and pork, poultry, beef, fish, and milk as representative animal products. Their weights are listed at **Table 4**.

According to Roser et al. [n.d.] and reasonable assumptions, we determine parameters of the Finnish food (**Table 4**), including Finnish citizens' preferences for diet, essential need for nutrition, and so on.

Table 4.

Finland parameter values.

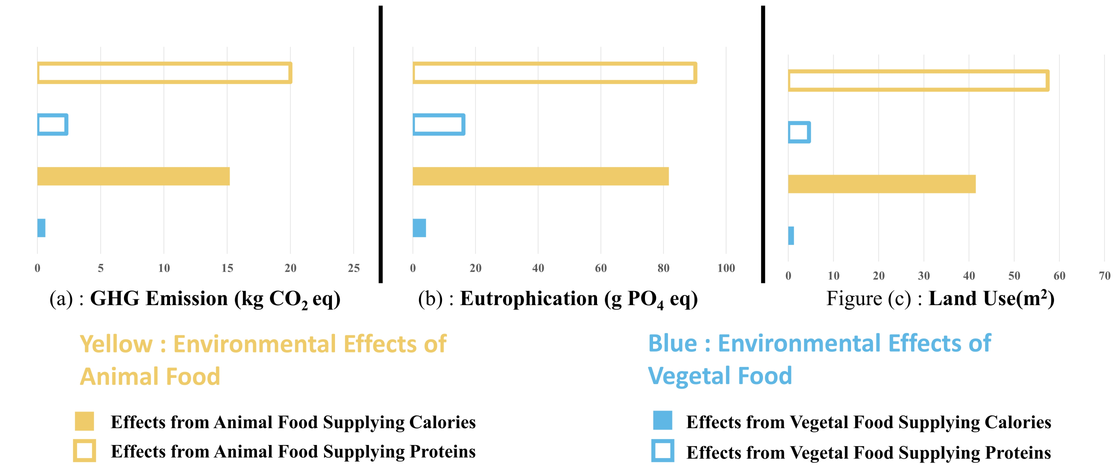
Parameter	Value	Weight	Value
Calories (kcal) x	3000	α_{potato}	0.7
Protein (g) y	110	α_{wheat}	0.3
μ_0	0.5	β_{pork}	0.1
λ_0	0.4	β_{poultry}	0.1
$\mu_{\max}$	0.7	β_{fish}	0.3
$\lambda_{\max}$	0.6	β_{beef}	0.3
Time coefficient r	0.2	β_{milk}	0.2

Using weights and environmental parameters for selected foods from Roser et al. [n.d.], we calculate the parameters for vegetal animal products indicated in **Figure 5**.

We insert all parameter values into the functions GHE(t), EUE(t), and LU(t) and plot the results in **Figure 6**.

In **Figure 6(a)** and **Figure 6(b)**, the blue dotted line represents the future situation when nothing is done, while the red solid curve means the future situation in our modified situation. In figure **Figure 6(c)**, the blue upper curve is the total area of farmland, and the red lower curve is land not used for agriculture.

From **Figure 6**, we can see that in our modified food system all of GHE(t), EUE(t), and LU(t) decline. After 20 years, in 2040, the environment will



(a) : **GHG Emission (kg CO_2 eq)** (b) : **Eutrophication (g PO_4 eq)** Figure (c) : **Land Use(m^2)**

Figure 5. Comparison between vegetal and animal products.

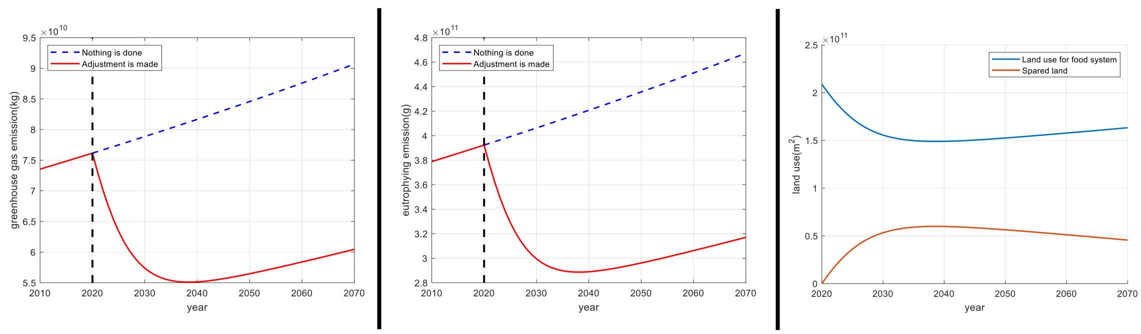


Figure (a) : **GHG Emission** Figure (b) : **Eutrophication** Figure (c) : **Land Use**

Figure 6. Future environmental effects in Finland.

have made huge progress, including:

- Total GHG emissions per year will decrease 33%.
- Phosphate in the soil will decrease 32%.
- 27% of agricultural land can be given back to the environment.

Food Delivery and Net Profits from Second and Third E

The hunger ratio of Finland is 2% [Roser et al. n.d.]. To improve this situation, government can deliver redundant food to the food-insecure area, paying for it by charging a food-equity tax to food producers and distributers.

Considering the Finnish economy, we set the assistance factor $A = 0.2$, then put the numbers into MATLAB calculation to obtain the $R(t)$ population for government assistance and the $W_{\text{net}}(t)$ net profit. We plot the result in **Figure 7**.

In **Figure 7(a)**, blue top curve is the hunger ratio $h(t)$, the red bottom curve is the hunger population $H^*(t)$,

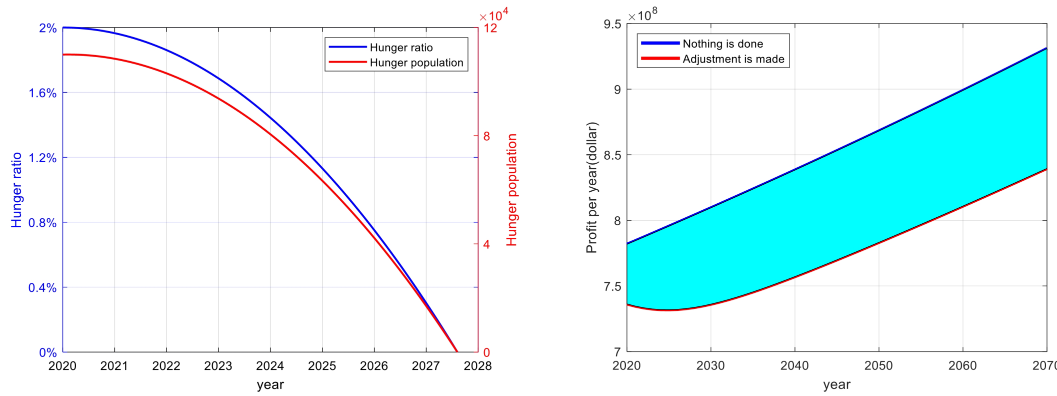


Figure (a) : **Hunger Ratio** Figure (b) : **Net Profit**

Figure 7. Hunger and net profit in Finland.

In **Figure 7(b)**, the blue top line is the future situation if nothing is done, while the red lower curve is the future situation in our modified situation, and the cyan area between the curves is foregone net profit.

Under our scenario, by the middle of 2027 there are no food-insecure people in Finland.

Such progress involves cost. We find that $W_{\text{net}}(t)$ would be about 10% lower each year under our modified food system. We consider that a reasonable sacrifice for sustainable development and eliminating hunger.

Conclusions for Finnish Food System

To summarize the effects of our re-optimizing food system, we list all the consequences in **Table 5**.

Table 5.

Effects of Finnish modified food system.

Aspect	Effect
Modification	Remove priorities of efficiency and profitability
Benefits:	33% less GHG emission in 2040
	32% less eutrophication in 2040
	27% more land back to the nature in 2040
	More people fed, lower hunger rate
Costs:	10% less profit
Implementation time:	Hunger ratio begins to reduce in first month
Accomplishment time:	No food-insecure people by 2027

To sum up, we sacrifice a part of economic profit, with the return of a better natural environment and a more equitable country—a sustainable outcome.

Discussion

Differences in Developed and Developing Countries

- **Benefits difference:**
  Developed countries initially have a greater use of animal food, so changing the priorities of their food systems contributes to a greater relative decrease in greenhouse gas emission and eutrophication than in developing countries. In addition, a highly-developed economy in a developed country can afford a greater assistance factor, so that the food-insecure population can be cut down to zero faster than in developing countries.

- **Costs difference:**
  Because of a higher animal-product tax in developed countries, their profit has a greater relative decrease than in developing countries.

Scalability

Finland has only 5.5 million people. China has the largest population in the world (1.4 billion)—250 times as large as Finland—which means that China has the largest food system in the world. Our model predicts and simulates well in both China and Finland, which indicates that our modified food system model works well on both large and small system and scales well.

However, our model focuses on the food system of an entire country. Therefore, our model has limited application to the food system in say, a village, a continent, or even the whole world.

Adaptability

People in some extremely poor regions almost don't consume animal products, so the environmental aspect of our model can't work well in these regions. But also because of that, the environmental pollution from the food system of these regions, which mainly produce vegetal products, is relatively small. These food systems by their nature satisfy environmental sustainability.

In some highly-developed countries, there are few hungry people and the government has sufficient funding for hungry people. The assistance expenses need not be paid by food producers in the form of tax. So the equity model may not work well in such countries.

To sum up, our model has relatively good adaptability to most regions.

Sensitivity Analysis

We change the weights of specific foods in vegetal foods and animal foods, i.e., α_i and β_j. The consequent changes in environmental parameters for vegetal and animal food, i.e., $\mathrm{GHE}_{\mathrm{cal,veg}}$, $\mathrm{GHE}_{\mathrm{cal,ani}}$, and so on, are slight.

We plot results of sensitivity analyses of the cases for China and Finland. As we can see from the **Figure** 8 and **Figure** 9, the overall tendencies of the curves of $\mathrm{GHE}(t)$, $\mathrm{EUE}(t)$ and $\mathrm{LU}(t)$ stay stable, which suggests robustness of our model.

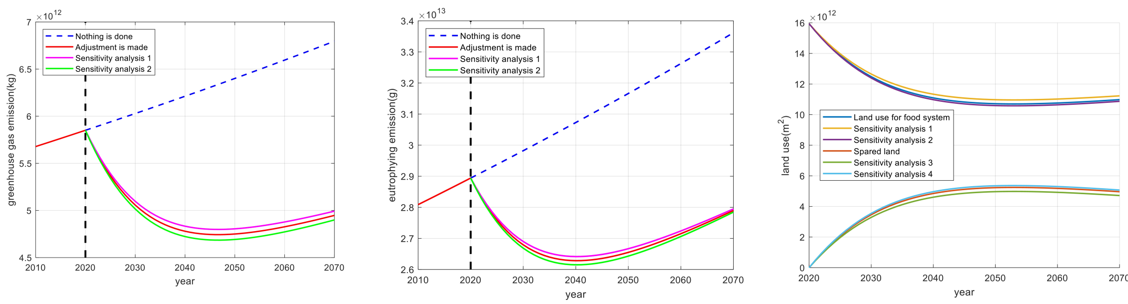


Figure 8. Sensitivity analysis for China.

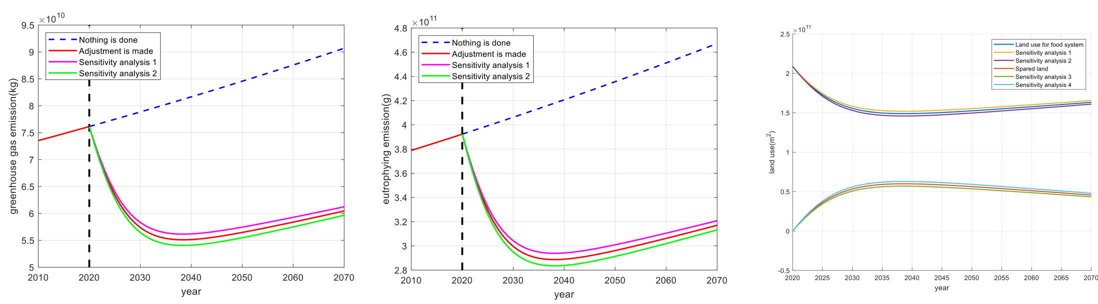


Figure 9. Sensitivity analysis for Finland.

Strengths and Weaknesses

Strengths

- Our sensitivity analyses show that our models are fairly robust to changes in parameter values.
- The results of our models agree with common sense and experience.
- We consider various indicators in environmental and social aspects, making our model comprehensive.

- Our model indicates significant progress on four indicators (GHG eimission, eutrophication, land use, hunger ratio), indicating that our model is effective.
- Our model works well on both large and small food systems, which means that our model is adaptable.

Weaknesses

- Some of the parameters are based on semi-educated guesses because some data are unavailable.
- We consider only calories and protein as the main elements of nutrition, not other elements such as vitamins and minerals.
- In extremely poor countries, people have a severe lack of animal food, so transformation of diet composition doesn't work well. That is a limitation of our model.
- The benefits of our model won't last forever—they decrease with the increase of population, therefore our model may need upgrade for long-term development. The most essential consideration is to restrict excessive population growth.

Future Work

The effect of transforming diet composition can last for decades, but not forever if there is increasing population. It is hard to produce more food while not elevating emissions of greenhouse gases and eutrophic materials. Therefore, more work has to be done to deal with such a future problem.

There are several potentially practical plans, such as improving agricultural production and adopting environmentally-friendly methods. Soilless culture, for instance, has the advantage of producing more food of higher quality, with less use of water, fertilizer, and labor. However, because of the higher investment and stricter production management, soilless culture can't be widely extended. But we believe that with the development of agricultural technology, environmentally-friendly but economically-unfriendly agricultural production patterns will one day be extended globally, to help build a more productive and sustainable food system.

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