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Quantitative Analysis of sustainable food system

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Abstract

Food system, a major component within the framework of The UN 2030 Agenda aiming at enhancing the community's environmental, economic and social well-being, is recently unstable worldwide. Therefore, it is of essential to establish and validate a sustainable food system model. Based on GECAFS food system approach and statistics from reliable databases such as FAO, we propose the Equity – Sustainability Aimed Model(ESA model) overall, which optimizes our food system from social and ecological dimensions. In terms of equity, the Degree of Supply and Demand Matching model is proposed to evaluate impartiality of food system production and distribution by calculating ideal solution distance. In terms of sustainability, food insecurity is evaluated by TOPSIS algorithm. Besides, ecological footprint, as the cross-cutting theme, is quantified in our Multi-Level Indicator System. In order to estimate when our global food system will take to implement, we create a piecewise function for the secondary indicators and utilize BP neural Network to predict equity and sustainability in the future. Our evaluation results on food system outcomes finely accord with reality and reveals that more than 70\% of the country's food system will be equal and sustainable enough in 2050.

Keywords

Food System; ESA Model; Topsis algorithm; BP neural Network Prediction.

1. Introduction

The unprecedented and long-term nature of environmental change in the 21st century has a tremendous impact on the previous food system. Through global food crisis and global climate change, we have witnessed great changes in the food system. Today's food systems are diverse and complex, involving everything from subsistence farming to multinational food companies. Every one eat; therefore, everyone relies on food system——everyone is more or less participating in food activities and enjoying the outcomes of this system. However, the persistent pursuit of efficiency and profitability has made the foot system unstable even in the parts of the world that it generally serves well. It may contributes to adverse ecological footprints, such as irreversible ruin of ecosystems and increasingly utilitarian resource allocation structures. Therefore, reasonable and warranted endeavor of developed and developing countries is badly needed to produce more food, sustain and improve the health of our environment.

2. The ESA Model

In this section, we introduce our food system based on GECAFS food system approach, and propose the ESA model (\textit{viz}., the Equity – Sustainability Aimed model) to optimize food systems from social and ecological dimensions.

2.1. Food System Introduction

\paragraph{Components}

the basic components of food system can be classified as consumers, producers, distributors and the government, who participate in individual or collective activities. Food system includes a range of activities from planting seeds to household waste disposal and recycle. And the scheme that the food system allows for food to be produced and distributed is the beginning of the system loop as is illustrated in Fig.1.

\paragraph{Outcomes}

Then, the food system activities lead to a number of outcomes, some contributing to food security and others contributing to environmental and social concerns. Among them, food security is a principal outcome of any current food system, which is described that the

public don not have reliable access to sufficient affordable and nutritious food. The social welfare outcomes arise because many people rely on the food system as sources of livelihoods; thus these outcomes including income, wealth and health status.

\paragraph{Feedbacks and drivers}

Finally, food system activities and outcomes result in processes which have an influence on environmental and socioeconomic drivers. In conclusion, food systems themselves are drivers of global environment changes (GEC).

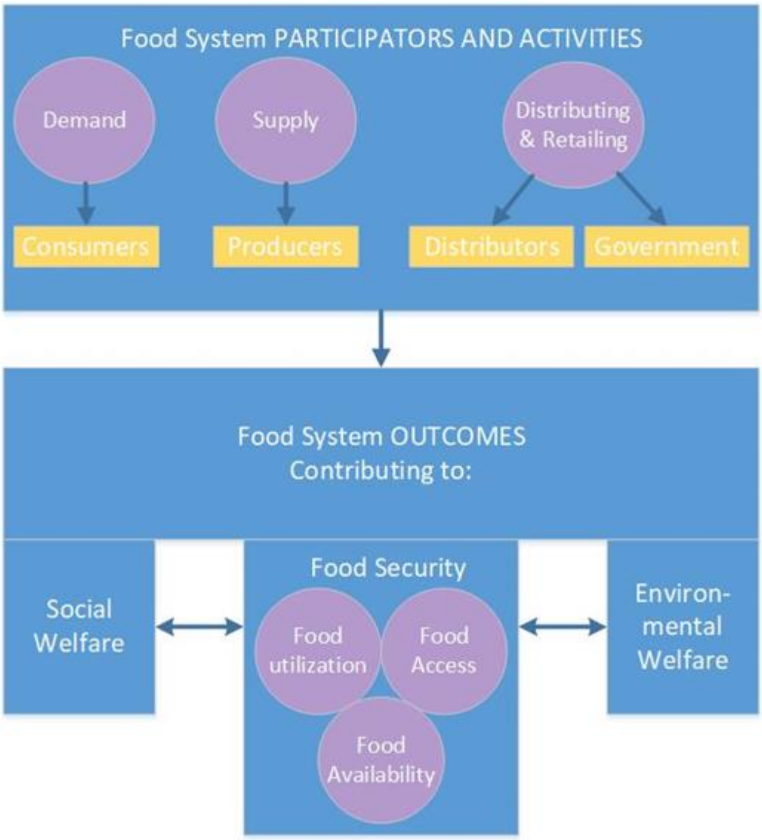

Fig.1 Components of food systems

2.2. Optimization for equity

From the perspective of social demands, the matching degree of supply and demand reflects whether the distribution of social resources is impartial. From the perspective of ecology, negative ecological footprints may lead to the surge of greenhouse gases, the deforestation of forests etc. Therefore, the matching degree of supply and demand and ecological footprints are integrated to evaluate the level of equity.

2.2.1. Definition of γ —— Food utilization rate

Food utilization is the proper biological use of food, requiring a diet providing sufficient energy and essential nutrients, potable water, and adequate sanitation. Effective food utilization depends in large measure on knowledge within the household of food storage and processing techniques, basic principles of nutrition and proper childcare.

According to the data in food loss and waste provided by FAO, we take the average of the upper and lower bounds of the estimated interval as the final value, delete and interpolate the missing values for data cleaning. Thereafter, it is found that the rate of food waste has generally increased in recent years in various countries, indicating that the higher the level of civilization, the greater the surplus of basic food supplies.

2.2.2. Definition of η —— Ratio of supply and demand

The ratio of supply and demand in food system can be classified as three cases, including supply exceeds demand, supply is less than demand, supply and demand are equal. When ratio is equal to one, it indicates that every consumers will get their needs fulfilled, and every producer will be able to sell all their products or services.

A country's food supply is determined by production, imports and exports, storage and waste rates. Among that, food production denotes the level of a country's food production capacity, the difference in imports and exports suggests the total amount of food a country imports from its society, and storage represents the country's capacity of responding to emergencies. At the same time, the increasing rate of waste is one of the most important factors in the food crisis. We have been able to obtain data from various countries, so the formula has been deduced as follows :

$$\text{Supply} = (\text{Production} + \text{import} - \text{export} - \text{save}) * (1\text{-loss})$$

Lei yang suggested that total food demand could be divided into three parts: food rations for urban and rural residents, feed foods, seed foods, industrial foods, storage, transportation and processing losses. However, due to the limitations of the national research background, we have improved it on the basis of the data provided by FAO. The formula is as follows:

Demand = Food + feed + seed + losses + tourist consumption + other use

2.2.3. Equity distance

Food utilization rate γ and ratio of supply and demand η is abstracted as point P on a two-dimensional Cartesian space（γ，η）, where the horizontal coordinates represent the food utilization rate, the vertical coordinate represents ratio of supply and demand. It is obvious that the ideal point q is (1,1) (Food utilization rate is 100% while Ratio of supply and demand is 1). When supply exceeds supply or supply is less than demand, the farther away from ideal point Q, and the closer to zero, the farther away from ideal point. So the matching degree of supply and demand lambda can be described by the Euclidean distance from the ideal point. According to (γ_r, η_r) in different time and space situation, as is normalized:

$$\lambda_{\mathrm{pq}} = \sqrt{\left(\frac{\eta_r - \eta *}{\eta *}\right)^2 + \left(\frac{\gamma_r - \gamma *}{\gamma *}\right)^2}$$

That is:

$$\lambda_{\mathrm{pq}} = \sqrt{(\eta_{\mathrm{r}} - 1)^2 + (\gamma_{\mathrm{r}} - 1)^2}$$

The matching degree of supply and demand λ is the criteria to measure the relationship between supply and demand. If λ_{pq}=0, then $\lambda = \lambda *$ has reached the ideal point. λ_{pq}>0 indicates an incomplete match between supply and demand. The smaller λ_{pq} is, the better the match.

2.3. Optimization for sustainability

Food insecurity is a growing concern worldwide. In many cases food security is not achieved; instead, people spend the major portion of their income on poor or inadequate diets. Generally, food insecurity is conceptualized as resting on three pillars: Scarcity, access, and utilization. In this section, we are dedicated to quantify them.

2.3.1. Food insecurity components and possible typology

To help analyse the factors underpinning food insecurity, the food insecurity can be explained in terms of the following three component:

\paragraph{Food Scarcity}

Food Scarcity is the availability of sufficient quantities of food of appropriate quality, supplied through domestic production and exchanged though imports and exports. The following formula can be obtained

$$x_1 = f(Food\ Production, Food\ Export, Food\ Import)$$

\paragragh{Food Utilization}

It is thought-provoking that widespread waste has gradually become the main factor leading to the hunger in the world today. Meanwhile, The food utilization rate will also be affected by social factors, and personal income and health level will be more or less affected. Therefore, the following formula can be obtained:

$$x_2 = f(Food\ Loss\ and\ Waste, Social\ Value)$$

\paragraph{Food Access}

Access to food can be analysed in terms of the affordability of food that is available and whether consumers can meet their social and other food preferences. Based on this, we define the ability to obtain food that includes the ability to pay and diet preferences of the individual. Among them, the ability to pay is closely related to the level of personal expenditure on food and the level of income. The following formula can be obtained:

$$x_3 = f(Affordability, Preference)$$

The choice of dimensions for food system typologies is critical to their value. Two obvious choices are the attributes of food security (availability, access and utilization) or important trends in the development of food systems (e.g. globalization, increasing use of petroleum products). Figure 2 shows one possible typology of the food security space by plotting components of food security against each other. Food security exists when utilization is high (the entire front face of Figure 2), but some food systems may enable high utilization despite low food access and availability (e.g. when a limited food supply is targeted to people with the lowest consumption rates). This is done when providing food aid in complex humanitarian emergencies.[4]

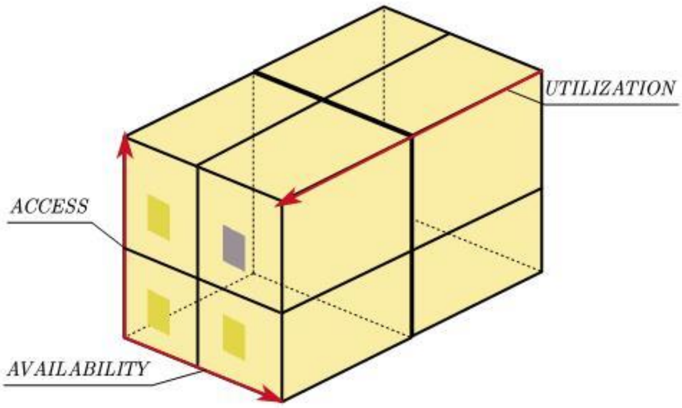

Fig. 2 Possible typology of the food security space

2.3.2. Model establishment

The TOPSIS method (approximate ideal ranking method) is often used as a multi-objective decision-making method in systems engineering. The central theme of the method is to find the best and the most inferior of the finite solutions. When a feasible solution is nearest to the

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optimal solution and is remotest to the worst solution, it can be recognized as the optimal impact evaluation indicator. The steps of the TOPSIS method are as follows:

Step 1. Data co-chemotaxis processing

There are many types of indicator attributes. The benefit attribute is the positive metric, the cost attribute is negative metric while interval attribute is the best in a certain interval, including:

$$\langle Affordability\ \ Food\ Production \cdots\ \ Income\rangle \rightarrow Benefit\ Indicators$$

$$\langle Food\ Loss\ and\ Waste\ \cdots\ Food\ Export\rangle \rightarrow Cost\ type\ Indicators$$

For cost attributes, we use the following formula to convert them into extremely large indicators:

$$X_1 = (\max(x) - x_1)$$

Step 2: Data standardization processing.

Step 3. Determine the positive ideal solution and the negative ideal solution

Step 4. Determine the distance between each index and the ideal solution. The formula is as follows:

$$z_i^+ = \sqrt{\sum\nolimits_{j=1}^{n} (c_{ij} - c_j^+)^2}$$

$$z_i^- = \sqrt{\sum\nolimits_{j=1}^{n} (c_{ij} - c_j^-)^2}$$

Step 5. Obtain the relative distance from the optimal value. The formula is as follows:

$$w_i = \frac{z_i^-}{z_i^- + z_i^+}$$

To this end, we have obtained the food scarcity x1, food utilization rate x2, and food acquisition capacity x3 of each country, and combined with the formula established above, These set the stage for the Multi-Level Indicator System in our global food system in Fig. 6.

2.4. Cross-cutting Theme —— Ecology

Ecology provides new knowledge of the interdependence between people and nature that is vital both for equity and sustainability.

2.4.1. Ecological Footprint Indicators

Global climate change has unpredictable effects on all countries. Droughts, earthquakes, floods, storms and other extreme climates are devastating disasters for all countries. If a country is short of food domestically and have to supply in the international market at the same time, a huge food crisis is inevitable. In the future, the impact of global climate change on food production and production methods will become more and more serious.

Considering these cases, we introduce ecological footprints into the food system in order to build a more applicable food system model, demonstrated as:

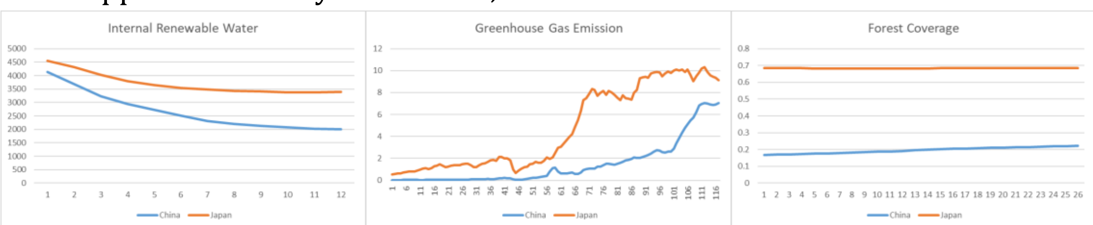

Figure.4 some of China and Japan's ecological footprint indicators over time

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It is evident that the number of greenhouse gases discharged has been increasing in recent years, which has obviously become an imperative factor leading to global warming. However, the coverage rate of forest in various countries does not change a lot. Although the rate of forest has a trend to increase, it cannot prevent the ascendance of greenhouse gas emission. Moreover, it can be concluded from the wildfire incident in Australia in early 2020, people and the government still pay little attention to protecting the ecology. However, the amount of renewable water in various countries is still decreasing year by year, which is remarkable. When producing food, we should also protect the ecology.

2.4.2. Comparison on ecological footprints

Based on the model in section 3.3.4, we use forest coverage, internal renewable water, greenhouse gas emission and agricultural land as indicators, and then quantify the ecological footprint indicators of each country.

The food system taking the ecological footprints into account is as follows:

According to the multi-level indicator system, it is necessary to improve the level of food security so as to maintain or enhance the sustainability of the food system and consciously protect the ecology and build a green home. We analyze the sustainability of the current food systems in various countries based on TOPSIS algorithm.

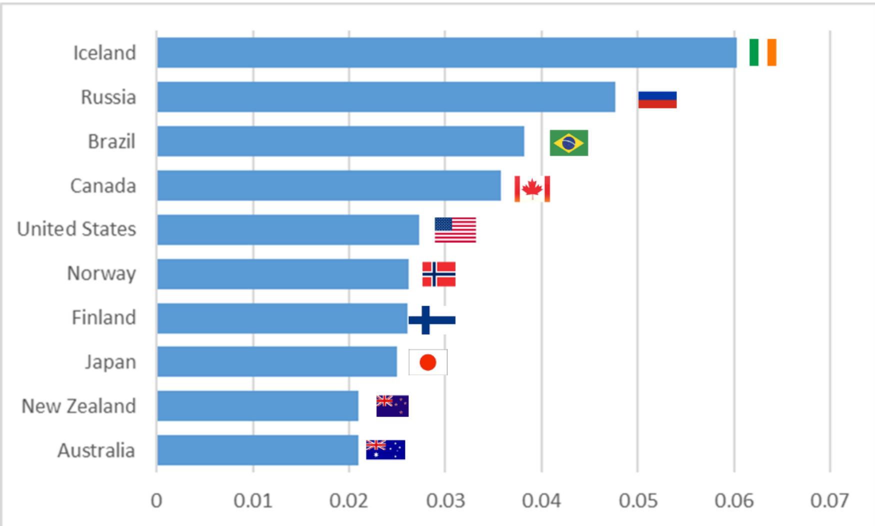

Figure.5 Current Top 10 Sustainable Countries

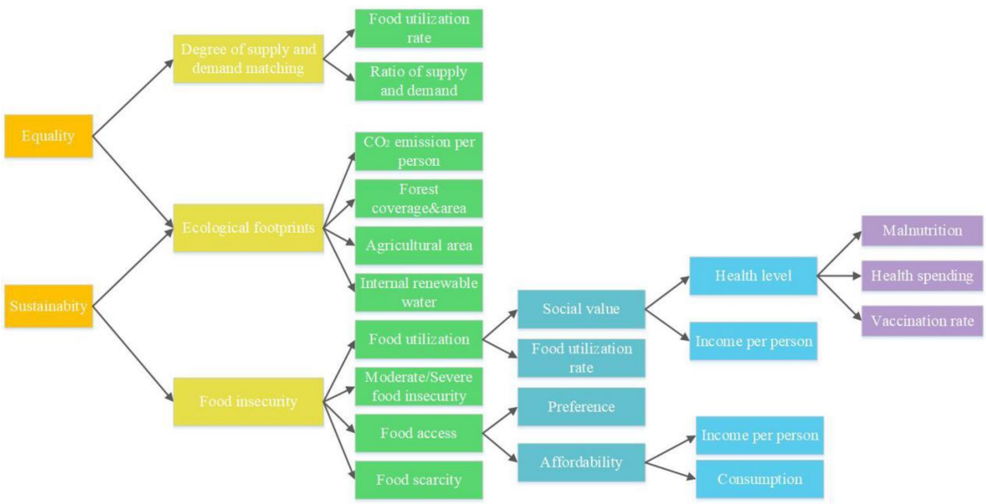

Fig. 6 Structure of Multi-Level Indicator System

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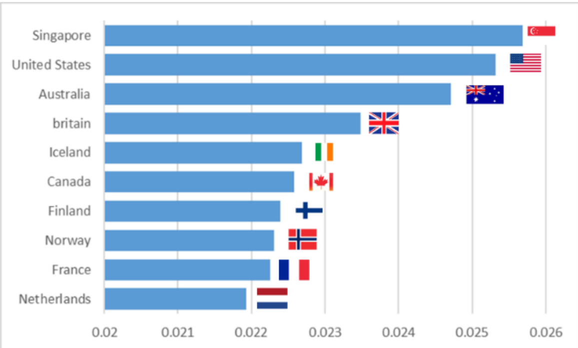
It can be seen from the figure that the sustainable capacity of the Irish food system is the strongest, which is consistent with the fact that it has a high degree of food security and a good ecological footprint. The United States, Canada, Australia, and Finland also have relatively strong sustainability, which is consistent with their high food security and ecological footprint, which once again demonstrates the applicability and reliability of the model.

2.5. Results

2.5.1. Food system outcomes

\paragraph{Analysis on Food Security and ecological footprint}

We utilize the TOPSIS algorithm in order to get the score of food security and ecological footprint in each country. According to the score, we can get the current food security ranking of each country. The top ten countries owing the highest food security is shown in the figure below:



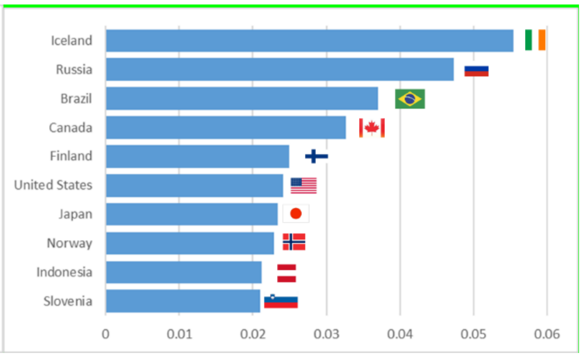


Fig.7 Top 10 Countries in Food Security Fig.8 Top ten countries with Ecological Footprint

It can be seen from the figure on the left that Singapore ranks first and has the highest level of food security, followed by the United States, Australia, and the United Kingdom. Although Singapore is mostly dependent on imported food, it is the country with the lowest import tariffs on agricultural products in the world, where people spend relatively low on food. The diversified channels to import food in Singapore have also enhanced food security. The United States has a lot of food stock, and Australia has a sound legal system to ensure food security. In addition, the problem of food shortage has been partly resolved, and it is relatively convenient to obtain food in these countries. That is why these countries leads the world in food security.

It can be seen from the figure on the right that Ireland, Russia, Brazil, and Canada have relatively better ecological footprints, while Ireland's food security is also very high. It can be foreseen that though the ecological footprint will have an increasing impact on the food system in the future, Ireland can still maintain a safe and sustainable food system. Similarly, the United States and Canada are confident in dealing with the challenge to food security in the future. As a part of Proposal, other countries must also make adequate preparations and implement encouraging policy to deal with the impact of the ecological footprint.

\paragraph{Analysis on Sustainability and Equity}

According to the established indicator system of food system, it can be concluded that in order to maintain or enhance the sustainability of the food system, it is necessary to improve the level of food security, consciously protect the ecology and build a green dwelling. Meanwhile, in order to maintain or enhance the equity of the food system, it is necessary to incite degree of the matching between supply and demand, consciously protect the ecology, promote environmental protection, and pursue a green life. In Fig.?? , we analyze the sustainability and the equity of the current food systems in various countries by TOPSIS:

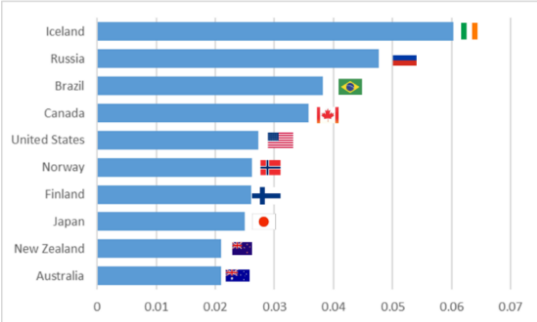


Figure Current Top 10 Sustainable Countries

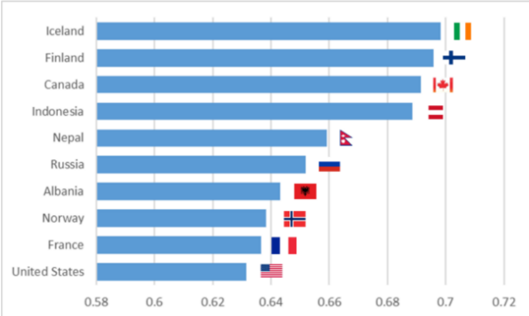


Figure Top 10 countries in current food system equity

It can be seen from the figure on the left that the sustainability of the Irish food system is the best, which is consistent with the fact that Iceland has a higher degree of food security and a better ecological footprint. The United States, Canada, Australia and Finland also have relatively better sustainability, which is consistent with their higher food security and better ecological footprints. Besides, Iceland, Finland and Canada are the top three countries that lead the world in equity. These conclusions demonstrate the applicability and reliability of the model.

2.5.2. Implementation Periods

According to the global food system we have established, the impact of global climate change will become greater and greater. In the established system, each country should attach great importance to this factor from now on and take measures to curb the trend of global environmental degradation. Ideally, not only the trend of global environmental degradation can be effectively controlled, but also the ecological environment will become better and better. For example, the amount of global greenhouse gas emissions will gradually decrease to a certain value. When people pay more attention to environmental protection and avoid actions like over-exploitation, over-fishing and over-harvesting, the incidence of global extreme weather will also decrease. What's more, people will also pay more attention to the degree of food security. The government will accordingly introduce relevant policies and regulations to increase investment. At the same time people's income will gradually rise. The level of health will also be improved by the increase in expenditure of the state and replenishment of medical supply. The relationships between supply and demand of food will also gradually reach a good balance, instead of appreciating the pursuit of profit and efficiency, in favor of equity and sustainability.

\paragraph{Index prediction}

Therefore, in order to estimate when a truly fair and sustainable food system will take to implement, we first predict the indicators such as ecological footprint, food security, and the degree of matching between supply and demand. Then we obtain the value of indicators several years later. At last, we apply neural network method to predict the equity and sustainability in the future.

The changes of indicators over time are divided into three stages according to their characteristics:

\item The first stage——stagnation zone. This stage indicators barely change according to the original trend, which also means this trend has be softened. That's because the stage is in the initial period when countries accept the new food system and implement it in its own way. The realization of this fair and sustainable food system depends on the publication of government policies. And the implementation of a policy takes several years. In China, policies take lots of time to be drafted, formed, and implemented, ranging from 1 years to 6 years. And taking the situation that the effect is not obvious among the first few years into consideration, we assume that this initial stage takes 5 years.

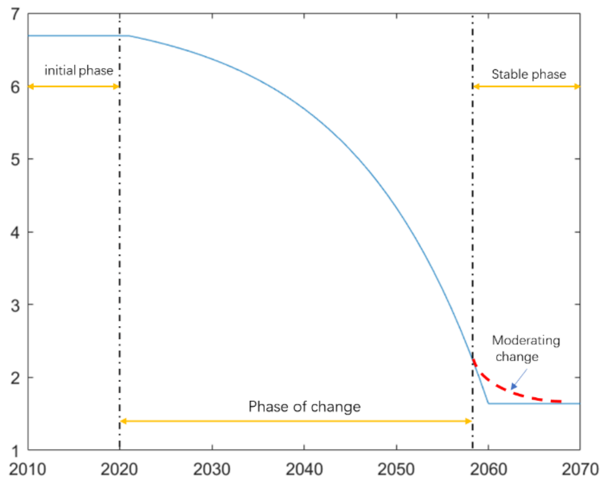
\item The second stage——change zone. In this stage, the indicators begin to change. but the changes in the early stage are relatively gentle, and the intermediate stage are relatively sharp.

\item The third stage——stable zone. the value converges to a certain number.

Indicators that match the above description like CO_2 is defined by the following formula:

$$y_t = \begin{cases} x_{2020}, & 2020 < t \le 2025 \\ (x_{2020} - cons)\left(1 - e^{\frac{t-\alpha}{\beta}}\right) + cons, & 2025 < t < \alpha \\ cons, & \alpha < t \end{cases}$$

In the formula, x2020 represents the current value of the indicator, cons represents the stable value after the indicator changes, α represents the time when the indicator changes softly, and β is the standard deviation of the period at time t. It is shown in the figure. :



? Graph index forecast curve

It can be seen that this formula can show the law of the changing index well. Although the final index does not change softly and approach a constant. However, it has little impact on our forecast.

Similarly, indicators such as income per person will increase, but there is not necessarily an upper limit. It needs to be determined based on specific circumstances. The formula is:

$$y_t = \begin{cases} x_{2020}, & 2020 < t \le 2025 \\ (cons - x_{2020})\left(1 + e^{\frac{t-\alpha}{\beta}}\right) + x_{2020}, & 2025 < t < \alpha \\ cons, & \alpha < t \end{cases}$$

According to the formula above, we can predict different indicators and get the predicted value of the indicator in the future.

Then, neural network in MATLAB toolbox are adopted to predict when a truly fair and sustainable food system will take to implement.

On the premise that the equity and sustainable score calculated by TOPSIS is the independent variable and each predictor as the dependent variable, we set up 10 hidden layers, take the first 70% of the samples as the training group, 15% of the samples as the validation group, and the remaining 15% of the samples as the test group. The Bayesian-regularization method is used for training. The results are shown below:

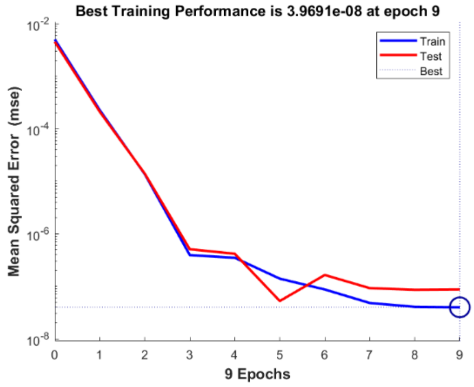


Figure neural network training effect diagram

It can be seen at 9 epochs, the mean square error is the smallest and less than 1, indicating that the neural network can make good predictions. Below, we use the predicted value of each indicator as input to make predictions. As shown in the figure, in the next 2068, the sustainability level of each country exceeds the current sustainable and fair average level. The graph is as follows:

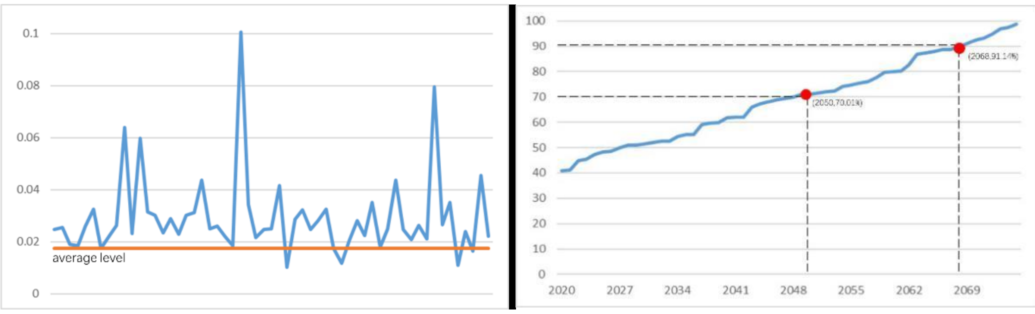


Figure Comprehensive level of sustainability and equity

It can be seen from the figure on the right that in the model we have established, the equity and sustainability of the food system of the entire world will ascend with little fluctuation in the future. Around 2050, more than 70\% of the country's food system will be sustainable and fair. The level of sustainability exceeds the current average level. By 2068, more than 90\% of the country's food system will have a sustainability and equity level that exceeds the current average level. Meanwhile, It is estimated that by the 2070s and 2080s, almost all of the country's food system. The level of sustainability and equity exceeds the current average.

3. Scalability and Adaptability of our model

In section 2, we established a global food system and evaluated the sustainability and fairness of the food system in various countries. In order to explore the scalability of the model, we will now reduce the scope of the research subject and study the food system of a certain province in China to show that our food system is highly scalable. Next, take Heilongjiang Province in China as the research object:

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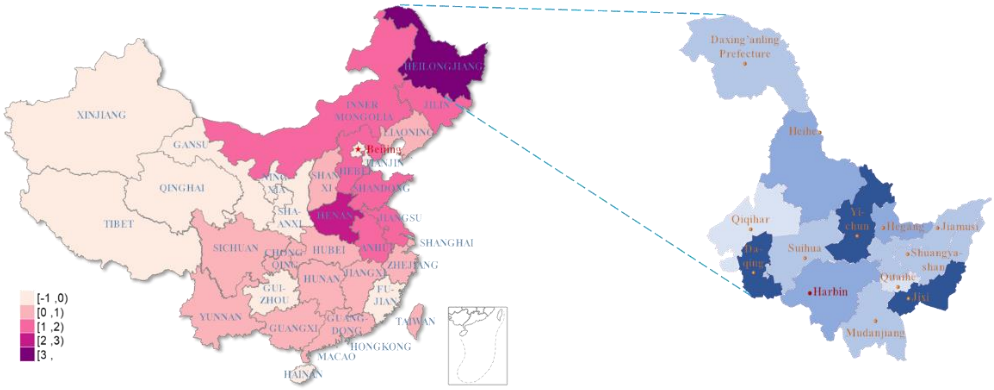

Figure Geographical Region of Heilongjiang Province

Heilongjiang Province is located in the eastern part of Eurasia in the mid-latitude region. It is the northernmost and highest latitude province in China. The administrative regions of Heilongjiang Province include Harbin City, Qiqihar City, Jixi City, Hegang City, Shuangyashan City, Daqing City, Yichun City, Jiamusi City, Qitaihe City, Mudanjiang City, Heihe City, Suihua City and Daxinganling Region, in total 13 prefecture-level cities. Most of the province is in the mid-temperate zone. Only Huma and Mohe in the northern region are cold-temperate zones. They belong to the continental monsoon climate, with four distinct seasons, summer rains and hot seasons, and long winters.

We obtained useful data through the Heilongjiang Provincial Bureau of Statistics, and after standardizing the collected data, we drew a radar chart of indicators for prefecture-level cities and analyzed them first. The following picture shows the radar chart of some prefecture-level cities and some indicators:

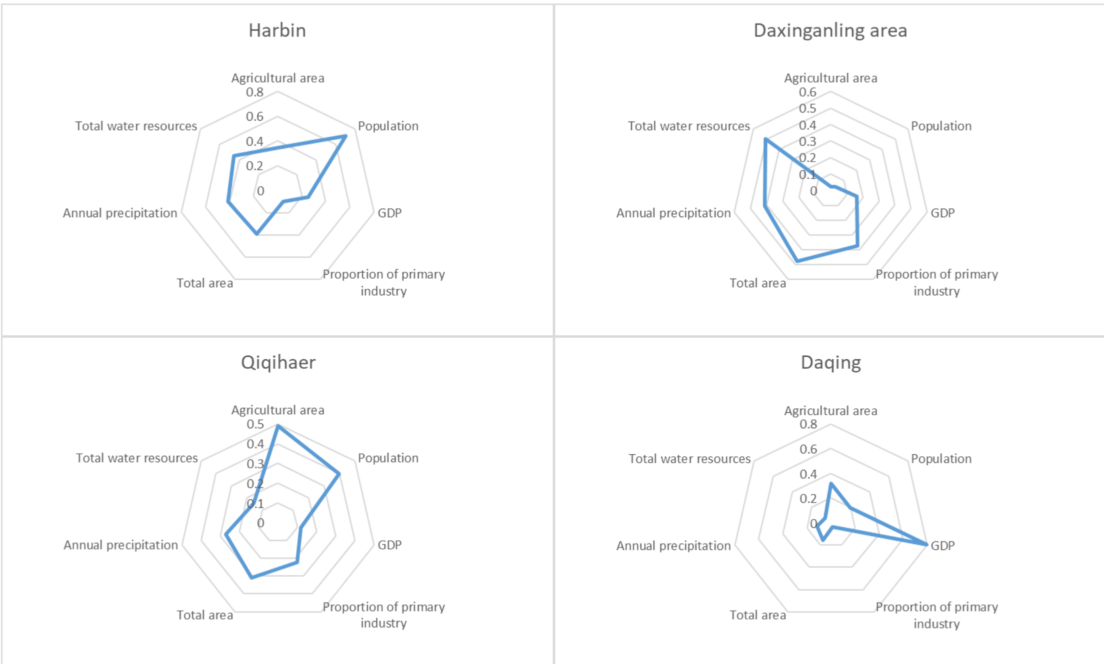

Figure Distribution of six indicators in four prefecture-level cities

It can be seen from the figure that although the cities at all levels belong to the same province, the living standards of people vary greatly and the distribution of resources is uneven. As the capital of the province, Harbin has a large population and low primary industry and agricultural land. The Daxinganling area is mostly a nature reserve, with annual rainfall, abundant water resources, few agricultural land and a relatively small population. Qiqihar is located in the western region, and it is mainly based on the primary industry, with more agricultural land.

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Daqing is famous for its oil fields, with developed manufacturing industries and high per capita GDP.

It can be seen that the overall level of the food system varies from region to region in Heilongjiang Province. We can get the overall level of the food system in each city in Heilongjiang Province through MATLAB based on relevant data and combining with ESA model, as shown in the left figure below. We divide it into 4 levels according to the different food levels of each city, as shown in the right figure below:

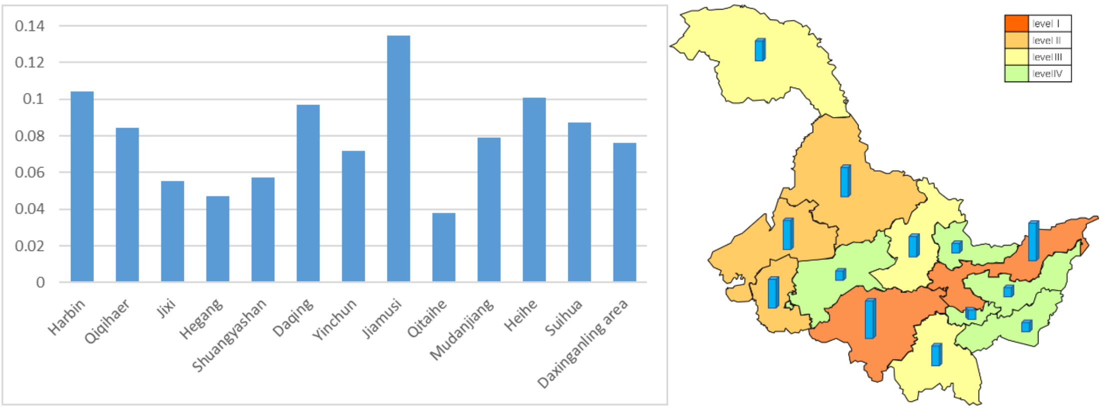

Figure The level of the food system of each city in Heilongjiang Province

It can be seen from the figure that the overall level of the food system in Jiamusi and Harbin is relatively high, and Jiamusi has been awarded the "Top 10 Food Safety Cities in China" for many years. The city's agricultural land accounts for 34%, and the rainfall is sufficient, while Harbin's food output High, the actual level of the two food systems is consistent with the value obtained by the model we built, indicating that the model has a certain applicability. In the Greater Xing'an Mountains region, the food output of Yichun, Qitaihe, Hegang, Shuangyashan, Jixi and other prefecture-level cities is mostly low, and the overall level of the corresponding food system is generally low; the food output of Daqing, Qiqihar, and Harbin is very low. High, the corresponding overall level of the food system is relatively high.

After the above analysis, we can see that the model we have established accurately gives the overall level of the food system in each city in Heilongjiang Province. It demonstrates strong scalability and applicability of the model proposed.

4. Conclusion

The originality of the work can be stated as follows:

(1) A multi-level indicator system is established to evaluate the equity and sustainability of our global food system.

(2) The ES – PEA model is proposed to optimize global food system from social and ecological dimensions.

(3) The income sharing model of food supply chain is generalized to describe the food trade between countries.

This study is mainly concentrated on the reprioritization our food systems through development of a model. In our work, we have established the ESA model and the ES-PEA model to optimize food systems from social and ecological dimensions while balancing efficiency and profit on this basis.

First of all, we propose a multi-level indicator system and define a series of indicators by referring to the literature. For indicators that are not easy to quantify, TOPSIS is applied to quantify them. These indicators reflect the characteristics of a country or a region's food system. Besides, we introduce ecological footprint into our model and further explore the equity and sustainability. We have found that more than 70\% of the country's food system will be equal and sustainable enough in 2050.

Then, we explored the maximization of profit through sharing revenue between countries, wherein China and Japan are taken as examples to verify the accuracy of the model. In order to explore the scalability and adaptability of the model, we narrowed the scope of the research subject to Heilongjiang Province, China. Based on the model proposed, the overall level of the food system in 13 cities in Heilongjiang Province are analyzed. The results ascertain conclusions we found.

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