Energy Proceedings
2022
ISSN 2004-2965

[1]Evaluation of Water -Energy Benefit in China Based on Inter-Provincial Food Trade

Miaoye Kang[1], Yongnan zhu [1*], Fan He[1], Guohua He[1], Mingming Yang[1]

1 State Key Laboratory of Simulation and Regulation of Water Cycles in River Basins, China Institute of Water Resources and Hydropower Research, Beijing 100038, China

ABSTRACT

Large amount of water and energy are consumed in the food production process, including food production, trade and consumption. This study employs Linear Interactive and General Optimizer (Lingo) to simulate the inter-provincial food trade pattern in China. Using ecological footprint, we evaluate the efficiency and resource benefits of water and energy footprint in food trade. Our research shows that provinces with food surpluses are primarily distributed in the north and provinces with food deficit are mainly in the south, resulting in national food trade amount of 304.23 million tons. The spatial distribution of the total water footprint and energy footprint of food production is the same, with eastern > central > western region. In 2020, nationwide food trade has saved 57.2 billion m³ of water resources and result in 3.13 million tce waste of energy.

Keywords: water footprint, energy footprint, food trade, resource benefit

1. INTRODUCTION

Water, energy, and food are the basis for humankind’s survival and socioeconomic development; thus, it is important to ensure water, energy, and food security[1]. China's water resources are currently under severe challenges[2]. The amount of water available per capita in China is about 2100 m³/year, which is only 1/4 of the global average[3]. Food production requires a lot of energy and produces carbon emissions, and many studies have concluded that agricultural output is the most important factor determining the global greenhouse effect[4]. Water and energy are the basis of food production, so quantifying water and energy usage in food production, consumption, and trade is important.

The existing studies focus primarily on the following aspects: (1) the coupling relationship between water, energy, and food[5] .(2) quantitative accounting of water consumption in energy production, processing, and conversion or energy consumption of the water system in the whole process[6-8], and the effect of virtual water flows on water resource stress in energy trade[9, 10]; (3) the water footprint issue in food production and consumption, and virtual water flows in trade[11]; (4) correlation between food and energy[12].

According to a literature review, it was discovered that there needs to be more research conducted on the water–energy–food correlation. Thus, based on past investigation, this paper conducted the following studies: (1)widen the food categories and examined the supply and demand structure of all food categories in 31 provinces in China in 2020; (2) simulated the inter-provincial food trade pattern using the Lingo Software and quantitatively evaluated the inter-provincial trade volume of different foods; (3) evaluated the water footprint and energy footprint of various foods and examined the spatial distribution characteristics of energy and water consumption of food production; (4) quantitatively evaluated the inter-provincial virtual water and energy flow patterns based on the inter-provincial food trade and the water and energy footprints of various foods, and evaluated the resource benefit based on this flow pattern; (5) Finally, based on the resource benefit brought by the virtual water and virtual energy flows, policy recommendations for water and energy savings were proposed.

2. METHODS AND DATA

2.1 Methods

2.1.1 Water footprint assessment of various foods

Food water footprint is divided into direct water footprint and indirect water footprint. The former represents the water consumed in the process of food production, and the latter represents the indirect water footprint brought by the material materials invested in the process of food production. The calculation method of water footprint in this paper refers to A.K. Chapagain and A.Y. Hoekstra[13, 14], etc. In this study, vegetable foods

This is a paper for the 14th International Conference on Applied Energy - ICAE2022, Aug. 8-11, 2022, Bochum, Germany.

include grain, vegetables, fruits, vegetable oils and sugar; animal foods include pork, beef, mutton, poultry, aquatic products, eggs and milk. Due to the fact that it is difficult to obtain the indirect water consumption data of vegetable foods, this paper only considers the direct water footprint, that is, the water consumed in the growth process of vegetable foods (blue water footprint and green water footprint). For animal foods, the direct water footprint is the water for animal drinking and service, and the indirect water footprint is the water footprint of animal feed.

$$WF_k = WF_{k,dir} + WF_{k,ind} \tag{1}$$

When k represents vegetable foods:

$$WF_{k,veg,dir} = WF_{k,,veg,blue} + WF_{k,veg,green} \tag{2}$$

When k represents animal foods:

$$WF_{k,ani,dir} = WF_{k,ani,drink} + WF_{k,ani,clean} \tag{3}$$

$$WF_{k,ani,ind} = WF_{k,ani,feed} \tag{4}$$

Where k represents different specific foods; WF_k, $WF_{k,dir}$ and $WF_{k,ind}$ represent the water footprint, direct water footprint and indirect water footprint of food k respectively; $WF_{k,veg,blue}$ and $WF_{k,veg,green}$ represent the blue water footprint and green water footprint of vegetable food k; $WF_{k,drink}$, $WF_{k,clean}$ and $WF_{k,ani,feed}$ represent the drinking water, cleaning water and water used for feed grain of animal food k; $WF_{k,ani,feed}$ can be calculated according to the composition of feed grain[15].

2.1.2 Energy footprint assessment of various foods

In the process of vegetable foods production, the energy input can be divided into direct energy and indirect energy. Because it is difficult to obtain the data of indirect energy consumption, this study only considers the direct energy consumption of vegetable foods production process. The calculation methods refer to the research of Zhang[16] .

The energy consumption of animal foods can be divided into direct energy consumption and indirect energy consumption. Direct energy consumption refers to electricity and coal consumed in the production of animal foods. Indirect energy consumption refers to the energy consumption of feed grain for the production of these animal foods. The calculation formulas are expressed as:

$$EF_{k,ani} = EF_{k,ani,,dir} + EF_{k,ani,ind} \tag{5}$$

$$EF_{k,ani,,dir} = EF_{k,coal} + EF_{k,electricity} \tag{6}$$

$$EF_{k,ani,ind} = \rho_k * EF_{k,feed} \tag{7}$$

Where $EF_{k,ani}$, $EF_{k,ani,,dir}$ and $EF_{k,ani,ind}$ respectively represent the energy footprint, direct energy consumption and indirect energy consumption of animal food k (tce/10^4ton). $EF_{k,coal}$ and $EF_{k,electricity}$ respectively represent the consumption of coal and electricity of animal food k, of which the calculation methods are similar to that of vegetable foods. ρ_k represent the conversation coefficients of animal food k[17]. $EF_{k,feed}$ represent the energy footprint of feed grain (tce/10^4ton) used by animal food k, which can be calculated according to the composition of feed grain[15].

2.1.3 Flow pattern of virtual water and virtual energy

Analysis of food surplus provinces and deficit provinces

When food supply and demand are unbalanced, trade will be carried out among different provinces. According to the positive and negative trade amount, the provinces in China can be divided into food surplus provinces and food deficit provinces. The trade amount of food is expressed as:

$$X_{i,k} = P_{i,k} + I_{i,k} + C_{i,k} \tag{8}$$

Where $P_{i,k}$, $I_{i,k}$, $C_{i,k}$ respectively represent the yield, import and consumption of food k in province i(ton), and $X_{i,k}$ represents surplus of food k (ton). When $X_{i,k}$ is positive, it is the province of food surplus; When $X_{i,k}$ is negative, it is the province of food deficit.

Simulation model of inter-provincial food trade

Taking the minimum transportation cost as the objective function, Lingo Software is used to calculate the amount and flow direction of inter-provincial food trade. The model is as follows:

$$minCost = \sum_{i=1}^{N} \sum_{j=1}^{M} x_{ij} \times C_{ij} \tag{9}$$

$$\sum_{i=1}^{N} x_{ij} \geq D_j \tag{10}$$

$$\sum_{j=1}^{M} x_{ij} \leq S_i \tag{11}$$

$$x_{ij} \geq 0 \tag{12}$$

Where N is the amount of food surplus province, M is the amount of food deficit province. x_{ij} is the amount of food transferred from province i to province j (ton); C_{ij} is the unit transportation cost of food transferred from province i to province j (yuan / ton); D_j is the food deficit in province j (ton); S_i is the food surplus in province i (ton).

Calculation of virtual water and virtual energy flow

When the food trade between provinces is carried out due to the imbalance between supply and demand, it will drive the flow of virtual water and virtual energy. The virtual water and virtual energy trade volume can be calculated as follows:

$$TVW_{ij} = x_{ij} \times WF_i \tag{13}$$

$$TVE_{ij} = x_{ij} \times EF_i \tag{14}$$

Where TVW_{ij} and TVE_{ij} respectively represent the virtual water (m^3) and virtual energy (tce) transferred from province i to province j; x_{ij} is the amount of food transferred from province i to province j (ton); WF_i and EF_i represent the water footprint (m^3 /t) and energy footprint (tce/10^4ton) in province i respectively.

Resource benefit evaluation based on virtual water and virtual energy flow pattern

When food is transferred from provinces with low unit water footprint (energy footprint) to provinces with high unit water footprint (energy footprint), resource conservation will occur; On the contrary, some resources will be wasted. In order to quantitatively describe the resource saving or waste caused by the flow of virtual water and virtual energy, this paper defines the resource benefit as follows: the difference between the water footprint (energy footprint) of food exporting provinces and the water footprint (energy footprint) of importing provinces is multiplied by the volume of food trade.

$$WB_{ij} = \left(WF_i - WF_j\right) * x_{ij} \tag{15}$$

$$EB_{ij} = \left(EF_i - EF_j\right) * x_{ij} \tag{16}$$

Where x_{ij} is the amount of food transferred from province i to province j (ton); WF_i （EF_i） and WF_j （EF_j） respectively represent the unit water footprint (energy footprint) in the exporting province i and importing province j; WB_{ij} and EB_{ij} respectively represent the water benefit and energy benefit brought by the transfer of food from province i to province j. If WB_{ij} (EB_{ij}) is positive, it means that resources are inefficient; otherwise, resources are saved.

2.2 Data collection

In this study, the data of food production and consumption are obtained from China Statistical Yearbook and China Household Survey Yearbook. The data of food import amount collected from the General Administration of Customs of China. Climate data is acquired from 820 meteorological stations of the Chinese ground climate data. The energy consumption data of food obtained from the national compilation of costs and benefits of agricultural products. The data of inter-provincial distance and transportation cost refer to the research of Lin[17] and Gao[18].

3. RESULTS

3.1 Analysis of inter-provincial food trade

3.1.1 Analysis of food surplus and deficit provinces

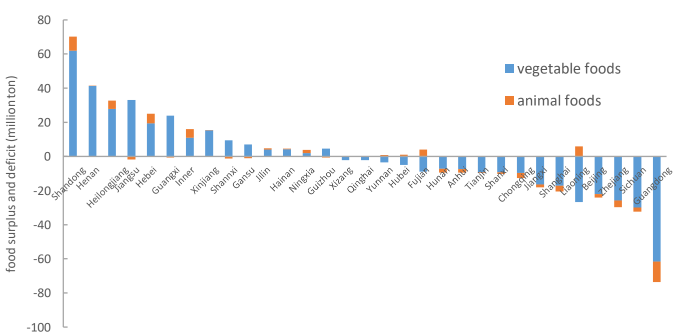

Fig. 1 Provinces with food surplus and deficit

In the distribution of surplus and deficit provinces of vegetable foods, there are 14 surplus provinces, mainly distributed in the north. Among them, Shandong has the largest surplus, which is 61.88 million tons, followed by Henan Province and Jiangsu Province, which are 41.34 million tons and 33.06 million tons respectively. There are 17 deficit provinces of vegetable food, mainly distributed in the eastern coastal areas and southwest areas, and a small amount in North China and Northeast China; Guangdong has the largest deficit of 61.6 million tons, accounting for 23% of the total deficit in China.

There are 15 surplus provinces of animal food, mainly distributed in northern China, of which Shandong, Liaoning, Hebei, Inner Mongolia, Heilongjiang and Fujian account for 85% of the total surplus. There are 16 animal food deficit provinces, mainly distributed in southern China. Guangdong has the largest deficit of 11.95 million tons, accounting for 30% of the total deficit in China.

3.1.2 Analysis of inter-provincial food Trade

According to the inter-provincial food trade model, Shandong's vegetable food is mainly transferred to Shanghai and Jiangxi, and the export amount accounts for 54% of its total surplus. Henan's vegetable food is mainly exported to Guangdong, accounting for 61% of its total export. Jiangsu's vegetable food is mainly exported to Zhejiang, accounting for 78% of its total surplus. As the largest import province of vegetable food, Guangdong imports the most food from Guangxi, followed by Henan.

According to the inter-provincial trade pattern of animal food, Shandong's animal food is mainly exported to Zhejiang, Anhui and Jiangsu, accounting for 46%, 26% and 23% of its surplus respectively. Guangdong imports the most animal food, of which 33% are imported from Fujian, 27% from Liaoning and 21% from Hebei. To sum up, animal food is mainly transferred from the north to the south.

3.2 water footprint of various foods

3.2.1 water footprint at national level

At the national level, the unit water footprint and total water footprint of different foods in 2020 are shown in the Table 1. It can be seen from the table that there are significant differences in unit water footprints of different foods. The unit water footprint of vegetable foods（623.09m^3 /ton） is lower than that of animal foods（2455.83m^3 /ton）. Among vegetable foods, the total water footprint of grain is the largest, accounting for 63% of the vegetable foods; the total water footprint of sugar is the smallest, which is less than 1% of vegetable food. Among animal foods, the total water footprint of aquatic products is the largest, accounting for 29% of animal foods; although the unit water footprint of mutton is larger than that of pork and aquatic products, its yield is the lowest, resulting in the lowest total water footprint.

3.2.2 Provincial distribution of water footprint

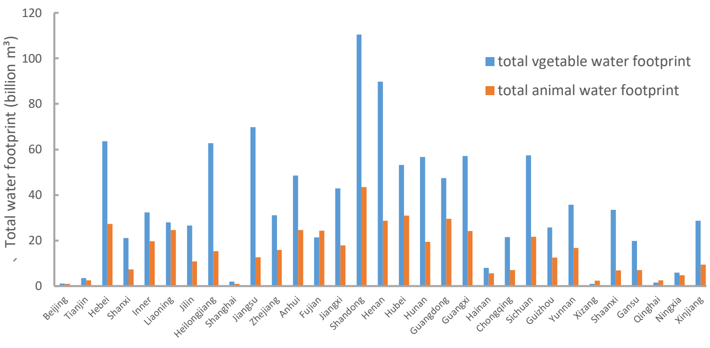

Fig. 2 Total water footprint of vegetable and animal foods

As can be seen from Fig. 2, the vegetable water footprint and animal water footprint in Southeast China are large, indicating that the utilization efficiency of water resources in the process of food production in this area is low; the unit water footprint of vegetable foods in the western region is small, while that of animal foods is large. From the inter-provincial distribution of the total water footprint, it can be seen that the distribution of the total water footprint of vegetable foods and animal foods is similar. The total water footprint in the eastern region is the largest, followed by the central region, and that in the western region is the smallest.

3.3 Energy footprint of various foods

3.3.1 energy footprint at national level

At the national level, the unit energy footprint and total energy footprint of various foods in 2020 are shown in Table 1. The unit energy footprint of vegetable foods (660.83 tce / 10^4ton) is lower than that of animal foods (1776.48 tce / 10^4ton). Among the vegetable foods, the total energy footprint of grain is the largest, about two fifths of that of vegetable foods; although the unit energy footprint of vegetables is the smallest, due to its largest output, its energy consumption is second only to grain, which is 30.13 million tce. Among the animal foods, aquatic products consume the most energy (10.8 million tce), about one third of that of animal foods; although beef has the largest unit energy footprint, its energy consumption is only half of that of pork due to its low production.

3.3.2 Provincial distribution of energy footprint

In the unit energy footprint distribution of vegetable foods, the unit energy footprint of northeast, North China and southwest is larger, and that of Central South and northwest is smaller. In the unit energy footprint distribution of animal foods, the provinces located in the Yellow River Basin have a large unit energy footprint, with an average value of 2499tce/ 10^4ton, indicating that the energy utilization efficiency in the production of animal foods in these areas is low, and the breeding technology needs to be further improved. From the inter-provincial distribution of the total energy footprint, it can be seen that the distribution of the total energy footprint of vegetable foods and animal foods is similar. The total energy footprint in the eastern region is the largest, followed by the central region, and that in the western region is the smallest.

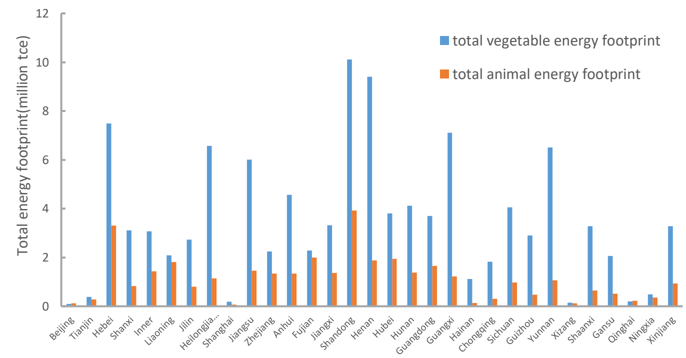

Fig. 3 Total energy footprint of vegetable and animal foods

3.4 *Benefit evaluation of virtual water and virtual energy flow pattern*

According to the inter-provincial trade pattern of vegetable foods, Heilongjiang's vegetable foods are mainly exported to Liaoning, resulting in a waste of 8.2 billion m^3 water; however, the vegetable foods in Jiangsu are mainly transferred to Zhejiang, saving 4.8 billion m^3 water; at the national level, the inter-provincial trade of vegetable foods has resulted in a total saving of water resources of 110 million m^3. According to the inter-provincial flow pattern of virtual energy, most vegetable food trade will produce energy inefficiency, resulting in an overall energy waste of 2.64 million tce.

According to the inter-provincial trade pattern of animal foods, most food trade will save water resources, saving 57.1 billion m^3 of water resources overall; among them, animal foods in Shandong are mainly transferred to Zhejiang, with the largest contribution rate to the total amount of water resources conservation, which is 25%. According to the inter-provincial flow pattern of virtual energy, most exporting provinces have lager unit energy footprint than that of importing provinces, resulting in an overall energy waste of 0.49 million tce.

To sum up, the national food trade will save 57.2 billion m^3 water, while wasting 3.13 million tce of energy.

4. DISCUSSION

(1) In this paper, the total blue footprint of feed grain accounts for the main part of animal foods water use; however, the blue water used in feed grain has been included in the grain blue water footprint. In addition, the blue water footprint of vegetable oil and sugar has been included in that of oil crops (soybean) and sugar crops (sugarcane). Therefore, excluding the double counting part, the actual water consumption of food should include the total water footprint of grain, vegetables, fruits, soybeans and sugarcane, which is about 322 billion m^3； The error between this value and agricultural water consumption in 2020 is less than 1%, indicating that the water footprint calculated in this paper is relatively accurate.

(2) Food is mainly exported from the northern region where water resources are scarce to the southern region where water resources are abundant. This trade pattern will aggravate the water resources pressure in the north. The virtual energy flow pattern based on food trade will not only lead to the result of energy inefficiency, but also aggravate the energy pressure in the north, resulting in the fierce competition of food and energy production for water resources in the north. Therefore, we should improve the utilization efficiency of water resources and energy, adjust the diet structure and reduce food waste, so as to alleviate the pressure of water resources and energy in China from the consumer side.

5. CONCLUSION

This study quantitatively evaluates the water and energy footprints of various foods in China, as well as the inter-provincial food trade based on virtual water and energy flow patterns. The study evaluates the resource benefit brought by virtual water and energy flows. The main conclusion can be summarized as follows:

(1) There are 14 provinces with vegetable food surpluses and 15 provinces with animal food surpluses, primarily in the north; Shandong has the largest surplus; there are 17 provinces with vegetable food deficit and 16 provinces with animal food deficit, primarily in the south; Guangdong has the largest deficit. Shandong, the province with the largest food surplus, exports its vegetable food primarily to Shanghai and Jiangxi; Guangdong, the province with the largest food deficit, gets its vegetable foods primarily from Guangxi and Henan.

(2) The unit water footprint and unit energy footprint of various foods are significantly different, and the unit water footprint and unit energy footprint of animal foods are higher than those of vegetable foods; the spatial distribution of the unit water footprint of foods is characterized by the following: in the southeast regions, both the unit water footprint and unit energy footprint of the vegetable foods are higher than those of other regions; in the western region, the unit water footprint of vegetable foods is low, while that of animal foods is high. The spatial distribution of the unit energy footprint of various foods is characterized as follows: northeast, north, and southwest China have a larger unit energy footprint for vegetable foods, and the Yellow River Basin has a larger unit energy footprint for animal foods; the spatial distribution of total water footprint is the same as that of total energy footprint: the eastern region has the highest total water footprint and total energy footprint, the western region has the lowest, and the central region is in the middle.

(3) The nationwide inter-provincial food trade saves 57.2 billion m^3 of water (including 110 million m^3 by vegetable food trade and 57.1 billion m^3 by animal food trade). However, the inter-provincial trade of food results in an energy waste of 3.13 million tce (including 2.64 million tce by vegetable food trade, 0.49 million tce by animal food trade).

ACKNOWLEDGEMENT

This work was funded by National Natural Science Foundation of China (No. 52009141, 52109042).

REFERENCE

[1] Wang Z, Zhang L, Ding X, Mi Z. Virtual water flow pattern of grain trade and its benefits in China. Journal of Cleaner Production 2019; 223:445-455.
[2] Niva V, Cai J, Taka M, Kummu M, Varis O. China's sustainable water-energy-food nexus by 2030: Impacts of urbanization on sectoral water demand. Journal of Cleaner Production 2020; 251:119755.
[3] Liu J, Li M, Wu M, Luan X, Wang W, Yu Z. Influences of the south–to-north water diversion project and virtual water flows on regional water resources considering both water quantity and quality. Journal of Cleaner Production 2020; 244:118920.
[4] Goodland R AJ. Livestock and climate change[J]. World watch 2009; 22(6):10.
[5] Sun C, Yan X, Zhao L. Coupling efficiency measurement and spatial correlation characteristic of water–energy–food nexus in China. Resources, Conservation and Recycling 2021; 164:105151.
[6] Liao X, Hall JW, Eyre N. Water use in China's thermoelectric power sector. Global Environmental Change 2016; 41:142-152.
[7] Zhou Y, Zhang B, Wang H, Bi J. Drops of Energy: Conserving Urban Water to Reduce Greenhouse Gas Emissions. Environmental Science & Technology 2013; 47(19):10753-10761.

[8] Lee M, Keller AA, Chiang P-C, Den W, Wang H, Hou C-H, et al. Water-energy nexus for urban water systems: A comparative review on energy intensity and environmental impacts in relation to global water risks. Applied Energy 2017; 205:589-601.
[9] Zhang J, Zhong R, Zhao P, Zhang H, Wang Y, Mao G. International energy trade impacts on water resource crises: An embodied water flows perspective. Environmental Research Letters 2016; 11:074023.
[10] Zhang C, Zhong L, Liang S, Sanders KT, Wang J, Xu M. Virtual scarce water embodied in inter-provincial electricity transmission in China. Applied Energy 2017; 187:438-448.
[11] Qian H, Engel BA, Tian X, Sun S, Wu P, Wang Y. Evaluating drivers and flow patterns of inter-provincial grain virtual water trade in China. Science of The Total Environment 2020; 732:139251.
[12] Xydis GA, Liaros S, Botsis K. Energy demand analysis via small scale hydroponic systems in suburban areas – An integrated energy-food nexus solution. Science of The Total Environment 2017; 593-594:610-617.
[13] Hoekstra AKCAY. Water footprints of nations. Volume 1: Main Report 2004.
[14] Hoekstra AKCAY. Virtual water flows between nations in relation to trade in livestock and livestock products. Value of Water Research, Report Series No 13 2003.
[15] He G, Zhao Y, Wang J, Li H, Zhu Y, Jiang S. The water–energy nexus: energy use for water supply in China. International Journal of Water Resources Development 2019; 35(4):587-604.
[16] Zhang R. A Study on the relationship between grain production and water and energy in Ningxia. Xi'an, China: Xi'an University of Technology; 2019.
[17] Lin L, Gao X, Zhao Y, Wang L, An T, Liu C, et al. Evaluation of the water consumption of animal products and the virtual water flow pattern associated with interprovincial trade in China. Journal of Cleaner Production 2021; 328.
[18] Gao S. Research on inter provincial grain transportation cost based on road network analysis. Logistics Technology 2014; 37(5):135-139.