Science of the Total Environment 887 (2023) 164128

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

The grain Food-Energy-Water nexus in China: Benchmarking sustainability with generalized data envelopment analysis

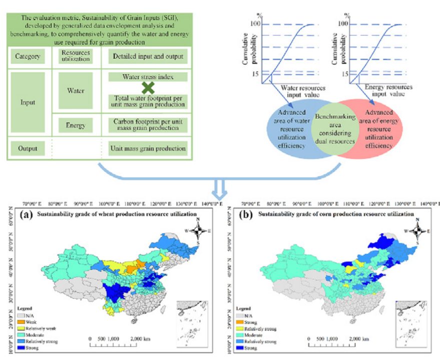
Jie Yang [a,b], Jianxia Chang [a,*], Megan Konar [c], Yimin Wang [a], Jun Yao [d]

[a] State Key Laboratory of Eco-hydraulics in Northwest Arid Region, Xi'an University of Technology, Xi'an 710048, China
[b] Northwest Land and Resources Research Center, Global Regional and Urban Research Institute, Institute of Transport Geography and Spatial Planning, Shaanxi Normal University, Xi'an 710119, China
[c] Civil and Environmental Engineering Department, University of Illinois at Urbana-Champaign, Urbana, IL, USA
[d] Hanjiang - to - Weihe River Valley Water Diversion Project Construction Co. Ltd., Shaanxi Province, Xi'an 710010, China

HIGHLIGHTS

- An eco-efficiency sustainability evaluation metric for grain production i.e., SGI, is developed.
- The SGI is developed by generalized data envelopment analysis and benchmarking.
- SGI simultaneously assesses water and energy use sustainability in grain production.
- Wheat and corn production in Northwest China are urgent to improve the eco-efficiency.

GRAPHICAL ABSTRACT



ARTICLE INFO

Editor: Kuishuang Feng

Keywords:
Water footprint
Carbon footprint
Generalized data envelopment analysis
Benchmarking
Sustainability
Food-Energy-Water nexus

ABSTRACT

Food insecurity can be considered as a significant cause to instability in some regions around the world. Grain production utilizes a multiple of inputs, such as: water resources, fertilizers, pesticides, energy, machinery, and labor. In China, grain production has led to huge irrigation water use, non-point source pollution, and greenhouse gas emissions. It is necessary to emphasize the synergy between food production and ecological environment. In this study, a grain Food-Energy-Water nexus is delivered and an eco-efficiency sustainability evaluation metric is introduced, Sustainability of Grain Inputs (SGI), for investigating the sustainability of water and energy use in grain production across China. SGI is constructed by using generalized data envelopment analysis to comprehensively incorporate differences of water and energy inputs (including indirect energy use contained in agricultural chemicals such as fertilizers, pesticides, agricultural film, and direct energy use such as the electricity and diesel used for irrigation and agricultural machinery) in different regions across China. Both water and energy are considered by the new metric at the same time, which is built on the single resources metrices that are often used in the sustainability literature. This study evaluates the water and energy use of wheat and corn production in China. Wheat production uses water and energy sustainably in Sichuan, Shandong, and Henan; Corn production has the highest combined sustainability index in Shandong, Jilin, Liaoning, and Henan. In these areas, the grain sown area could be increased. However, wheat production in Inner Mongolia and corn production in Xinjiang rely on unsustainable water and energy inputs, and their grain sown areas could be reduced. The SGI is a tool that researchers and policy makers can use to better quantify the sustainability of water and energy inputs to grain production. It facilitates formulating policies about water saving and carbon emission reduce of grain production.

* Corresponding author.
E-mail address: chxiang@xaut.edu.cn (J. Chang).

http://dx.doi.org/10.1016/j.scitotenv.2023.164128
Received 11 December 2022; Received in revised form 10 April 2023; Accepted 9 May 2023
Available online 10 May 2023

1. Introduction

China is a large grain producer and consumer whose domestic grain supply is an important part of national security (Chen et al., 2021; Hou et al., 2022). Grain security has been emphasized in the No. 1 Central Document issued by the government over the years (Liu et al., 2021). Document in 2022 still stated that China should ensure a stable grain sown area, ensure grain security, and keep the grain production over 650 billion kilos. To ensure the grain security, China has issued a series of policies to support agriculture and give favorable treatment to farmers (Lopez et al., 2017). Since 2004, China has implemented the subsides for superior seed varieties, direct subside for grain production to give farmers certain subsides, general subsides for agricultural supplies. In 2016, agriculture support and protection subside, a combination of above three subsides was implemented for green, ecological, and organic production. These policies effectively enhance the enthusiasm of farmers to produce grain thus the grain production is in growth (Rada et al., 2015).

Water plays an important role in grain production (Sarker et al., 2020; Jabeen et al., 2022). In China, grain production heavily depends on irrigation water, which accounting for about 60 % of the total water consumption (Zhang et al., 2022). As the society and economy develops and population increases, the demand for water has also been rising as shown in CHINA WATER RESOURCES BULLETIN published by Ministry of Water Resources of the People's Republic of China. It is expected to continue under future climate change (Miller et al., 2021; Stringer et al., 2021; Hasanzadeh Saray et al., 2022). Imbalances in water supply and demand have led to the extensive exploitation of groundwater throughout China, particularly in the North (Chen et al., 2021). The water used in agriculture underpins domestic and international supply chains stemming from China (Sun et al., 2022). The unsustainable use of groundwater in particular threatens the sustainability of grain production within China and poses a risk to its supply chains (Sun et al., 2022). The sustainable utilization of water resources is a key factor in working towards sustainable grain security (Cao et al., 2015).

Energy is another important input in agricultural production. Energy use in grain production includes the indirect energy use such as fertilizers, pesticides, agricultural films, seeds, etc., and direct energy use such as the electricity consumption for irrigation and fossil energy consumption for agricultural machinery (Mahmood et al., 2021). A large number of energy utilization has resulted in non-point source pollution, water eutrophication, soil compaction, agricultural production capacity decline, and also emit a large amount of greenhouse gases (Koondhar et al., 2021; Yu et al., 2022). The People's Republic of China Second National Communication on Climate Change pointed out that agricultural activities in China accounted for 11 % of China's greenhouse gas emissions. As a large energy production and consumption country, China faces a severe carbon reduction challenge (Zhao et al., 2022). China has pledged to reduce CO_2 emissions per unit of GDP by 60–65 % by 2030 compared to that in 2005 in “China's Intended Nationally Determined Contributions” document (Li et al., 2021a). Recently, on October 24th, 2021, the State Council issued a Notification of Action Plan to Peak Carbon by 2030 to promote green and low-carbon development. Reducing the carbon emissions in grain production would contribute to national goals of reducing total carbon emissions (Saeed et al., 2022).

China's agricultural development has made great contributions to increasing food supply and reducing hunger. However, it has also led to many environmental problems such as non-point source pollution (Liu et al., 2012), water pollution (Zhao et al., 2023), greenhouse gas emissions (Guo and Zhang, 2023) and so on. These environmental problems have become main obstacles to the sustainable development of agriculture. In recent years, China has increased the emphasis on sustainable agriculture consistent with the “Sustainable Development Goals” (UN, 2015). For example, the Fourteenth Fiver Year Plan (2021–2025) and the No. 1 Central Document in 2022 pointed that China should vigorously carry out green, high-quality, and efficient actions to promote the increase of per unit yield and the quality of grain. In order to realize sustainable grain production, it is necessary to ensure that the inputs to agricultural production are themselves sustainably used (de Moura et al., 2021; Li et al., 2022). Promoting the sustainable use of inputs in agriculture, such as through improving the efficiency of their utilization coupled with policies to promote sustainability is the basis of realizing sustainable grain production. This topic has drawn widespread attention recently (Nisar et al., 2021; Cui et al., 2022).

Agricultural eco-efficiency is an important tool to measure the level of agricultural sustainable development (Yang et al., 2022). The eco-efficiency was proposed by Schaltegger and Sturm in 1990. It refers to the ratio of added socioeconomic value to its impact on the environment. Based on this definition, many influential international agencies, or governmental organizations such as World Business Council for Sustainable Development (WBCSD, 1998) have defined the eco-efficiency from different perspectives. Generally, eco-efficiency means the reduce of negative environmental impact during the pursuit of economic benefits (Moutinho et al., 2017). It enables the agricultural sustainable evaluation. Agricultural eco-efficiency could effectively reveal the relationship between crop production and environmental quality (Yang et al., 2022).

Scholars have conducted a series of studies on agricultural eco-efficiency. For example, Iribarren et al. (2011) identified the eco-efficiency of 72 dairy farms considering the outputs of greenhouse emissions, raw milk, wastewater, municipal solid waste to treatment and silage plastic to recycling. Picazo-Tadeo et al. (2011) evaluated the farming eco-efficiency which is economic value added per hectare considering the sale of agricultural products, subsides received by producers, payments received for farmers signing agri-environmental contracts, and intermediate costs. Coluccia et al. (2020) assessed the agricultural eco-efficiency taking economic variables i.e., labor and gross capital, environmental variables i.e., land, fertilizer and irrigation area, and agricultural production into consideration. Yang et al. (2022) evaluated the agricultural eco-efficiency considering undesirable outputs of carbon emissions and pollutants. Current studies on agricultural eco-efficiency mainly focus on the whole agriculture, including planting industry, fishery industry, livestock industry, forestry industry and so on. Limited studies focus on the eco-efficiency of planting industry especially the eco-efficiency analyses of diverse crop species. In addition, studies pay more attention on single resource consumption or single environmental impact. Relatively few studies take water resources, energy consumption and greenhouse gas emissions into consideration for comprehensive eco-efficiency analyses.

Based on the outline above, the main purpose of this study is to propose a framework to assess the eco-efficiency of diverse crop species. Food, energy, and water interlinked with each other in highly complex ways (Yang et al., 2018; Hasanzadeh Saray et al., 2022). By 2030, global food, energy, water demand is estimated to increase by 50 %, 40 %, and 30 % (Molajou et al., 2021). Increasing grain demand will amplify the limited water and energy resource which are vital for grain production (Hasanzadeh Saray et al., 2022). Agricultural eco-efficiency analysis in this study not only includes the water resources but also the energy resources. Efficient utilization of water and energy in grain production is an example of the Food-Energy-Water nexus.

This study focuses on the grain Food-Energy-Water (FEW) nexus with China. Using water and energy more sustainably in agriculture would further contribute to national sustainability objectives and grain security. The goal is to quantify the sustainability of key components inside the grain FEW nexus in China. Specifically, water footprint (Hoekstra and Chapagain, 2007) and carbon footprint (Bajgai et al., 2019) are utilized to quantify the water and energy use required for grain production. Then, an eco-efficiency sustainability evaluation metric, Sustainability of Grain Inputs (SGI), is established based on the combination of both water and carbon footprints. SGI is different from traditional single resources metrices that are usually utilized in food-water or food-energy eco-efficiency sustainability evaluation literature. SGI reveals the water and energy used simultaneously in a sustainable and unsustainable manner across mainland China. It contributes to understanding the environmental impact of grain production in different regions and helps to explore ways to improve the eco-efficiency of grain production in China according to local conditions. As a result, future planting structure regulation, better agricultural management policy making and sustainable development of agriculture could be implemented.

2. Materials and methods

2.1. Study area and data

2.1.1. Study area

In China, because of the precipitation, soil, terrain, temperature, hydrology, social and economic development differences, grain production vary from region to region. In general, grain production pattern presents from "grain sent from the South to the North" to "grain sent from the North to the South". China's major grain producing areas include Heilongjiang, Jilin, Liaoning, Inner Mongolia, Hebei, Shandong, Jiangsu, Henan, Anhui, Jiangxi, Hubei, Hunan, and Sichuan total 13 provincial administrative regions as shown in the 2004 No. 1 Central Document. These areas are mainly located in Northern China, and grain production in the Northern China accounts for about 60 % of total value in China (Yan et al., 2022).

However, the ecological environment of the Northern China is more fragile than that of the Southern China, especially the water resources problems (Ye et al., 2022). The water resource, which is the most important factor affecting the crop production, is <20 % of the value in China (Yan et al., 2022). In the Northern China, such as the North China Plain and Sanjiang Plain, large amounts of groundwater have been extracted to sustain agricultural production due to the shortage of surface water resources (Li et al., 2021b). This leads to a series of ecological problems, such as drop of groundwater level, groundwater depression cone, ground fissure and so on (Li et al., 2021b). In return, it threatens the sustainable development of agriculture. Therefore, more attention should be paid to grain production in the Northern China.

As wheat and corn are two major grain species in the Northern China (annual average grain productions of wheat and corn in mainland China are displayed in Fig. 1), in this study, wheat and corn are highlighted as demonstrations for the feasibility and practicality of the established eco-efficiency sustainability evaluation metric. Main wheat-growing areas include Henan, Shandong, Hebei, Anhui, and Jiangsu Provinces. Main corn-growing areas mainly locate in Heilongjiang, Jilin, Shandong, Inner Mongolia, Hebei, and Henan Provinces.

2.1.2. Data

In this section, empirical information on climate, sown area, irrigated area, crop production, water use, and energy use in agriculture are collected. These data sources enable to quantify the water and energy footprints in grain production, that are utilized in the eco-efficiency sustainability evaluation metric (see Section 2.2). Detailed input data are in Table 1. Time span of the data varies with the source. Due to different time spans, data period in this study is set to be the co-covered period which is from 2011 to 2018.

Table 1
Key data and corresponding sources.

Data	Data sources
Monthly meteorological data including precipitation (mm); minimum temperature (°C), maximum temperature (°C), average temperature (°C), relative humidity (%), average wind speed (m/s), sunshine duration (h), atmospheric pressure (Pa), longitude, latitude, and altitude data of meteorological stations	China Meteorological Data Service Center (http://data.cma.cn/);
Water consumption data	China Water Resources Bulletin; Water Resources Bulletin of each province or autonomous region;
Grain growth characteristics and irrigation quotas	Norm of water intake for industries of each province or autonomous region; *China's agricultural water demand and construction of water-saving and efficient agriculture* (Shi and Lu, 2001);
Main crop water requirement and irrigation of China	Chen and Guo, 1995; a large number of local reports and papers;
Pesticides usage and energy input for agricultural machinery	Master's thesis entitled "Carbon Footprint of Chinese Export Grains" (Liang, 2015);
Seed, chemical fertilizer, and agricultural film usage	National Farm Product Cost-benefit Survey;
Grain production, grain sown area	China Statistical Yearbook; Statistical Yearbook of each province and autonomous region;
Irrigated sown area	Global Spatial Production Allocation Model (SPAM) 2010 dataset;

2.2. Eco-efficiency sustainability evaluation metric construction process

Agricultural eco-efficiency evaluation reveals the relationship between agricultural output with the environmental impact. It is beneficial for understanding of the grain production environmental impact gaps between different regions and making agricultural policies. Based on the definition of agricultural eco-efficiency, considering environment improvement, and efficient resources utilization are important drivers to promote virtuous circle of resources utilization and sustainable food production (de Moura et al., 2021; Li et al., 2022), this study defines grain production eco-efficiency as a metric to measure the relationship among agricultural materials input, grain production and the undesirable impact on the environment in the process of grain

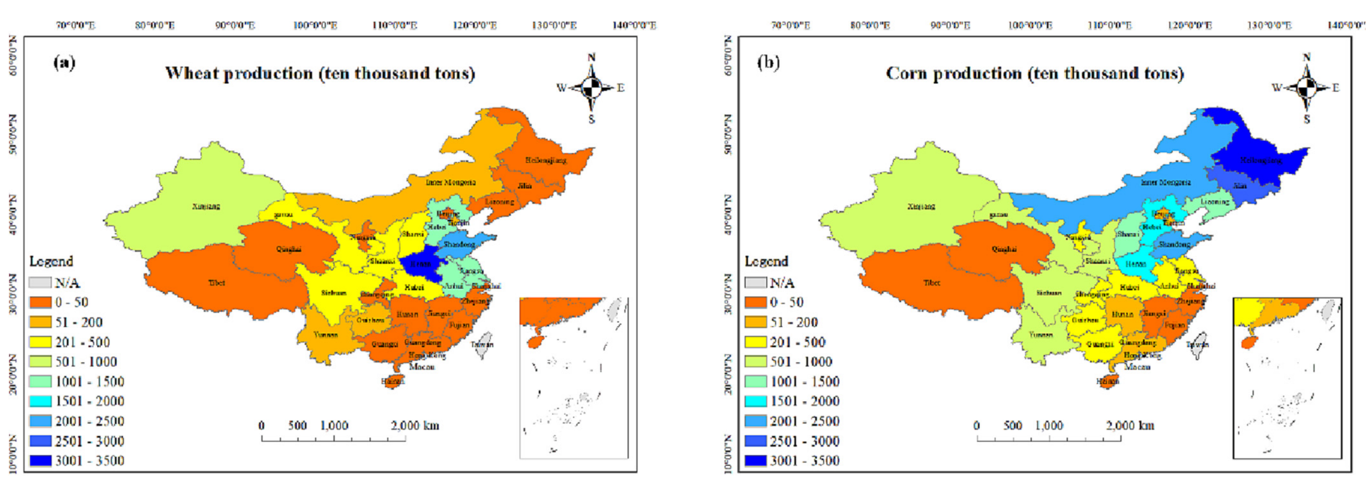


Fig. 1. Annual average grain production in mainland China: (a) Wheat; (b) Corn. In this study, China encompasses 31 provincial administrative regions excluding Hong Kong, Macao, and Taiwan. The geographic coordinate system in this study is the GCS_WGS_1984.

production. Improving the eco-efficiency of grain production is to minimize the agricultural materials input and negative environmental impact and to maximize the grain production for meeting the grain demand.

This study achieves the eco-efficiency sustainability evaluation of grain production considering water and energy dual resources through the relative efficiency comparison. Resources relative efficiency does not mean the actual efficiency, and it is a relative value which could reflect the differences or gaps of resources utilization extent among similar objectives. The higher the value is, the higher the resources utilization extent is, or the more resources saves. On the contrary, lower values indicate more resources wasted. There are multiple relative efficiency evaluation approaches such as analytic hierarchy process (Saaty, 2000), principal component analysis (Whitlark and Dunteman, 1990), fuzzy comprehensive evaluation method (Zadeh, 1965), data envelopment analysis (Charnes et al., 1978) and so on. Each method has its own strengths and weaknesses.

Data envelopment analysis (DEA) is of non-dimensional parameters convenient for cross-region comparison. At the same time, functional relationship between input and output are not restricted, it can be linear or nonlinear. Also, the objective weight defining by DEA reduces the impact of subjective decisions on results. However, the reference set of the DEA can only be an efficient decision unit. If there are too many efficient decision units, it is not suitable to use the DEA for comparative analysis as the relative efficiency of these units are all equal to 1.

Due to the limitation of traditional DEA models as discussed above, this study employs the generalized data envelopment analysis (GDEA) for the relative efficiency calculation which was proposed by Yun et al., 2004 based on the concept of traditional DEA models. GDEA basically includes almost all the properties of traditional DEA (Yun et al., 2004). Furthermore, it is also more flexible to determine the evaluation reference set compared to the traditional DEA (Yun et al., 2016). It is of flexible reference set selection characteristics whose reference unit could be pass lines or other special units rather than the only efficient unit of traditional DEA. The calculation process of GDEA please refer to Yun et al., 2004.

The evaluation reference set determination will directly affect the relative efficiency and subsequent eco-efficiency sustainability evaluation results. Therefore, this study introduced the idea of benchmarking to determine the evaluation reference set. Benchmarking was developed in Xerox in the 1979 (Pickering and Chambers, 1991). It refers to comparing research projects with excellent ones to find out their own problems, shortcomings, gaps, and improvement directions (Kline, 2003). The following sections gradually introduce the establishment of the eco-efficiency sustainability evaluation metric.

2.2.1. Eco-efficiency sustainability evaluation metric establishment

The principle of sustainability requires reasonable utilization of resources by contemporary people and ensures the right of resources utilization for future generations consistent with the “Sustainable Development Goals” (SDGs) (UN, 2015). Clean production should be promoted to reduce the resources input as much as possible for better coordination of resources utilization, society, and economy development (Castrejon-Campos et al., 2022). In this study, two resources inputs: water resources and energy resources (including indirect energy use such as fertilizers, agricultural films, pesticides, and other direct energy uses such as diesel and electricity for irrigation and agricultural machinery) are taken into account to establish the eco-efficiency sustainability evaluation metric of grain production resources utilization. Detailed input and output of the established eco-efficiency sustainability evaluation metric named Sustainability of Grain Inputs (SGI) is displayed in Fig. 2.

Regarding the region characterized by higher water resources input in grain growth stage and scarce water resources, according to the policy guidance, the region may further reduce the crop sown area and water use, which will affect the future sustainability of grain production. Thus, water stress index × total water footprint per unit mass grain production is chosen as the water resources input which could reflect the regional

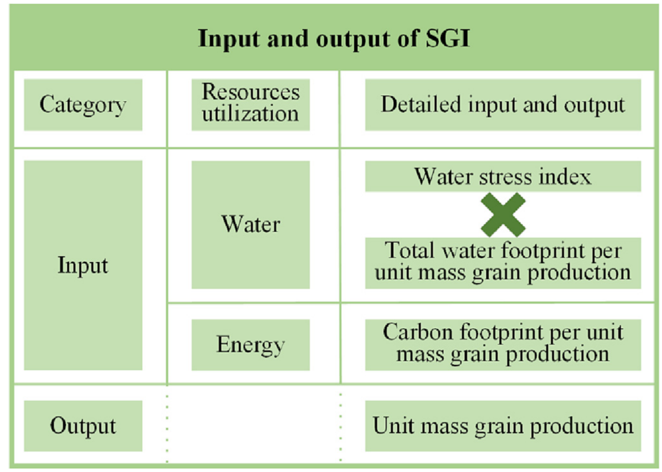


Fig. 2. Input and output of established eco-efficiency sustainability evaluation metric (SGI).

water resources utilization status and grain production water resources utilization condition at the same time. The carbon footprint per unit mass grain production is selected as the energy resources input mirroring the grain production energy resources utilization condition. The final output is grain production per unit mass. Equations to calculate water stress index (*WSI*, Lin et al., 2021) refers to Eq. (1).

$$WSI = \frac{ACT}{TRL} \tag{1}$$

where *ACT* is the actual utilization of water resources while *TRL* is the total water consumption control red line of each municipal administrative region. The higher the *WSI* is, the greater the regional water pressure is, the more unfavorable the sustainable utilization of water resources is.

Through the water stress index, water footprint and carbon footprint, the utilization of water and energy resources in each region can be quantitatively studied in a unified way. Therefore, the sustainability system is of good universality, that could reflect the resources utilization differences between regions. It also provides a comparison and improvement direction for future resources utilization compared with the advanced area in mainland China.

2.2.2. Benchmarking area selection

Benchmarking is utilized to determine the evaluation reference set. In this paper, the evaluation reference set is called as the benchmarking area referring to the reference point of the grain production resources utilization efficiency in similar samples. Specifically, it refers to the area with excellent resources utilization efficiency, that is the area whose water resources input value of grain production per unit mass (total water footprint, m^3/kg as unit, multiplied by water stress index) and energy input value of grain production per unit mass (kg/kg as unit) is relatively lower. The area is the role model of similar samples in the process of grain production.

Since there are relatively few studies on the relative efficiency considering water and energy dual resources, and there is no clear benchmarking area, this study proposes a following process to determine the benchmarking area (Fig. 3).

Step 1: Determine the best-fit probability distribution function of water and energy resources utilization efficiency in the grain growth stage.

The Anderson-Darling test (Anderson and Darling, 1952) is used to test whether water and energy resources utilization efficiency follows the same distribution. If yes, it indicates the samples have general regularity and good representativeness, which can be used to establish the evaluation standard of the comprehensive score. Seven distribution functions are chosen as candidates: Gamma, Weibull, Normal, Exponential, Rayleigh, Generalized Pareto and Lognormal distribution. Then,

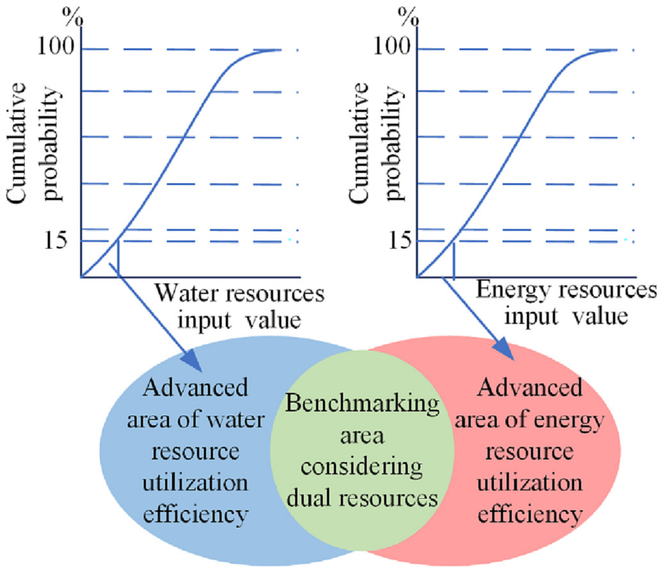


Fig. 3. Benchmarking area determination considering water and energy dual resources.

the distribution function with the smallest test statistics is chosen as the best-fit distribution function.

Step 2: Determine the advanced area of water and energy resources utilization efficiency.

On the premise that the data series follow the same distribution, single resources utilization efficiency (cumulative probability) is divided into five grades. Considering the lower the resources input, the higher the efficiency, the cumulative probability of single resources input value smaller than 15 % is defined as advanced resources utilization efficiency, between 15 % and 35 % is relatively advanced resources utilization efficiency, between 35 % and 65 % is moderate resources utilization efficiency, between 65 % and 85 % is relatively backward resources utilization efficiency, and over 85 % is the backward resources utilization efficiency. Then the advanced area of water resources, and energy resources utilization efficiency are deduced based on the 15 % cumulative probability.

Step 3: Determine the benchmarking area.

The intersections of advanced area of water and energy resources utilization efficiency are considered as the benchmarking area of grain production resources utilization considering dual resources.

2.2.3. Sustainability grade classification

According to the benchmarking area, the relative efficiency of grain production resources utilization (*REV*) in each municipal administrative region can be calculated by the established SGI eco-efficiency sustainability evaluation metric. Then, the *REV* is further divided into 5 sustainability grades for sustainability evaluation analysis (shown in Table 2).

It's worth noting that more efficiency does not necessarily guarantee that resources will be used more sustainably. For example, locations that install drip irrigation (which is more efficient, i.e., less water used per unit land area, or per unit mass grain production) often see expansions in irrigated area and more total water use (Grafton et al., 2018). The sustainability evaluation results obtained in this study have to be paired with policies to regulate the basin/irrigation district/farm field total resource use for promoting sustainable use of resources.

Table 2
Sustainability grade of grain production resources utilization.

Relative efficiency (*REV*)	Sustainability grade
$REV < 0.15$	Weak
$0.15 \leq REV < 0.35$	Relatively weak
$0.35 \leq REV < 0.65$	Moderate
$0.65 \leq REV < 0.85$	Relatively strong
$0.85 \leq REV$	Strong

2.3. Water footprint calculation

Water footprint reflects the amount of water needed for product manufacturing or service in a certain area (Hoekstra and Chapagain, 2007). It is a valuable method to evaluate the direct and indirect virtual water use characteristics. In this study, the water footprint concept is introduced to quantify the water resources utilization of grain production (this study focuses on the grain growth stage). Water footprint of grain production refers to the amount of water resources consumed directly or indirectly used to dilute pollutants for unit mass grain production in a certain area (Sun et al., 2013).

Water footprint of grain production could be divided into three parts: green, blue, and grey water footprint (Chapagain and Hoekstra, 2011; Tomaz et al., 2021). Green water footprint of grain production basically means the precipitation did not form the runoff but infiltrated into the unsaturated soil layer which could be used for grain growth. Blue water footprint refers to the amount of blue water (surface water and groundwater) for grain growth which is usually expressed as the irrigation water. Grey water footprint of grain production is the amount of water utilized to dilute water pollution caused by grain production to make the wastewater meet the environmental standards.

As grey water of grain production is the non-consumptive water use during grain growth stage, in this study, the grey water footprint is not considered while only green and blue water are considered to reflect the water consumption in the grain growth stage. Green water footprint is quantified according to the effective precipitation while blue water footprint is calculated based on a modified method based on actual irrigation water (including the water loss and return flow from water source to the field), irrigated area and irrigation quota (Sun et al., 2013), detailed calculations are as follows.

$$WFP = WFP_G + WFP_B = \frac{W_g}{Y} + \frac{W_b}{Y} \tag{2}$$

$$W_g = 10\ min\left(\Sigma_1^{dt} ET_c, \Sigma_1^{dt} P_e\right) \tag{3}$$

$$W_b = IRC \tag{4}$$

where *WFP*, WFP_G, WFP_B is the total, green and blue water footprint of grain production (in the grain growth stage), respectively (m^3/kg); W_g and W_b is green and blue water utilization per unit grain sown area, respectively (m^3/$hm^{2)}$; *Y* means the grain production per unit sown area, kg/hm^2; 10 is the conversion coefficient; ET_c reflects the grain evapotranspiration referred to the water requirement for transpiration under ideal conditions, mm; P_e denotes the effective precipitation on behalf of the sum of precipitation that can be directly or indirectly used for crop growth or other necessary consumption, mm; *IRC* is the irrigation water per unit grain sown area, m^3/hm^2; *dt* means the length of the growth period.

Crop coefficient approach (Mhawej et al., 2021) is applied to calculate the ET_c.

$$ET_c = ET_0 \times K_c \tag{5}$$

where ET_0 is the reference crop evapotranspiration which is computed based on Penman-Monteith Equation (Allen et al., 1998), mm; K_c denotes the crop coefficient.

Effective precipitation (P_e) can be calculated by the SCS method recommended by the United States Department of Agriculture (USDA) (Smith, 1992).

$$\begin{cases} P_e = \dfrac{P(125-0.2P)}{125}; P < 250\text{mm} \\ P_e = 125 + 0.1P; P \geq 250\text{mm} \end{cases} \tag{6}$$

where *P* means the monthly precipitation, mm.

Equations to compute the irrigation water per unit grain sown area are described as follows.

$$IRC = \frac{W_A \times P_w}{IA} \tag{7}$$

where W_A is total regional irrigation water, m^3; P_w means the proportion of grain irrigation water in the total regional irrigation water; It could be further calculated by Eq. (8) when there is irrigation quota; Otherwise, it is calculated by Eq. (9).

$$P_w = \frac{IQ \times IA}{\sum_{cn=1}^{z} (IQ_{cn} \times IA_{cn})} \tag{8}$$

$$P_w = \frac{(ET_c - P_e) \times IA}{\sum_{cn=1}^{z} \left[\left(ET_c^{cn} - P_e^{cn} \right) \times IA_{cn} \right]} \tag{9}$$

where IQ reflects the irrigation quota, m^3/hm^2; IA denotes crop irrigation area, hm^2; cn is the irrigated crop species. As detailed irrigated areas of each crop species are unavailable, in this study, these values of each crop species are extracted based on the Global Spatial Production Allocation Model (SPAM) 2010 dataset, with a resolution of 5 arc minute (International Food Policy Research Institute, 2019). The SPAM remote sensing dataset is recommended by the Food and Agriculture Organization of the United Nations. From the whole China perspective, the SPAM data is basically consistent with the magnitude and spatial distribution of Chinses statistics (Chen et al., 2021). Thus, it is used in this study to make up the missing/unavailable irrigated area data shortage.

2.4. Carbon footprint calculation

Carbon footprint reflects the amount of greenhouse gases emitted directly or indirectly during a certain period (Bajgai et al., 2019). Here, the carbon footprint is employed to uniformly analyze the greenhouse gas emission of indirect and direct energy input in the grain growth stage. This study focuses on the carbon emissions in the grain growth stage.

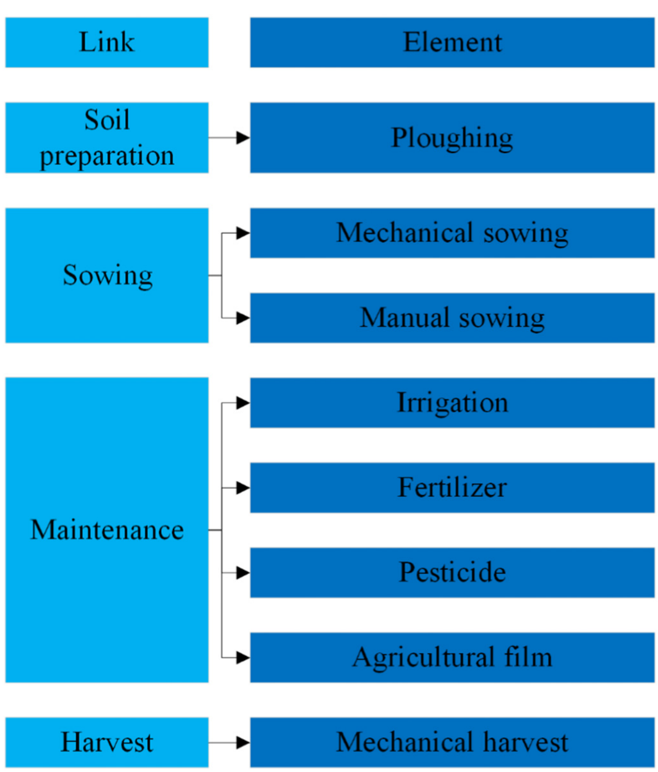


Fig. 4. Processes and inputs considered for calculating the carbon footprint.

Following the "up to the farm gate" principle, processes and inputs considered for calculating the carbon footprint are displayed in Fig. 4.

As shown in Fig. 4, main sources of carbon emission in grain growth stage include 1) organic carbon loss by farmland ploughing; 2) Seed utilization carbon emission; 3) Carbon emission caused by indirect energy use such as fertilizer, pesticide and agricultural film; and 4) carbon emission of direct fossil energy use. The use of agricultural machinery (such as ploughing, sowing, irrigation, and harvest) consumes fossil fuels, and emits carbon. Total carbon emissions (uniform use of carbon equivalent) in grain growth stage can be calculated by Eq. (10).

$$CE = CE_{turn} + CE_{seed} + CE_{fertilizer} + CE_{pesticide} + CE_{film} + CE_{machine} + CE_{irrigation} \tag{10}$$

where CE, CE_{turn}, CE_{seed}, $CE_{fertilizer}$, $CE_{pesticide}$, CE_{film}, $CE_{machine}$, and $CE_{irrigation}$ stands for total, ploughing, seed, fertilizer, pesticide, agricultural film, agricultural machinery, and irrigation carbon emission (carbon equivalent: ten thousand tons), detailed calculations are described in following equations.

$$CE_{turn} = A_{turn} \times EF_{turn} \div 10^7 \tag{11}$$

where A_{turn} stands for ploughing area, km^2; EF_{turn} is carbon emission of ploughing, kg/km^2; $EF_{turn} = 312.60\ kg/km^2$ (collected from the Institute of Agriculture and Biotechnology of China Agricultural University, IABCAU).

$$CE_{seed} = SA \times Unit_{seed} \times EF_{seed} \div 10^7 \tag{12}$$

where SA is the sown area, ha; $Unit_{seed}$ means the seed usage per unit sown area, kg/ha; EF_{seed} is carbon emission of seed, kg/kg; For wheat, $EF_{seed} = 0.11$ kg/kg; For corn, $EF_{seed} = 1.05$ kg/kg; These values are from West and Marland, 2002.

$$CE_{fertilizer} = SA \times Unit_{fertilizer} \times EF_{fertilizer} \div 10^7 \tag{13}$$

where $Unit_{fertilizer}$ represents the fertilizer usage per unit sown area (kg/ha) including nitrogen, phosphate, potash, and compound fertilizers. $EF_{fertilizer}$ is carbon emission of fertilizer, kg/kg; For nitrogen, phosphate, potash, and compound fertilizer, $EF_{fertilizer} = 1.74$, 0.16509, 0.12028 and 0.38097 kg/kg, respectively (Tian et al., 2015).

$$CE_{pesticide} = DC \times Unit_{pesticide} \times EF_{pesticide} \div 10^7 \tag{14}$$

where DC reflects grain production, ton (abbreviated as t); $Unit_{pesticide}$ denotes the pesticide usage per unit grain production, kg/t; For wheat, $Unit_{pesticide} = 0.599$ kg/t; For corn, $Unit_{pesticide} = 0.608$ kg/t (Liang, 2015); $EF_{pesticide}$ is carbon emission of pesticide, kg/kg; $EF_{pesticide} = 4.9341$ kg/kg (collected from the Oak Ridge National Laboratory, ORNL).

$$CE_{film} = SA \times Unit_{agricultural\ film} \times EF_{agricultural\ film} \div 10^7 \tag{15}$$

where $Unit_{agricultural\ film}$ is on behalf of the agricultural film usage per unit sown area, kg/ha; $EF_{agricultural\ film}$ is carbon emission of agricultural film, kg/kg; $EF_{agricultural\ film} = 5.18$ kg/kg (data from the Institute of Resources, Ecosystem and Environment of Agriculture, IREEA).

$$CE_{machine} = SA \times Unit_{diesel} \times EF_{diesel} \div 10^7 \tag{16}$$

where $Unit_{diesel}$ means the diesel usage per unit sown area, kg/ha; Utilization of agricultural machinery relies on diesel consumption which will emit carbon at the same time. Diesel consumption per hectare of grain production filed operation is displayed in Table 3 (Liang, 2015). EF_{diesel} reflects

Table 3
Diesel consumption per hectare of grain production field operation (unit: kg/ha).

Grain type	Sowing	Soil preparation	Harvest
Wheat or corn	38.9	63.2	65.9

carbon emission of diesel, kg/kg; EF_{diesel} = 0.5927 kg/kg (Tian et al., 2015).

$$CE_{irrigation} = WF_{blue} \times \left(U_{diesel} \times EF_{diesel} + U_{electricity} \times EF_{electricity}\right) \div 10^7 \quad (17)$$

$$WF_{blue} = WFP_B \times DC \times 1000 \quad (18)$$

where WF_{blue} stands for blue water resources utilization quantity, m^3; Diesel and electricity are essential energy for pumping and lifting irrigation water, U_{diesel} and $U_{electricity}$ denotes the diesel and electricity usage per cubic meter of pumped or lifted water whose unit is kg/m^3 and kWh/m^3, respectively; U_{diesel} = 0.00397908 kg and $U_{electricity}$ = 0.03967kWh (Liang, 2015). $EF_{electricity}$ represents carbon emission of electricity; $EF_{electricity}$ is set to be 0.25 kg/kWh considering the hybrid electricity distribution of China shown by Ding et al., 2017.

Using the above equations, carbon footprint per unit mass grain production (*UCE*, kg/kg) can be calculated reflecting the warming effect of producing per unit mass grain. The higher the value, the greater the adverse environmental impact of grain production.

$$UCE = \frac{CE \times 10000}{DC} \quad (19)$$

3. Results

3.1. Calculation of water and energy resources input values

Based on the methods, water and energy input values of grain production have been calculated and shown in Figs. 5 and 6, respectively. Detailed green, blue, and total water footprints of grain production per unit mass in mainland China are exhibited in Appendix A supplementary data Figs. S1, S2, and S3, respectively. In Fig. 5 and following figures, region marked in grey indicates the data shortage. However, compared to Fig. 1, regions considered in this study basically include the regions whose annual wheat productions are over 500 thousand tons and the regions whose annual corn productions are over 2000 thousand tons. Data is still of comprehensiveness and representativeness, can be used for following sustainability evaluation of wheat and corn production resources utilization.

In Fig. 5(a), for wheat production, more water resources are put in the Inner Mongolia for producing per unit mass grain especially in the Hohhot, Erdos and Ulanchap inside Inner Mongolia. From the whole provincial-level administrative region perspective, average total water footprints of wheat production in Inner Mongolia and Ningxia are the highest about 1.80 m^3/kg and 1.81 m^3/kg, respectively. The water resources input values further considering the water stress index are about 1.05 and 1.35, respectively. Some regions in Shaanxi, Xinjiang, Gansu, Qinghai, and Yunnan also consume relatively more water. Water resources input in Henan and Shandong is relatively lower (location of provincial-level administrative region is shown in Fig. 1). Average total water footprints in Shandong and Henan are about 0.25 m^3/kg and 0.3 m^3/kg, while the water resources input values are 0.46 and 0.51, respectively.

In Fig. 5(b), corn production per unit mass in Inner Mongolia also rely heavily on water resources especially in Hohhot, Erdos and Ulanchap. The total water footprints in these regions are all higher than 1 m^3/kg; the water resources input values are also higher than 1 with the highest value in Ulanchap. Possible reasons are as follows. Precipitation in Inner Mongolia is less. However, the evaporation is larger. Therefore, numerous large-scale irrigation districts were built in this area such as Hetao Irrigation district resulting in more irrigation water. Total water footprint values in Anhui, Xinjiang, Ningxia and Shaanxi are higher. Values in Guizhou, Shandong, Jilin, and Henan are lower. Total water footprints are all lower than 0.5 m^3/kg and the water resources input values are all smaller than 0.45.

In Fig. 6, energy resources input i.e., carbon footprint per unit mass grain production (*UCE*, kg/kg) vary in space due to diverse energy inputs per unit mass grain production such as fertilizers, pesticides, irrigation water required, seeds and so on. As shown in Fig. 6(a), energy resources input i.e., carbon footprint for wheat production per unit mass in Inner Mongolia is the highest which may also generate tallest carbon emission. From the whole provincial-level administrative region perspective, average carbon footprint of corn production in Inner Mongolia is about 0.27 kg/kg. Whereas, that in Ningxia, Qinghai, Gansu, Shaanxi, and Yunan also requires larger energy resources input, values higher than 0.13 kg/kg. That in Sichuan, Henan, and Shandong is in a relatively greener production path, values smaller than 0.075 kg/kg. Highest value in Inner Mongolia is due to larger fertilizer, especially the nitrogen fertilizer. Also, more irrigation water also needs energy for pumping and lifting.

In Fig. 6(b), corn production per unit mass in Gansu, Shaanxi, and Yunnan basically inputs highest energy (carbon footprint values higher than 0.13 kg/kg) while some regions in Inner Mongolia, Xinjiang, Hubei, Shanxi also rely on sizeable energy. On the contrary, energy inputs in Guizhou and Jilin are lower, values smaller than 0.055 kg/kg. Corn production in Gansu, Shaanxi, and Yunnan ties to a large amount of agricultural film and fertilizer compared to other regions in mainland China.

3.2. Benchmarking area determination

According to the method in Section 2.2.1, seven distribution functions are chosen to fit the resources input value. Results show that Log-normal distribution function is the optimal candidate no matter for water or energy

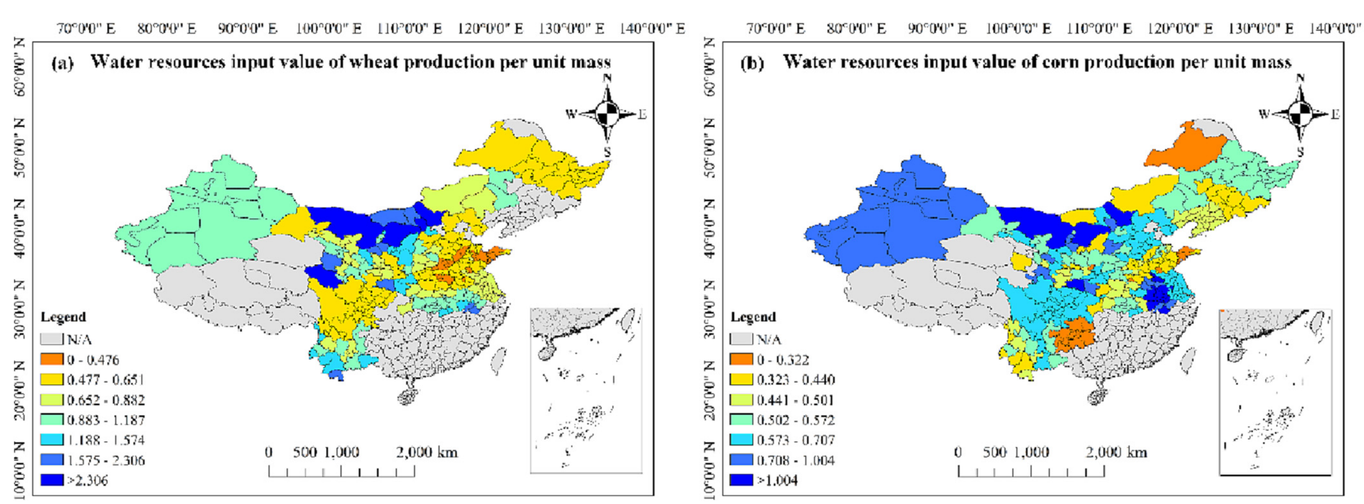


Fig. 5. Water resources input values for grain production in mainland China: (a) Wheat; (b) Corn. Area colored in grey indicates no available data for this area. Larger value is less desired as grain production in this region relies on more resources.

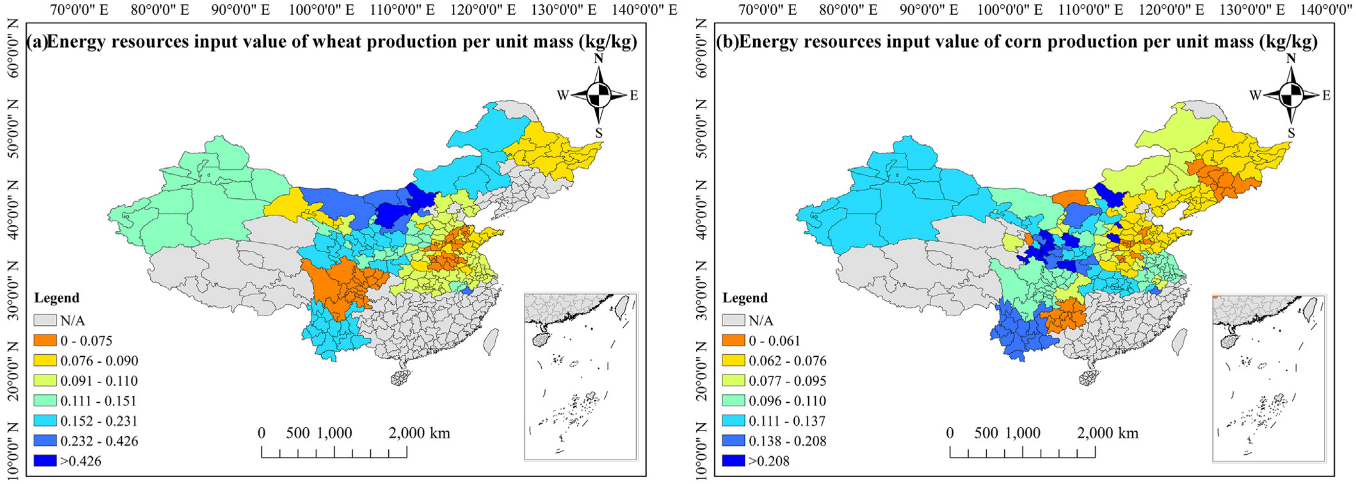


Fig. 6. Energy resources input values for grain production in mainland China: (a) Wheat; (b) Corn. Area colored in grey indicates no available data for this area. Larger value is less desired as grain production in this region relies on more resources.

use of wheat and corn production. And results all pass the Anderson-Darling tests verifying the robustness and rationality of the distribution function selection.

Next, based on five grades of resources utilization efficiency, the areas of advanced resources (water or energy single resource) utilization efficiency are determined based on cumulative probability <15 %. Further, Benchmarking areas considering dual resources are deduced by identifying the intersections i.e., the area of both advanced water and energy utilization efficiency.

For wheat production, benchmarking areas considering dual resources include Huaibei in Anhui (representing municipal district in provincial district), Luohe, Xuchang, Jiaozuo, Hebi, Xinxiang, Zhoukou, and Puyang in Henan, Dezhou and Tai'an in Shandong with a total of 10 municipal districts. In these regions, water resources input values are all smaller than 0.49 (total water footprint values all smaller than 0.54 m^3/kg) and energy resources input values are all lower than 0.071 kg/kg.

For corn production, benchmarking areas considering dual resources include Guiyang, Zuiyi, Anshun, Qiandongnan, Tongren, Bijie, Liupanshui, and Qianxinan in Guizhou, total 9 municipal districts. Water resources input values are all smaller than 0.26 (total water footprint values all smaller than 0.31 m^3/kg) and energy resources input values are all lower than 0.054 kg/kg.

Guizhou, in actual production, is not an advantageous area for corn cultivation. For example, He (2016) pointed that the wheat land productivity in Shandong, Xinjiang, Hebei, Henan, Anhui and Jiangsu and the corn land productivity in Xinjiang, Gansu, Shanxi, Ningxia, Jilin, Inner Mongolia, Liaoning, Hebei, and Shandong were above the national average level. Ning (2016) evaluated the suitable growth area. Results showed that the suitable growth area of wheat production mainly locates in Henan, Hebei, Shandong, Anhui, Jiangsu, and Sichuan provinces; Suitable growth area of corn production are basically in Heilongjiang, Jilin, Liaoning, Sichuan, Henan, Shandong, Hebei, Anhui, and Shanxi provinces. As Guizhou is not suitable to be the benchmarking area for corn production, the sustainability of corn production is reevaluated by removing the data with larger deviations (detailed analysis shown in Section 4.2) in the benchmarking area determination process. Results are as follows.

The results show that log-normal distribution function is still the optimal function to fit the water and energy use of corn production. The benchmarking areas are Luohe and Xuchang in Henan, Siping and Baishan in Jilin, Tai'an in Shandong, Bayannur in Inner Mongolia with a total of 6 municipal districts. Water resources input values are all smaller than 0.37 (total water footprint values all smaller than 0.41 m^3/kg) and energy resources input values are all lower than 0.062 kg/kg.

3.3. Sustainability evaluation of grain production resources utilization

Through resources input values calculation and benchmarking area determination, the sustainability grade of grain production resources utilization is evaluated and displayed in Fig. 7. Further, provincial results are summarized and exhibited in Fig. 8.

Fig. 7 shows that grain production in most part of the mainland China presents a moderate sustainability grade no matter for wheat or corn. This indicates that China should couple policies that promote the efficiency of resources utilization with sustainability targets to bring resource use within sustainable limits.

From Figs. 7(a) and 8(a), generally, wheat production of resources utilization in Sichuan, Shandong, and Henan presents a strong sustainability grade, while that in Inner Mongolia presents a relatively weak sustainability grade. Weak grade is probably due to the higher water and energy resources input in the growth stage as shown in Figs. 5 and 6. In general, the Northwest region (including Shaanxi, Inner Mongolia, Gansu, Qinghai, Ningxia, and Xinjiang) produces wheat in relatively more unsustainable manners. The geographical division of China can be found in Hou et al. (2022).

Figs. 7(b) and 8(b), relative efficiency of corn production in Shandong and Jilin is especially higher than that in other provinces, leading to the strong sustainability grade. Relative efficiency in Anhui and Xinjiang is the lowest. Overall, Northeast China (including Heilongjiang, Jilin, and Liaoning) and North China (such as Henan and Shandong) produce corn in relatively greener ways. On the contrary, Northwest region produces corn by using larger resources.

Furthermore, based on the redundancy analysis of the GDEA method, the insufficient output reason of the region whose grain sustainability grade is of moderate, relatively weak, and weak is analyzed, mainly shown in Fig. 9.

In Fig. 9, lower relative efficiency of wheat production in Shaanxi, Yunnan, and Inner Mongolia is mainly due to unreasonable use of the energy resources. Lower relative efficiency of corn production in Shaanxi and Gansu is also caused by extensive utilization of energy. Those provinces should further develop carbon reduction policies, to improve the efficiency of indirect and direct energy use in the grain production.

Similarly, lower relative efficiency of wheat production in those regions such as Hubei, Jiangsu, …, Ningxia and Qinghai and corn production in Hebei, Shanxi, …, Anhui and Xinjiang are mainly resulted by extensive

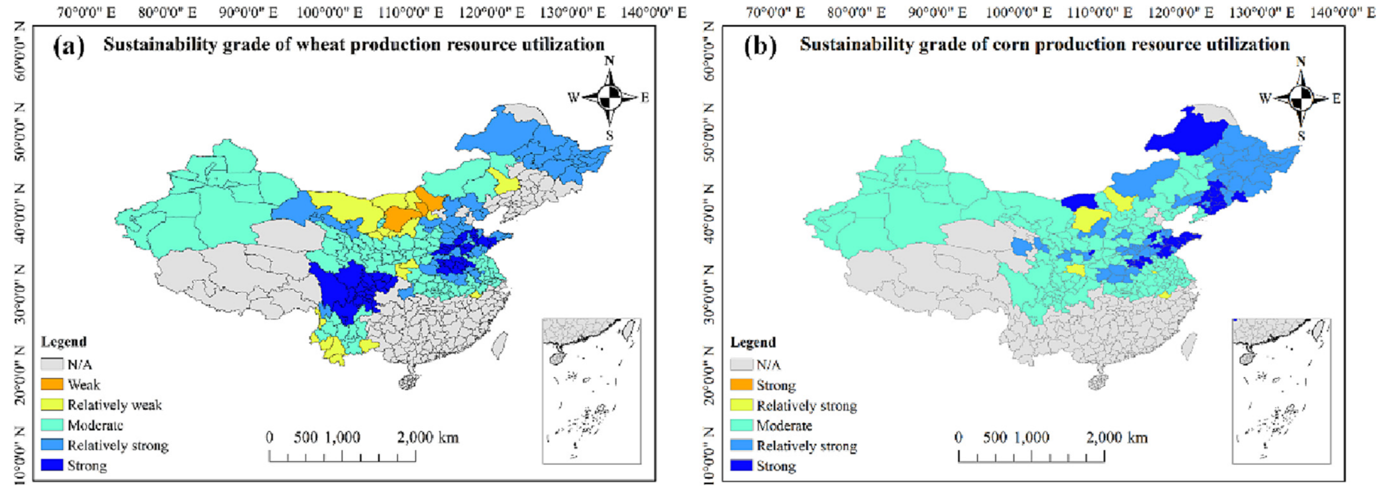


Fig. 7. Sustainability evaluation results of grain production resources utilization in mainland China: (a) Wheat; (b) Corn. Area colored in grey indicates no available data for this area.

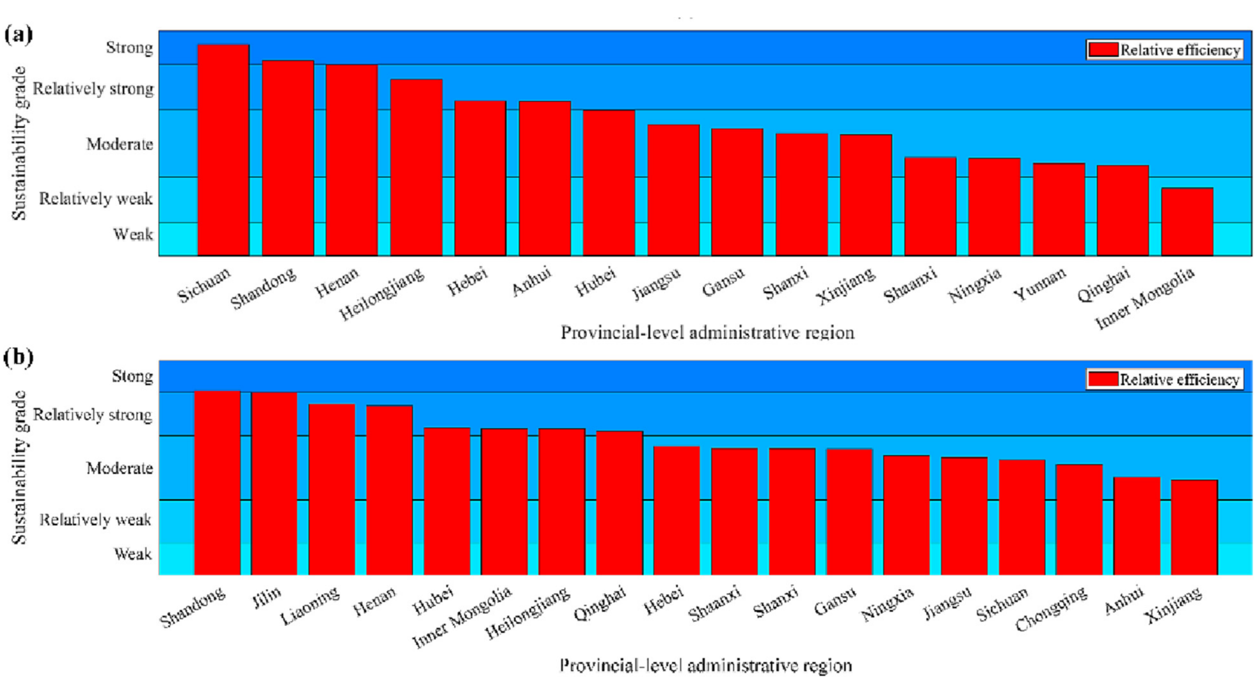


Fig. 8. Sustainability evaluation results of grain production resources utilization in each province (region) of the mainland China: (a) Wheat; (b) Corn.

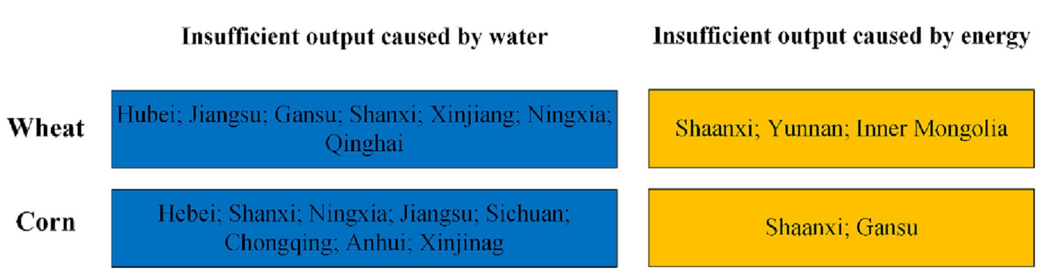


Fig. 9. Insufficient output reason analysis.

water utilization. It is necessary to improve the utilization efficiency of water resources.

4. Discussions

4.1. Policy implications

This study conducts the eco-efficiency sustainability evaluation of grain production resources utilization for future sustainable policy makings. Results can show practical conditions of grain production. For example, in Sun et al. (2016), higher water footprint regions of wheat production include Inner Mongolia, Yunnan, Ningxia, Gansu, and Shanxi; Higher water footprint regions of corn production contain Gansu, Ningxia, Inner Mongolia, Xinjiang. Feng et al. (2022) found Inner Mongolia, Ningxia and Yunnan rely heavily on water resources to produce wheat while Xinjiang consumes more water to produce corn. Feng et al. (2022) discovered higher carbon footprint regions of wheat production are mainly located in Inner Mongolia, Shaanxi, Yunnan while higher carbon footprint regions of corn production are mainly in Shaanxi and Xinjiang. Li and Li (2022) found that wheat production in Inner Mongolia and corn production in Gansu, Xinjiang, Shaanxi, Shanxi, and Yunnan emit more carbon emissions. In Tian et al. (2021, 2022), wheat production in Inner Mongolia, Ningxia, Shaanxi, Gansu, Shanxi, and Heilongjiang and corn production in Inner Mongolia, Xinjiang, Gansu, and Shaanxi, Shanxi and Hebei are characterized by higher carbon footprint. These findings are basically consistent with the spatial distribution of water and carbon footprints in this study. This indicates the reliability of results.

The analysis in this study agrees with the "Sustainable Development Goals" (SDGs) (UN, 2015). For example, the goal of this study is to promote sustainable grain production consistent with the SDG2: zero hunger. At the same time, this study aims to assess the resources utilization characteristics to further reduce the water and energy input, it is also in accordance with the SDG6: Clean Water and Sanitation and SDG7: Affordable and Clean Energy. Therefore, the analysis is meaningful research to a certain degree.

The developed SGI is universal that can be utilized in other regions as shown in Section 2.2.1. The SGI as well as the analysis in this study are of importance in future agricultural management. As eco-efficiency of grain production varies across different regions, it is suggested that China could make targeted adjustments to the agricultural planting structure i.e., plant more superior grains in accordance with local conditions under the guidance of national policies. Wheat sown area in the strong or relatively strong sustainability grade regions such as Sichuan, Shandong, and Henan could be increased. Sown area in relatively weak, weak regions and even moderate sustainability grade regions such as Inner Mongolia, Qinghai, Yunnan, Ningxia, and Shaanxi could be reduced. Similarly, Shandong, Jilin, Liaoning, and Henan could expand corn sown areas, whereas Anhui and Xinjiang need to reduce some corn sown areas. Grain planting structure regulation can better meet the grain demand and protect the environment (Adeyemo and Otieno, 2010). It facilitates sustainable green development.

While appropriately adjusting the planting structure, it is urgent to improve the resources utilization efficiency. It is necessary to strengthen the promotion of water-saving technology research and improve the utilization efficiency of irrigation water use. It is especially true in areas whose grain production sustainability grade is not strong, and the sufficient output is mainly caused by water such as the corn production in Xinjiang. It is also important to improve the level of agricultural mechanization, develop low-carbon agricultural machine, and strengthen the popularization of green agricultural technology. Under the premise of stabilizing grain production, traditional fertilizers should be gradually replaced by green organic fertilizers and farm manure. This might avoid soil compaction and soil fertility decrease to a certain degree and reduce the non-point source pollution (Zhang and Fu, 2023). In addition, it is essential to strengthen farmers' awareness of environmental protection, and to guide them to transform to green production.

At the same time, China could strengthen subsides in line with green and sustainable development. It is suggested that more subsides should be given to the dominant varieties (characterized by higher eco-efficiency i.e., lower resources input) in each provincial-level administrative region to encourage the production of the dominant varieties. For example, the wheat production in Sichuan, Shandong, and Henan and corn production in Shandong, Jilin, Liaoning, and Henan. Also, it is vital to establish a water-saving compensation mechanism to provide subsidies to farmers or regions with strong water-saving consciousness. It is necessary to moderately reduce the financial subsides for traditional chemical fertilizers and increase subsides for organic fertilizers, ecological pesticides, and energy-saving agricultural machines (Wang et al., 2018). It increases the cost of traditional chemical resources, and gradually reduces their excessive uses in grain production. Appropriate subsidy policies could support the realization of coordinated development of grain production and environment protection.

4.2. Limitations and potential future research

The data required in this study is large in quantity, wide in scope and across the whole China. Because of different spans of each data type, the co-covered period is 2011 to 2018. In addition, only wheat and corn are considered. Still due to the data limitation, data shortage exists in some parts of the country. In some regions such as Heilongjiang Province, data of municipal administrative regions are replaced by the data of the provincial administrative region. Furthermore, as no detailed irrigation water data are available, this study uses the SPAM data only updated to 2010 to extract the irrigated land. The extracted irrigated land areas are then utilized to calculate the water demand proportions of each crop species on irrigated land for blue water footprint quantifications. SPAM data makes up for the data deficit. However, due to the influence of mixed pixels, atmospheric interference, terrain, and other factors, there may be some deviations between the remote sensing data and the actual data (Xiao et al., 2005). For example, the Guizhou and Yunnan are the two provinces with the largest mountainous areas in China whose values are about 93 % and 89 %, respectively. The irrigated land of corn provided by the SPAM data is basically 0. The relatively larger error may be caused by terrain. This leads to no irrigations for corn production i.e., blue water footprints equal to 0. Thus, lower water resources input values are induced. In the future, more data such as more crop species and higher resolution spatial data sets can be used to expand the scope of the metric, and the sustainability evaluation could be obtained to a finer scale.

Furthermore, this study utilizes the uniform formulas to calculate the effective precipitation and assumes the carbon emission coefficient are equal in different regions. In fact, the parameters may vary due to different natural and socioeconomic conditions (Tigkas et al., 2016). Through field experiments, more reliable parameters can be calibrated, and sensitivity analysis will also be conducted to improve the applicability of the results and provide more feasible supports under different conditions.

It's also noteworthy that the qualitative eco-efficiency sustainability evaluation in this study should be further extended to quantitative analysis combined with more factors. For example, crop production is an agricultural process in which nature (such as land, climate, and water) and socioeconomic development (such as labor, practical knowledge, and engineering services) are interwoven (Musafiri et al., 2022). Carrying out quantitative analysis and analyzing the range of planning structure regulation is vital, which are also authors' future research directions.

5. Conclusions

Grain production in China is an example of the Food-Energy-Water nexus. Grain production relies on a large number of resource inputs, including water resources, indirect and direct energy use. China is facing water supply pressures, increasing greenhouse gas emissions, and declining land productivity. It is urgent to reduce the resources input and its impact on the environment during grain production on the premise of grain security. This study delivers a grain Food-Energy-Water nexus. Within the scope of FEW nexus, a systematic comparison of water and energy footprint in grain production is presented through the introduction of data envelopment analysis and spatial benchmarking. The novel metric developed to measure the eco-efficiency sustainability of grain production is Sustainability of Grain Inputs (SGI).

Some locations in China are producing grain sustainably, while others are not. Wheat production uses water and energy sustainably in Sichuan, Shandong, and Henan; Corn production has the highest combined sustainability index in Shandong and Jilin. It is advised to produce more grain in these regions. However, wheat production in Inner Mongolia and corn production in Xinjiang rely on unsustainable water and energy inputs. Production in these areas could be decreased to a certain degree. China should further formulate policies that promote the efficient use of water and energy in grain production. Importantly, efficiency should be twinned with policies that constrain resource consumption within sustainable limits, in order to avoid the irrigation efficiency trap (Grafton et al., 2018), or Jevon's paradox of energy efficiency (Pellegrini and Fernández, 2018).

Since the methods adopted in this study are all universal or statistical, the eco-efficiency sustainability evaluation metric introduced here can be used in other locations around the world. The metric reflects differences in water and energy inputs in different regions and is versatile, flexible, and not restricted by geographic, as long as the required input data is available. The grain eco-efficiency sustainability evaluation metric could be used to inform future sustainable agricultural policy evaluation to determine how to bring water and energy use in staple grain production within sustainable limits. For example, it is beneficial to promote the grain production in the region of strong sustainability grade while it is not recommended to expand the grain production in the region of weak sustainability grade. Achieving sustainability in grain Food-Energy-Water systems is key for food, water and energy security, as well as sustainable development goals.

CRediT authorship contribution statement

Jie Yang: Methodology, Software, Formal analysis, Writing – original draft, Project administration. **Jianxia Chang:** Validation, Project administration, Writing – review & editing. **Megan Konar:** Writing – review & editing. **Yimin Wang:** Formal analysis. **Jun Yao:** Software, Data curation.

Data availability

Data will be made available on request.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This research is supported by the National Natural Science Foundation of China (52209030), National Natural Science Foundation of China (U2243233), the Fundamental Research Funds for the Central Universities (GK202207005). Appreciation is extended to editors and reviewers for their constructive comments and suggestions.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2023.164128.

References

Adeyemo, J., Otieno, F., 2010. Differential evolution algorithm for solving multi-objective crop planning model. Agric. Water Manag. 97 (6), 848–856.

Allen, R.G., Pereira, L.S., Raes, D., Smith, M., 1998. Crop evapotranspiration-guidelines for computing crop water requirements-FAO irrigation and drainage paper 56. FAO Rome 300 (9), D05109.

Anderson, T.W., Darling, D.A., 1952. Asymptotic theory of certain "goodness of fit" criteria based on stochastic processes. Ann. Math. Stat. 23, 193–212.

Bajgai, Y., Yeshey, Y., De Mastro, G., Ghimiray, M., Chhogyel, N., Tshewang, S., Ali, S.A., 2019. Influence of nitrogen application on wheat crop performance, soil properties, greenhouse gas emissions and carbon footprint in central Bhutan. Environ. Dev. 32 (1), 100469.

Cao, X.C., Wang, Y.B., Wu, P., Zhao, X.N., Wang, J., 2015. An evaluation of the water utilization and grain production of irrigated and rain-fed croplands in China. Sci. Total Environ. 529, 10–20.

Castrejon-Campos, O., Aye, L., Hui, F.K.P., 2022. Competition, coordination, or institutional change? A multi-perspective analysis of historical electricity transitions in Mexico. Energy Res. Soc. Sci. 84, 102362.

Chapagain, A.M., Hoekstra, A.Y., 2011. The blue, green and grey water footprint of rice from production and consumption perspectives. Ecol. Econ. 70 (4), 749–758.

Charnes, A., Cooper, W.W., Rhodes, E., 1978. Measuring the efficiency of decision making units. Eur. J. Oper. Res. 2 (6), 429–444.

Chen, L., Chang, J.X., Wang, Y.M., Guo, A.J., Liu, Y.Y., Wang, Q.Q., Zhu, Y.L., Zhang, Y., Xie, Z.Y., 2021. Disclosing the future food security risk of China based on crop production and water scarcity under diverse socioeconomic and climate scenarios. Sci. Total Environ. 790, 148110.

Chen, Y., Guo, G., 1995. China's Agricultural Water Demand and Construction of Water-saving and Efficient Agriculture. China WaterPower Press (in Chinese).

Coluccia, B., Valente, D., Fusco, G., De Leo, F., Porrini, D., 2020. Assessing agricultural eco-efficiency in Italian Regions. Ecol. Indic. 116, 106483.

Cui, S.M., Wu, M.Y., Huang, X., Cao, X.C., 2022. Unravelling resources use efficiency and its drivers for water transfer and grain production processes in pumping irrigation system. Sci. Total Environ. 818, 151810.

de Moura, E.G., de Sousa, R.M., Campos, L.S., Cardoso-Silva, A.J., Mooney, S.J., Aguiar, A.D.F., 2021. Could more efficient utilization of ecosystem services improve soil quality indicators to allow sustainable intensification of Amazonian family farming. Ecol. Indic. 127, 107723.

Ding, N., Liu, J.R., Yang, J.X., Yang, D., 2017. Comparative life cycle assessment of regional electricity supplies in China. Resour. Conserv. Recycl. 119, 47–59.

Feng, B., Zhuo, L., Menkonnen, M.M., Marston, L.T., Yang, X., Xu, Z., Liu, Y., Wang, W., Li, Z., Li, M., Ji, X., Wu, P., 2022. Inputs for staple crop production in China drive burden shifting of water and carbon footprints transgressing part of provincial planetary boundaries. Water Res. 221, 118803.

Grafton, R.Q., Williams, J., Perry, C.J., Molle, F., Ringler, C., Steduto, P., Udall, B., Wheeley, S.A., Wang, Y., Garrick, D., Allen, R.G., 2018. The paradox of irrigation efficiency. Science 361 (6404), 748–750.

Guo, Z., Zhang, X., 2023. Carbon reduction effect of agricultural green production technology: a new evidence from China. Sci. Total Environ. 27, 162483.

Hasanzadeh Saray, M., Baubekova, A., Gohari, A., Eslamian, S.S., Klöve, B., Torabi Haghighi, A., 2022. Optimization of Water-Energy-Food Nexus considering CO_2 emissions from cropland: a case study in northwest Iran. Appl. Energy 307 (1), 118236.

He, Y., 2016. Agricultural Geographical Agglomeration in China: Spatial and Temporal Characteristic, Formation Mechanism and Growth Effect. Huazhong Agricultural University (in Chinese).

Hoekstra, A.Y., Chapagain, A.K., 2007. Water footprints of nations: water use by people as a function of their consumption pattern. Water Resour. Manag. 21 (1), 35–48.

Hou, M.Y., Deng, Y.J., Yao, S.B., 2022. Coordinated relationship between urbanization and grain production in China: degree measurement, spatial differentiation and its factors detection. J. Clean. Prod. 331, 129957.

International Food Policy Research Institute, 2019. Global Spatially-disaggregated Crop Productino Statistics Data for 2010 Version 1.1. Cambridge University Press, Cambridge, U.K.

Iribarren, D., Hospido, A., Moreira, M.T., Feijoo, G., 2011. Benchmarking environmental and operational parameters through eco-efficiency criteria for dairy farms. Sci. Total Environ. 409, 1786–1798.

Jabeen, M., Ahmed, S.R., Ahmed, M., 2022. Enhancing water use efficiency and grain yield of wheat by optimization irrigation supply in arid and semi-arid regions of Pakistan. Saudi J. Biol. 29 (2), 878–885.

Kline, J., 2003. Activity-based costing and benchmarking: a tandem for quality-oriented governments. J. Gov. Financ. Manag. 52 (3), 50–54.

Koondhar, M.A., Aziz, N., Tan, Z., Yang, S., Abbasi, K.R., Kong, R., 2021. Green growth of cereal food production under the constraints of agricultural carbon emissions: a new insights from ARDL and VECM models. Sustain. Energy Technol. Assess. 47, 101452.

Li, D., Tian, P., Luo, Y., Dong, B., Cui, Y., Khan, S., 2021b. Importance of stopping groundwater irrigation for balancing agriculture and wetland ecosystem. Ecol. Indic. 127, 107747.

Li, M., Liu, S., Sun, Y., Liu, Y., 2021a. Agriculture and animal husbandry increased carbon footprint on the Qinghai-Tibet Plateau during past three decades. J. Clean. Prod. 278, 123963.

Li, M., Cao, X., Liu, D., Fu, Q., Li, T., Shang, D., 2022. Sustainable management of agricultural water and land resources under changing climate and socio-economic conditions: a multi-dimensional optimization approach. Agric. Water Manag. 259, 107235.

Li, Z., Li, J., 2022. The influence mechanism and spatial effect of carbon emission intensity in the agricultural sustainable supply: evidence from china's grain production. Environ. Sci. Pollut. Res. 29, 44442–44460.

Liang, X.R., 2015. Carbon Footprint of Chinese Export Grains. University of Science and Technology (in Chinese).

Lin, L., Gao, X., Zhao, Y., Wang, L., An, T., Liu, C., Qiao, Y., Wu, P., 2021. Evaluation of the water consumption of animal products and the virtual water flow pattern associated with interprovincial trade in China. J. Clean. Prod. 328 (15), 129599.

Liu, D., Zhu, X., Wang, Y., 2021. China's agricultural green total factor productivity based on carbon emission: An analysis of evolution trend and influencing factors. J. Clean. Prod. 278, 123692.
Liu, G., Chen, Y., He, H., 2012. China's environmental challenges going rural and west. Environ. Plan. 44, 1657–1660.
Lopez, R.A., He, X., De Falcis, E., 2017. What drives China's new agricultural subsidies? World Dev. 93, 279–292.
Mahmood, M., Tian, Y., Ma, Q., Hui, X., Elrys, A.S., Ahmed, W., Mehmood, S., Wang, Z., 2021. Changes in phosphorus fractions in response to long-term nitrogen fertilization in loess plateau of China. Field Crop Res. 270, 108207.
Mhawej, M., Nasrallah, A., Abunnasr, Y., Fadel, A., Faour, G., 2021. Better irrigation management using the satellite-based adjusted single crop coefficient (aKc) for over sixty crop types in California, USA. Agric. Water Manag. 256 (1), 107059.
Miller, O.L., Putman, A.L., Alder, J., Miller, M., Jones, D.K., Wise, D.R., 2021. Changing climate drives future streamflow declines and challenges in meeting water demand across the southwestern United States. J. Hydrol. X 11, 100074.
Molajou, A., Pouladi, P., Afshar, A., 2021. Incorporating social system into Water-Food-Energy nexus. Water Resour. Manag. 35, 4561–4580.
Moutinho, V., Madaleno, M., Robaina, M., 2017. The economic and environmental efficiency assessment in EU cross-country: evidence from DEA and quantile regression approach. Ecol. Indic. 78, 85–97.
Musafiri, C.M., Kiboi, M., Macharia, J., Ng'etich, O.K., Kosgei, D.K., Mulianga, B., Okoti, M., Ngetich, F.K., 2022. Adoption of climate-smart agricultural practices among smallholder farmers in Western Kenya: do socioeconomic, institutional, and biophysical factors matter? Heliyon 8 (1), e08677.
Ning, X., 2016. Study on Adaptation of the Growth Environment of Major Grain Crops to Climate Change in China. Henan University (in Chinese).
Nisar, S., Benbi, D.K., Toor, A.S., 2021. Energy budgeting and carbon footprints of three tillage systems in maize-wheat sequence of north-western Indo-Gangetic Plains. Energy 229, 120661.
Pellegrini, P., Fernández, B.J., 2018. Crop intensification, land use, and on-farm energy-use efficiency during the worldwide spread of the green revolution. PNAS 115 (10), 2335–2340.
Picazo-Tadeo, A.J., Gómez-Limón, J.A., Reig-Martínez, E., 2011. Assessing farming eco-efficiency: a data envelopment analysis approach. J. Environ. Manag. 92, 1154–1164.
Pickering, I.M., Chambers, S., 1991. Competitive benchmarking: process and future development. Comput. Integr. Manuf. Syst. 4 (2), 98–102.
Rada, N., Wang, C., Qin, L., 2015. Subsidy or market reform? Rethinking China's farm consolidation strategy. Food Policy 57, 93–103.
Saaty, T.L., 2000. Fundamentals of Decision Making and Priority Theory With the Analytic Hierarchy Process. Analytic Hierarchy Process.
Saeed, Q., Zhang, A., Mustafa, A., Sun, B., Zhang, S., Yang, X., 2022. Effect of long-term fertilization on greenhouse gas emissions and carbon footprints in northwest China: a field scale investigation using wheat-maize-fallow rotation cycles. J. Clean. Prod. 332 (15), 130075.
Sarker, K.K., Hossain, A., Timsina, J., Biswas, S.K., Malone, S.L., Alam, M.K., Loescher, H.W., Bazzaz, M., 2020. Alternate furrow irrigation can maintain grain yield and nutrient content, and increase crop water productivity in dry season maize in sub-tropical climate of South Asia. Agric. Water Manag. 238, 106229.
Schaltegger, S., Sturm, A., 1990. Ökologische Rationalität: Ansatzpunkte zur Ausgestaltung von ökologieorientierten Managementinstrumenten. Die Unternehmung 44, 273–290.
Shi, Y., Lu, L., 2001. Main Crop Water Requirement and Irrigation of China. China Water-Power Press (in Chinese).
Smith, M., 1992. A computer program for irrigation planning and management. FAO Irrigation and Drainage Paper 46, CROPWAT.
Stringer, L.C., Mirzabaev, A., Benjaminsen, T.A., Harris, R.M.B., Jafari, M., Lissner, T.K., Stevens, N., Tirado-Von der Pahlen, C., 2021. Climate change impacts on water security in global drylands. One Earth 4 (6), 851–864.
Sun, S., Wu, P., Wang, Y., Zhao, X., Liu, J., Zhang, X., 2013. The impacts of interannual climate variability and agricultural inputs on water footprint of crop production in an irrigation district of China. Sci. Total Environ. 444, 498–507.
Sun, S., Tang, Q.H., Konar, M., Huang, Z.W., Gleeson, T., Ma, T., Fang, C.L., Cai, X.M., 2022. Domestic groundwater depletion supports China's full supply chains. Water Resour. Res. 58 (5).
Sun, S.K., Wang, Y.B., Liu, J., Wu, P., 2016. Quantification and evaluation of water footprint of major grain crops in China. J. Hydraul. Eng. 47 (9), 1115–1124 (in Chinese).
Tian, P., Li, D., Lu, H., Feng, S., Nie, Q., 2021. Trends, distribution, and impact factors of carbon footprints of main grains production in China. J. Clean. Prod. 278, 123347.
Tian, P., Lu, H., Heijungs, R., Li, D., Xue, Y., Yang, Y., 2022. Patterns of carbon footprints of main grains production in China: comparison between main and non-main producing areas. Environ. Sci. Pollut. Res. 29, 23595–23606.
Tian, Z.H., Ma, X.Y., Liu, R.H., 2015. Interannual variations of the carbon footprint and carbon eco-efficiency in agro-ecosystem of Beijing, China. J. Agric. Resour. Environ. 32 (6), 603–612 (in Chinese).
Tigkas, D., Vangelis, H., Tsakiris, G., 2016. Introducing a modified Reconnaissance Drought Index (RDIe) incorporating effective precipitation. Procedia Eng. 162, 332–339.
Tomaz, A., Palma, J.F., Romas, T., Costa, M.N., Rosa, E., Santos, M., Boteta, L., Dôresa, J., Patanita, M., 2021. Yield, technological quality and water footprints of wheat under Mediterranean climate conditions: a field experiment to evaluate the effects of irrigation and nitrogen fertilization strategies. Agric. Water Manag. 258 (1), 107214.
United Nations (UN), 2015. Transforming Our World: The 2030 Agenda for Sustainable Development.
Wang, Y., Zhu, Y., Zhang, S., Wang, Y., 2018. What could promote farmers to replace chemical fertilizers with organic fertilizers? J. Clean. Prod. 199, 882–890.
West, T.O., Marland, G., 2002. A synthesis of carbon sequestration, carbon emissions, and net carbon flux in agriculture: comparing tillage practices in the United States. Agric. Ecosyst. Environ. 91 (1–3), 217–232.
Whitlark, D., Dunteman, G.H., 1990. Principal components analysis. J. Mark. Res. 27 (2), 243.
World Business Council for Sustainable Development (WBCSD), 1998. Eco-efficient Leadership for Improved Economic and Environmental Performance.
Xiao, X., Boles, S., Liu, J., Zhuang, D., Frolking, S., Li, C., Salas, W., Berrien, M.I., 2005. Mapping paddy rice agriculture in southern China using multi-temporal MODIS images. Remote Sens. Environ. 95 (4), 480–492.
Yan, D., Wu, S., Tang, Y., Zhu, J., Zhou, S., Xu, Z., 2022. Arable land and water footprints for food consumption in China: from the perspective of urban and rural dietary change. Sci. Total Environ. 838, 155749.
Yang, B., Zhang, Z., Wu, H., 2022. Detection and attribution of changes in agricultural eco-efficiency within rapid urbanized areas: a case study in the Urban agglomeration in the middle Reaches of Yangtze River, China. Ecol. Indic. 144, 109533.
Yang, J., Yang, Y.C.E., Khan, H.F., Xie, H., Ringler, C., Ogilvie, A., Seidou, O., Djibo, A.G., van Weert, F., Tharme, R., 2018. Quantifying the sustainability of water availability for the water-food-energy-ecosystem nexus in the Niger River Basin. Earth's Future 6 (9), 1292–1310.
Ye, Q., Wang, R., Schyns, J.F., Zhuo, L., Yang, L., Krol, M.S., 2022. Effects of production fragmentation and inter-provincial trade on spatial blue water consumption and scarcity patterns in China. J. Clean. Prod. 334, 130186.
Yu, W., Yue, Y., Wang, F., 2022. The spatial-temporal coupling pattern of grain yield and fertilization in the North China plain. Agric. Syst. 196, 103330.
Yun, Y.B., Nakayama, H., Tanino, T., 2004. A generalized model for data envelopment analysis. Eur. J. Oper. Res. 157, 87–105.
Yun, Y.B., Nakayama, H., Yoon, M., 2016. Generation of Pareto optimal solutions using generalized DEA and PSO. J. Glob. Optim. 64 (1), 49–61.
Zadeh, L.A., 1965. Fuzzy sets. Inf. Control. 8, 338–353.
Zhang, B., Fu, S., 2023. Do market pressure and social network affect farmers' adoption of low-carbon fertilization practices? Evidence from China. Environ. Sci. Pollut. 30, 51804–51815.
Zhang, C., Dong, J., Zuo, L., Ge, Q., 2022. Tracking spatiotemporal dynamics of irrigated croplands in China from 2000 to 2019 through the synergy of remote sensing, statistics, and historical irrigation datasets. Agric. Water Manag. 263, 107458.
Zhao, D., Liu, W., Gao, R., Zhang, P., Li, M., Wu, P., Zhuo, L., 2023. Spatiotemporal evolution of crop grey water footprint and associated water pollution levels in arid regions of western China. Agric. Water Manag. 280 (30), 108224.
Zhao, X., Ma, X., Chen, B., Shang, Y., Song, M., 2022. Challenges toward carbon neutrality in China: strategies and countermeasures. Resour. Conserv. Recycl. 176, 105959.