Ecological Indicators 150 (2023) 110240

Contents lists available at ScienceDirect

Ecological Indicators

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

Extended exergy accounting for assessing the sustainability of agriculture: A case study of Hebei Province, China

Hai Qi [a], Zhiliang Dong [b,*], Xinshang You [a,*], Yu Li [c], Yiran Zhao [c], Xiaotian Sun [c]

[a] School of Economics and Management, Hebei University of Science and Technology, Hebei, Shijiazhuang 050018, PR China
[b] School of Management, Hebei GEO University, Hebei, Shijiazhuang 050031, PR China
[c] School of Economics and Management, China University of Geosciences, Beijing 100083, PR China

ARTICLE INFO

Keywords:
Extended exergy
Hebei Province
Agriculture
Resource accounting
Sustainability indicator

ABSTRACT

Along with the growing demand and improving diet, the agricultural sector faces challenges in balancing resource consumption, environmental impacts and yields. This study presents an extended exergy accounting to capture the changing characteristics of the usefulness of resources in the agricultural sector of Hebei Province during 2000–2018 from thermodynamics perspective. The accounting includes exergy fluxes of energy, materials, environmental remediation, labor, capital and yields quantified by joules. The agricultural sector of Hebei Province comprising the cropping, forestry, stockbreeding and fishery sub industries, has experienced transformation into a modern pattern. The results showed that (1) the extended exergy in the agricultural sector of Hebei Province exhibited a declining trend; the natural resource exergy, particularly energy exergy, dominated the investments in the sector. (2) The capital exergy, labor exergy and environmental remediation exergy all decreased; the capital exergy and labor exergy decreased more than the environmental remediation exergy. The shares of the labor exergy from the services of agriculture declined, while those of the labor exergy from forestry and stockbreeding notably increased. (3) Since the cropping accounts for a large part of the yields, the large quantity of crop residues should be considered seriously. The potential of the other three sub industries was very high. The comparison between the agricultural sector in Hebei Province and that in China as a whole involving exergy indicators showed that Hebei Province was more modernized and had achieved great progresses. Extended exergy accounting captures the agro ecological economic system to help identify resource depletion and environmental costs in other areas or industries from a sustainable development perspective.

1. Introduction

As a specific sector that sits between the natural environment and the socioeconomic system, agriculture is bounded by various resources, environmental and economic aspects. The sustainability of modern agriculture in China needs a clear ecological diagnosis for lots of non-renewable resource investments, such as fertilizer, pesticide, plastic film and fossil energy (Zhang et al., 2019). Traditional economic analysis methods undervalue the worth of environmental inputs (Zhou et al., 2010). To improve the efficiency of resource utilization and reduce environmental impacts, studies have focused on the continuous development of agriculture (Huang et al., 2022; Zhang et al., 2016). These studies do not reflect the usefulness of resources from a sustainability perspective.

In contrast to economic analysis, exergy analysis evaluates resource utilization levels and environmental impacts based on the second-law of thermodynamics, therefore ascertaining the potential to improve sustainability. Defined as “the maximum amount of work produced by a system reaching a thermodynamic equilibrium with the reference environment”, exergy describes not only the quantity but also the quality of energy and materials (Wall, 1977). A higher value indicates a higher potential to do work (Mosquim and Keutenedjian Mady, 2021). Exergy unifies various resources and materials, and system accounting by exergy resource consumption reveals the supersession and supports corresponding ecological diagnosis with physical sustainability (Chen and Qi, 2007; Zhang et al., 2012).

Scholars have analyzed energy or material flow in different nations and industries by exergy assessments to strengthen sustainable development. Countries or regions such as Asia (India (Jadhao et al., 2017) and China (Brockway et al., 2015; Li et al., 2019)); Europe (Norway

* Corresponding authors at: Shijiangzhuang, Hebei University of Science and Technology, Shijiazhuang 050031, PR China (X. You).
E-mail addresses: dongzhl@126.com (Z. Dong), youxinshang@hebust.edu.cn (X. You).

https://doi.org/10.1016/j.ecolind.2023.110240
Received 6 February 2023; Received in revised form 6 April 2023; Accepted 8 April 2023
Available online 14 April 2023

(Ertesvåg and Mielnik, 2000), the UK (Gasparatos et al., 2009; Warr et al., 2008), regions of Denmark (Nielsen and Jørgensen, 2015), Spain (Valero et al., 2014), Italy (Wall et al., 1994), Greece (Koroneos et al., 2011) and all of Europe (Calvo et al., 2016)); America (regions of Canada (Bligh and Ismet Ugursal, 2012), the United States (Ayres et al., 2003; Warr and Ayres, 2010), Colombia (Gabriel Carmona et al., 2015) and Latin America (Palacios et al., 2018)); have been analyzed. Different industries were also considered; for example, transportation in Greece (Koroneos and Nanaki, 2008), Turkey (Ediger and Çamdalı, 2007; Seckin et al., 2013), Jordan (Jaber et al., 2008), Saudi Arabia (Dincer et al., 2004c), and China (Dai et al., 2014; Ji and Chen, 2006); agriculture in Saudi Arabia (Dincer et al., 2005), China (Chen et al., 2009; Zhang et al., 2019) and Malaysia (Ahamed et al., 2011); energy-intensive industries in Denmark (Bühler et al., 2016), the residential-commercial sector in Turkey (Utlu and Hepbasli, 2005); the residential and industrial sectors (Dincer et al., 2004a), and public and private sectors in Saudi Arabia (Dincer et al., 2004b); commerce in Malaysia (Saidur et al., 2007); the smelting and pressing of metals industry in China (Qi et al., 2021), and the energy sector of Mexico (Pacheco-Rojas et al., 2022). Moreover, some studies compare the exergy efficiency among nations (Heun and Brockway, 2019; Utlu and Hepbasli, 2007).

These papers are grouped into three main categories. First, Reistad focused on energy depletion in Organization for Economic Cooperation and Development (OECD) and non-OECD countries (Nakicenovic et al., 1996) and Saudi Arabia (Dincer et al., 2005); second, Wall supplemented the exergy content of materials in Norway (Ertesvåg and Mielnik, 2000), China (Chen et al., 2006) and the world (Carmona et al., 2021); third, Sciubba considered labor, currency and environmental remediation costs in Norway (Ertesvåg, 2005), Italy (Biondi, 2022), Turkey (Seckin et al., 2012), a district in Iran (Ahmadi et al., 2022) and China (Meng et al., 2022; Yang and Chen, 2014). Environmental emissions including greenhouse gases (GHGs) and the "three wastes" (waste water, waste gas and solid waste) have been assessed to explore the ecological exergy (Chen and Zhang, 2010; Zhang et al., 2012). These studies show that exergy analysis has been improved to maintain its advantages in ecological evaluation (Tan et al., 2019).

The social system exergy accounting assesses resource consumption in a single social system by the approach of Wall (Chen et al., 2006) or extended exergy accounting (EEA) (Chen et al., 2014). Cumulative exergy method extends exergy analysis beyond a single process to deal with all processes from natural resources to final production. It is the sum of the exergy contained in all resources entering the product or process, providing insights into potential improvements (Szargut et al., 2002). Extended exergy accounting (EEA) is an extension of exergy analysis, including labor and capital in terms of joules. EEA includes energy carriers, materials, labor, capital, and environmental remediation. It is easier and more meaningful to compare different investments and productions by EEA expressed in joules based on the second law of thermodynamics (Sciubba, 2011). Furthermore, this assessment of natural-social-environmental impacts may be reflected as the "ecological cost'' of different resources containing material, energy, human labor, capital, and environmental costs related to one system. The EEA is a tool to bridge the thermodynamic, economic and ecological costs and measure resource exergy consumption (Chen et al., 2014; Dai et al., 2012).

Low-productivity agriculture did not meet the new demand resulting from incremental population and upgraded dietary structure. China has achieved great success in feeding a huge population with 7% of the arable land worldwide (Piao et al., 2010), and Hebei Province hosted 5.3% of the Chinese population and 4.9% of the sown land in China in 2018. The population density in Hebei Province is much higher than that in China. Hebei Province, located in North-Central China and as a water-scarce area, surrounds one of China's most economically developed regions, Beijing and Tianjin, being the main supplier of agricultural products for the area (Li et al., 2021). The land-cover types in the province include plateaus, mountains, hills, basins, and plains covering an area of 18.88 million ha. As one of the main grain production zones in China, agriculture is significant for Hebei Province (Deng et al., 2017).

Researchers have examined Chinese society, thereby covering the agricultural sector from the perspective of exergy (Chen and Chen, 2006; Zhang et al., 2018). In particular, Chen executed analysis of agricultural products from 1980 to 2002 based on exergy (Chen and Chen, 2007a; Chen and Chen, 2007b). Exergetic assessment showed that Chinese agriculture experienced a transition from renewable resource dependence to increasing non-renewable resource depletion from 1980 to 2000 (Chen et al., 2009). Then Zhang analyzed Chinese agriculture from an exergy perspective (Zhang et al., 2019). However, these studies did not assess the situation of agricultural sector in Hebei Province by extended exergy accounting. Its physical sustainability remains to be comprehensively revealed.

To fill this gap, EEA was performed to capture the usefulness of resources and the sustainable development of the agricultural sector in Hebei Province from a thermodynamics perspective from 2000 to 2018. Resource investment, production, environmental emissions, exergy input/output structure and assessment indicators were calculated by accounting for major exergy fluxes with the agricultural sector of Hebei Province from the thermodynamics point. The EEA may facilitate the optimization of resource utilization and the reduction in environmental impacts for future sustainable development of the agricultural sector in not only Hebei Province but also in other areas or industries.

2. Methodology and data sources

Based on previous research (Chen et al., 2009; Zhang et al., 2019), the exergy inputs were grouped into four classes: free renewable resources (FR) including sunlight, geothermal heat, rain and wind; free non-renewable resources (FN) containing soil erosion and topsoil loss; purchased renewable resources (PR) incorporating irrigation water (I_{water}), seeds and labors; and purchased non-renewable resource (PN) encompassing fossil fuels, electricity, chemical fertilizers, machinery, pesticides and plastic mulch. The yield (Y) comprises products of cropping, stockbreeding, forestry, fisheries and straws being by-products. Exergy equivalent of the remediation cost (E_R) includes animal wastes, residues of the fertilizer, pesticide waste, and plastic mulch. In this paper, we supplemented the greenhouse gases (GHGs) in agricultural production. The GHGs comprising CO_2, CH_4 and N_2O, the corresponding exergetic values are 0.45, 51.98 and 2.4 PJ/Mt, respectively (Zhang and Chen, 2010).

In EEA tool, different energy and material resources, capital, labor and waste emissions are all unified into joules (Chen et al., 2014; Dai et al., 2014),

which are formulated as follows:

$$EE = CEC + E_K + E_L + E_R \quad (1)$$

where CEC indicates the cumulative resource exergy consumption, including E_E and E_M. E_E means the energy resource investment, including FR and energy inputs of PN. E_M represents the kinds of material investment, comprising FN, PR excepting labor and PN except energy inputs. E_K, E_L and E_R are the exergy equivalents of the capital flows, human labor, and remediation costs, respectively.

According to former studies (Dai et al., 2012; Sciubba, 2011),

E_L and E_K are quantified as follows:

$$E_L = \alpha \times E_{in} \quad (2)$$

$$E_K = \beta \times E_L \quad (3)$$

E_{in} represents the exergy flow into the Chinese society. The α and β are exergo-economic coefficients describing the relationship with other parameters. They are expressed as

$$\alpha = \frac{f \times e_{surv} \times N_h}{E_{in}} \quad (4)$$

$$\beta = \frac{M2}{s \times N_w \times W} \quad (5)$$

where f means the correction factor associated with the level of life in different countries or regions (f = HDI/HDI$_0$, HDI indicates the Human Development Index released by the United Nations); e_{surv} implies the essential exergy consumption, 10^7 J/(person × day); N_h is the population of China; M2 signifies the money stock in one year (in China, different with the Western banking systems, a large part of M2 is deposits. Thus, we prefer to adopt the gross domestic product (GDP) of China as the monetary circulation indicator); s and N_w are the average wage and the number of workers, respectively; W is the average workload and a value of 2000 h is chosen (Chen et al., 2014; Chen and Chen, 2009). In this research, the accounting boundary of EEA includes only the area of Hebei Province. The scopes of capital exergy and labor exergy were determined in the Hebei Province and data were retrieved from the China Labor Statistical Yearbook (CLSY, 2001-2019). We calculated the E_L in China, and we obtained the E_L of agricultural production in Hebei Province according to the working population and average wage (Chen et al., 2014). Next we got the E_K of the agricultural sector in Hebei Province.

Since exergy unifies various resources from the perspective of sustainable development, we can evaluate the structure of the agricultural ecological economic system in Hebei Province using indices and ratios applied in previous studies (Chen et al., 2009; Zhang et al., 2019).

Renewability index (RI) is the ratio of renewable resources to nonrenewable resources. A higher value means lower resource stress on the environment.

$$\text{Renewability index (RI)} = (\text{FR} + \text{PR})/(\text{FN} + \text{PN}) \quad (6)$$

Purchased resource yield ratio (PRYR) is the agricultural yield (Y) divided by the purchased resources. The higher the ratio is, the higherthe return per unit invested.

$$\text{Purchased resource yield ratio(PRYR)} = \text{Y}/(\text{PR} + \text{PN}) \quad (7)$$

Economic investment ratio (EIR) is defined as the economic input divided by the free natural resource cost. A larger index value illustrates a greater burden of economic investment.

$$\text{Economic investment ratio(EIR)} = (\text{PR} + \text{PN})/(\text{FR} + \text{FN}) \quad (8)$$

Environmental resource yield ratio (ERYR) represents the yield divided by the free environmental resource input. This index expresses the contribution of the environmental resource in the production system. A larger value suggests that fewer environmental resources are required for one unit of production.

$$\text{Environmental resource yield ratio(ERYR)} = \text{Y}/(\text{E}_\text{R} + \text{FR} + \text{FN}) \quad (9)$$

Environmental stress index (ESI) is the environmental resource input comprising irrigation water divided by the purchased investment excluding irrigation water, thus reflecting the direct stress on the environment.

$$\text{Environmental stress index (ESI)} = (\text{FR} + \text{FN} + \text{E}_\text{R} + \text{I}_\text{water})/(\text{PR} - \text{I}_\text{water} + \text{PN}) \quad (10)$$

System transformity (STr) is the ratio of yield to the total ecological inputs. This index implies system transformity of the agricultural sector.

$$\text{System transformity (STr)} = \text{Y}/(\text{FR} + \text{FN} + \text{E}_\text{R} + \text{PR} + \text{PN}) \quad (11)$$

Considering the exergy accounting at the provincial and country levels, it is reasonable to select the ecosystem environment of the Earth as the reference (Meng et al., 2022; Zhang and Chen, 2010). The exergy coefficients of resources were retrieved from previous studies (Zhang and Chen, 2010; Zhang et al., 2018) as listed in Table S. In regard to unavailable data, we chose the studied period from 2000 to 2018. The resource data originated from the official statistical yearbooks, Hebei Economic Yearbook (HEY, 2001-2019), China Statistical Yearbook (CSY, 2001-2019), China Energy Statistical Yearbook (CESY, 2001-2019), China Agriculture Yearbook (CAY, 2001–2019), China Labor Statistical Yearbook (CLSY, 2001-2019) and China Forestry Yearbook (CFY, 2001-2019).

3. Results

3.1. Structural changes of extended exergy

Fig. 1 displays the changes in the five extended exergy components (energy, material, capital, labor and environmental remediation) in the agricultural sector of Hebei Province from 2000 to 2018. The whole extended exergy decreased slowly during the 19 years considered. The growth rate of the sector increased in six years (2003, 2005, 2008, 2012, 2015 and 2016), and it reached 0.98% and 13.53% in 2008 and 2012, respectively. First, the material exergy and energy exergy investments declined from 964.53 PJ and 4129.95 PJ, respectively, in 2000 to 739.33 PJ and 3437.72 PJ, respectively, in 2018 decreasing to 76.65% and 83.24%, of the initial levels. The proportion of these two factors in the total extended exergy increased from 88.94% to 91.80% during the study period. Second, the labor, capital and the environment exergetic values decreased from 18.43 PJ, 13.19 TJ and 615.27 PJ, respectively, in 2000 to 2.95 PJ, 1.99 TJ and 369.98 PJ, respectively, in 2018, thus accounting for 15.98%, 15.09% and 60.13% of their values in 2000. For the improvement of the social and economic levels in Hebei Province and the conversion to intensive growth, agricultural production did not demand much labor. Facing resource shortages relatively and an expanding demand, the government of Hebei Province should continuously reduce emissions and improve the efficiency of different resources. In conclusion, the energy exergy and material exergy inputs played a key role in agricultural sector development. Most of the energy exergy originating from the natural environment remained stable relatively. Therefore, more attention should be focused on the quantity and kinds of material investments. The proportion of the materials exergy in the total extended exergy remained at approximately 16.63% throughout the study period, with irrigation water accounting for the majority.

3.2. Inter-annual variation in the extended exergy

The PN was the only growing factor during this period. Overall, the resource input was dominated by renewable input, reflecting the actual influence of natural environment to agriculture.

3.2.1. Free natural resource input

The free renewable resources (FR) inputs contain sunlight, rain, wind and geothermal heat. Since the natural environment of the agricultural sector remained relatively stable, the exergy of FR always remained at approximately 3.69 EJ from 2000 to 2018, as shown in Fig. 2(a). In reality, the sown areas of crops, orchards and pastures decreased from 9.02, 1.04 and 0.56 million ha, respectively, to 8.20, 0.53 and 0.28 million ha, reducing 9.17%, 49.04% and 50%, respectively. The forest land area increased from 4.33 to 5.03 million ha during the study period. In China, the pasture area declined 33.88% while the area of forest increased 59.05% and the area of crops kept stable around 130 million ha during the same period (CSY, 2001-2019). Located in northern China, Hebei Province is influenced by public affairs. Lack of vegetation protection on the surface of the land is one of the causes of sand and dust storms. To improve the atmospheric environment of Beijing and northern China, Hebei Province increased the forestland area, although the forest might generate no economic benefit in the short term. The fishery area experienced a process of first increasing and then decreasing, with a prominent decline reaching −36.51% in 2007. The ratio of the sea water breeding area in the fishery area expanded from 45.18% to 73.34%. Photosynthetic exergy was the largest contributor to the input of FR;In 2018, it accounted for 53.48% of the FR input,

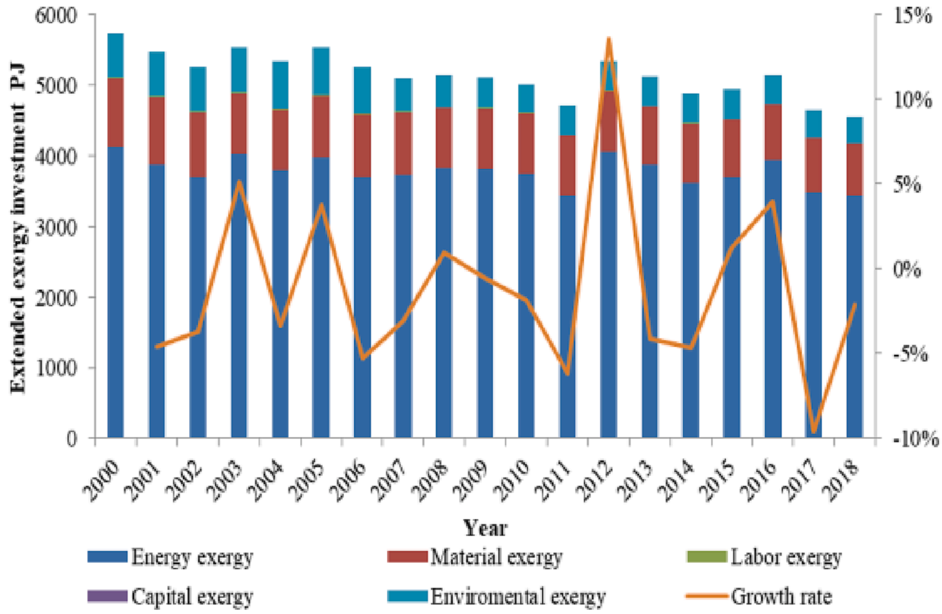
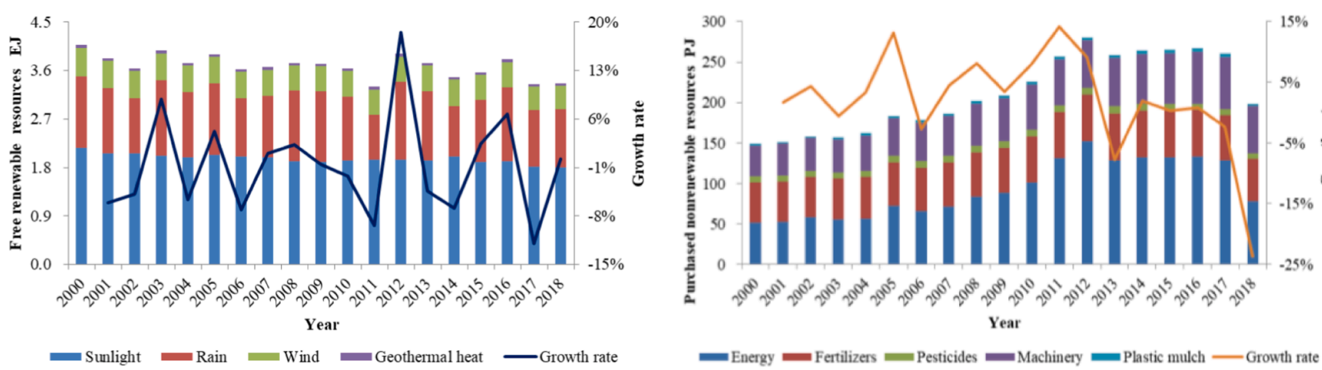


Fig. 1. Structural changes of extended exergy.



(a)Free renewable resources

(b) Purchased nonrenewable resources

Fig. 2. Free renewable resources and purchased nonrenewable resources.

followed by rain (32.10%), wind (13.08%), and geothermal heat (1.34%). Referencing the previous paper (Zhang et al., 2019), we found that the annual exergy of topsoil loss in Hebei Province was stable relatively, at 10.01 PJ in 2000 and 9.53 PJ in 2018, corresponding to 0.28% of the free resource input. Although the exergy of topsoil loss was lower than that of the other categories, it was not ignored in agricultural production.

3.2.2. Purchased economic investments

The purchased renewable investments in the agricultural sector of Hebei Province contained irrigation water, human labor and seeds. The exergy value of PR decreased with fluctuations from 875.79 PJ in 2000 to 612.06 PJ in 2018. Irrigation water dominated PR, accounting for 97% in 2000 and 2002, and 99% from 2012 to 2018. Water consumption in agriculture was the largest water expenditure in Hebei Province, occupying 83.2% and 69.4% of the total water consumption in 2000 and 2018, respectively. Located in the North China Plain, Hebei Province contains no large rivers and few external water resources, mainly relying on natural precipitation. As one of the grain-producing provinces, efforts were made to reduce water consumption and ensure grain production with less water resource. First, the provincial government adjusted the planting structure and expanded the planting of drought-tolerant crops. Second, it attempted to greatly promote water-saving irrigation. Third, the province selected and cultivated drought-tolerant plant species.

The exergy equivalent of human labor exhibited a remarkable reduction. It decreased from 18.43 PJ in 2000 to 2.95 PJ in 2018, accounting for only 2.10% and 0.48%, respectively, of the purchased renewable investment. Chinese human labor in the agricultural sector decreased from 1.21 EJ in 2000 to 0.35 EJ in 2018, declining 71.07% less than that in Hebei Province (83.99%). The rural labor force may continue to decline in the future. Since the shrinking of the sown area, the exergetic value of seeds declined also from 4.01 PJ to 3.61 PJ in the period.

The purchased nonrenewable resources (PN) comprising energy, agricultural machinery, fertilizers, plastic mulch and pesticides are necessary in modern agriculture to ensure the yield. Fig. 2(b) displays that it increased from 148.93 PJ in 2000 to 280.36 PJ in 2012 and then declined to 198.63 PJ in 2018, with an average annual growth rate of 1.98%. The average annual growth rates of energy, agricultural machinery, fertilizers, pesticides and plastic mulch were 3.61%, 2.42%, 0.36%, −0.76%, and 3.46%, respectively. Nitrogen, phosphate, potash and compound fertilizer were applied in Hebei Province with a slight increase in exergy and decrease from 49.37 PJ in 2000 to 52.45 PJ in 2018. The exergy consumption of phosphate and potash remained relatively stable in the study period. The exergy consumption of nitrogen decreased from 35.55 PJ in 2000 to 27.50 PJ in 2018;At the same time, that of compound fertilizer expanded from 8.58 PJ to 20.76 PJ. In 2000, Hebei Province consumed 7.20 GJ exergy of fertilizers per hectare of arable land, compared to approximately 5.68 GJ in the whole country (CSY, 2001–2019). The ratio of the unit area of fertilizer investment between Hebei Province and the entire country grew from 1.27 in 2000 to 1.33 in 2005, and then declined to 1.14 in 2018. That is, the fertilizer consumption per hectare of arable land in Hebei Province was always much higher than the Chinese average level. Since the manufacture of fertilizer produced lots of GHGs, China began to reduce fertilizer use, so did the Hebei Province (Xie et al., 2019). Moreover, the Hebei government tried to supply the necessary nutrient elements of the cultivated crops according to the investigation results of the nutrient element status in different cultivated land areas and promoted the replacement of chemical fertilizer with organic fertilizer.

The increase in the level of mechanization in agriculture could compensate for the reduction in rural labor to a certain extent. The input of mechanical equipment in the agricultural production process was estimated at 64.49 PJ in 2017, the highest value, and 58.49 PJ in 2018, which is much higher than the value of 38.44 PJ in 2000. The exergy proportion of machinery was outweighed by that of energy and fertilizer from 2000 to 2011, and it became the second one from 2012 to 2018. The energy input always ranked first among the purchased non-renewable investments, with the proportion ranging from 34.49% to 54.34%. The exergy input was 51.78 PJ in 2000, increasing over the next few years, reached 152.36 PJ in 2012 and decreased to 77.94 PJ in 2018. Electricity accounted for the largest part from 2000 to 2010, followed by diesel. From 2011 to 2017, diesel consumption became the largest contributor and turned into the second one again in 2018. Most of the time, the exergy consumption of coal was higher than that of gasoline. The exergy depletion of coke was the lowest overall. The input of pesticides increased from 7.31 PJ in 2000 to 8.71 PJ in 2013 and then decreased to 6.18 PJ in 2018. The exergy value of plastic mulch increased from 2.03 PJ in 2000 to 4.50 PJ in 2016 and decreased to 3.57 PJ in 2018, accounting for only 1.80% of the purchased non-renewable input (PN).

3.2.3. Labor and capital

The equivalent exergetic values of the labor input into the five sectors cropping, stockbreeding, forestry, fishery and services of agriculture were calculated. From 2000 to 2007, the services of agriculture exhibited the largest E_L input, with an average share of 46.89%, and declined slowly, followed by cropping at 33.07%, forestry at 12.54%, stockbreeding at 5.0% and fishery at 2.50%. In 2008, the largest contributor to E_L was cropping accounting for 40.11%, and the service was the second largest contributor, accounting for 39.95%. The shares of forestry, stockbreeding and fishery were 13.26%, 4.50% and 2.17%, respectively. Over the next years, the E_L shares of cropping, services and fishery declined, while those of forestry and stockbreeding increased overall. Female labors accounted for 34.96% on average of the total labor force in the agricultural sector in Hebei Province in the study period. The proportion of cropping, forestry, stockbreeding, fishery and services were 37.09%, 24.80%, 38.16%, 18.38% and 34.13%, respectively, indicating that forestry and fishery were more dependent on male labor with fewer machines.

The role of E_K in the industry in Hebei Province declined to 15.09% of the initial level, from 13.19 TJ in 2000 to 1.99 TJ in 2018, with slight fluctuations. Similar to E_K, the role of E_L in agriculture declined to 15.98% from 18.43 PJ in 2000 to 2.95 PJ in 2018. E_K was much lower than E_L in the study period. Meanwhile, the exergy values and the percentages of E_K and E_L declined, reflecting that capital and labor were not as crucial as before. The traditional mode of agricultural production, which depends on the labor force, was transformed into a modern production mode relying on fertilizers, pesticides, agricultural machines and other elements. Table 1 shows the exergy values of free nonrenewable resources, purchased renewable investments and capital.

Table 1
Comparison of FN PR and E_K in agriculture of Hebei Province Unit PJ.

	FN	Irrigating water	Seeds	Labor	Capital
2000	10.01	853.35	4.01	18.43	1.32E-02
2001	10.01	830.10	3.93	16.92	1.15E-02
2002	9.77	806.85	3.91	18.36	1.18E-02
2003	9.47	747.78	3.76	15.27	9.76E-03
2004	9.41	735.35	3.81	14.21	9.29E-03
2005	9.34	751.10	3.87	13.63	8.89E-03
2006	9.22	762.85	3.88	12.72	8.43E-03
2007	9.22	757.95	3.85	11.92	8.15E-03
2008	9.25	716.15	3.87	12.22	8.38E-03
2009	9.58	719.57	3.85	12.02	8.20E-03
2010	9.57	718.85	3.87	10.75	7.54E-03
2011	9.59	716.77	3.90	7.71	5.55E-03
2012	9.58	714.70	3.90	6.82	4.80E-03
2013	9.57	688.18	3.88	5.09	3.55E-03
2014	9.55	696.00	3.86	4.60	3.26E-03
2015	9.53	676.50	3.87	4.97	3.42E-03
2016	9.52	640.00	3.80	4.85	3.28E-03
2017	9.52	630.50	3.66	4.29	2.93E-03
2018	9.53	605.50	3.61	2.95	1.99E-03

3.2.4. Waste emissions

The large amount of resources invested in agriculture led to environmental emissions. Fig. 3 shows the main waste emissions resulting from agriculture in Hebei Province from 2000 to 2018. Animal wastes were the largest part, although shares decreased slightly from 88.41% in 2000 to82.01% in 2018, while the exergy value decreased from 543.96 PJ to 303.41 PJ significantly. The shares of GHGs and fertilizers ranked the second and the third place, increasing from 8.20% and 2.81% in 2000 to 12.01% and 4.96%, respectively, in 2018. Compared to those in 2000, the residues of pesticide decreased to 84.48% in 2018, while that of plastic mulch increased 75.68%, although their shares were much smaller than those of the other categories. A clean environment is one of indices of national development level. Surrounding the Beijing municipality, Hebei Province attempted to reduce kinds of waste emissions in agricultural production in the study period, especially in 2007, when the growth rate of waste emissions declined 30.6%.

Animal wastes from large animals, hogs, sheep and poultry expanded from 543.96 PJ in 2000 to 600.37 PJ in 2005.Thereafter, the growth rate of animal wastes fell suddenly to −32.67% in 2007, and the wastes amount decreased slightly in the next years. It is noted that the amount of animal wastes originating from large animals, hogs and sheep decreased 37.95%, 36.75% and 34.71%, respectively, in 2007; however, that of poultry increased 4.30%. Waste from large animals, including cattle, horses, donkeys and mules, accounted for largest part, showing a downward trend from 52.17% in 2000 to 36.75% in 2018. Waste from hogs ranked the second, with increased shares of 24.57% in 2000 and 33.20% in 2018. The poultry waste emissions took the third place with the share greatly increasing from 14.02% to 21.24%, while that of sheep was stable, at approximately 9.0% in the period. Improper disposal of these animal wastes could cause environmental problems. Therefore, the reasonable application of livestock waste may be an option to reduce waste emissions.

The waste emissions from fertilizers application were steady, and they slightly increased from 17.28 PJ in 2000 to 20.27 PJ in 2014 and then fell to 18.36 PJ in 2018. Nitrogen fertilizer use symbolized the largest emission component. Its share in fertilizer residues declined from 72.01% to 52.43%; however, that of compound fertilizer rose to 39.58% in 2018 from 17.38% in 2000. Excessive use of fertilizer could generate environmental consequences, such as soil compaction and arable land productivity decrease. Pesticides and plastic mulch are essential substances widely used in agricultural production. The excessive consumption of these two materials could lead to environmental pollution and other public problems. The exergy of pesticide residues increased

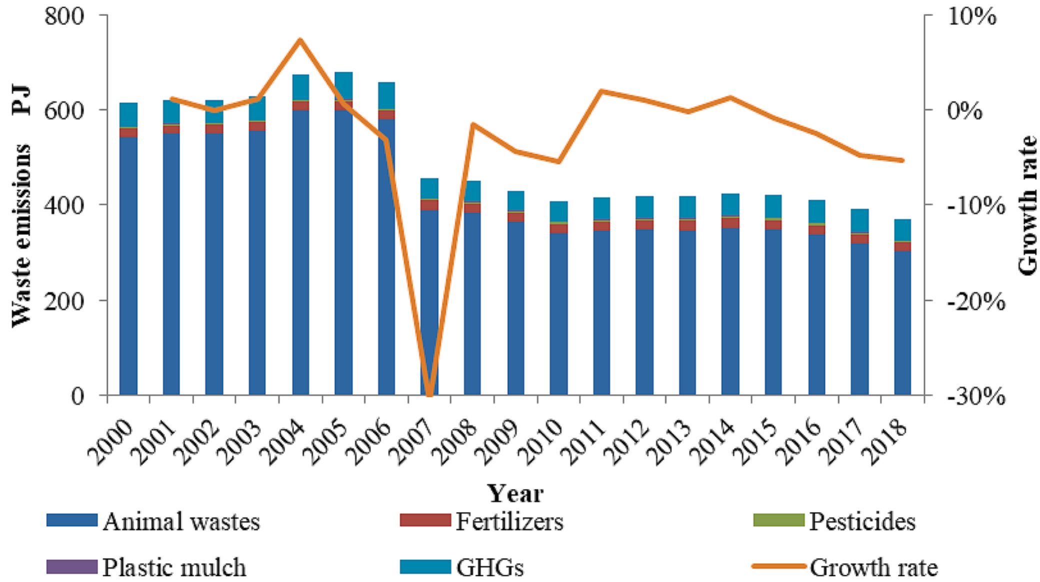


Fig. 3. Waste emissions.

from 2.70 PJ in 2000 to 3.22 PJ in 2013 and then fell to 2.29 PJ in 2018. Similar to pesticide residues, the exergy of plastic mulch residues grew from 0.85 PJ to 1.89 PJ from 2000 to 2016 and decreased to 1.50 PJ in 2018.

Considering previous studies (Zhang and Chen, 2010; Zhang et al., 2019), we calculated the exergy of greenhouse gases (GHGs), mainly including CO_2, N_2O and CH_4, in agricultural production in Hebei Province. Methane emissions were from livestock and poultry, energy consumption (coal, oil and natural gas), and grain production. Carbon dioxide emissions were produced in the process of energy depletion. Nitrous oxide emissions came from three categories: use of energy, application of fertilizer and livestock and poultry. GHG emissions grew from 50.48 PJ in 2000 to 55.85 PJ in 2005 and decreased with some fluctuations to 44.42 PJ in 2018. Methane emissions dominated all GHG emissions, maintaining a proportion of approximately 96.10%. They mainly came from two classifications: grain production and livestock and poultry, accounting for 37.53% and 62.25%, respectively, of the total emissions in 2000. In the period, the methane emissions from grain production increased and those from livestock and poultry declined. In 2008, the methane emissions produced during grain production occupied 50.02% of the total emissions, compared with those of livestock and poultry accounted for 49.77%, and they became 62.88% and 36.64% in 2018, respectively. It is worth noting that the exergy emissions of nitrous oxide and methane decreased to 68.47% and 86.58% in 2018 compared to 2000, respectively. However, that of carbon dioxide increased 1.65 times during the same period, with oil as the largest contributor, although the share was small in the GHG emissions.

3.2.5. *Yield of agricultural products*

Agricultural yield increased over the past 19 years with fluctuations at the growth rate. It encompassed four sub industries: cropping, forestry, stockbreeding and fishery, as shown in Fig. 4(a). The cropping occupied the dominant position, with a yield increase of 35.05% between 2000 and 2018, from 0.93 EJ (89.12% of the total yield) to 1.25 EJ (89.12%), with some changes. Forestry was the fastest growing industry, with the yield increasing from 5.67 PJ in 2000 to 15.47 PJ in 2018. The growth rate of stockbreeding was the slowest, increasing 27.45% from 102.97 PJ to 131.24 PJ. Aquatic production increased from 4.70 PJ to 6.36 PJ, although its shares were small.

Hebei Province is an important cotton and grain producer in China. Its cereal yield (rice, wheat and corn) was 35.25 million tons, accounting for 5.78% of the total cereal yield of China, and its cotton production was only less than that in Xinjiang Province in 2018. The grain yields in exergy had a 41.42% increase from 2000 to 2018, as shown in Fig. 4(b). Wheat and maize were the major grain crops, accounting for 93.61% in 2000 and 96.27% in 2018 of the grain production. The exergy proportion of wheat declined slowly from 62.02% to 52.67% compared to that of maize, which grew from 31.59% to 43.60% over these years. The yields of wheat, maize and tubers in 2018 were 1.20, 1.95 and 1.22 times those in 2000, respectively. In contrast, the outputs of rice and soybean declined over this period. Rice and soybean in exergy were 8.29 PJ and 1.10 PJ, respectively, in 2018, accounting for 79.76% and 37.74%, respectively, of their exergetic values in 2000.

Cash crops mainly include vegetables, oil crops, fruits, sugar crops, fiber crops, cotton and tobacco. In total, the cash crops first increased and decreased in recent years. Hebei Province is the main vegetable supplier in the Jing-Jin region (Beijing, and Tianjin). The vegetables produced in Hebei Province ranked the second from 2000 to 2016, accounting for more than 10% of the total vegetable production in China. Vegetable production in Hebei Province ranked fourth in 2017 and 2018, with its production accounting for 7.3% of the total vegetable production of China. The vegetable in exergy was 84.26 PJ in 2000, reaching 155.67 PJ, 96.11 PJ and 97.94 PJ in 2016, 2017 and 2018, respectively. Oil crops include rape seed, peanut, sunflower seed, sesame seed, and flaxseed. The exergy of oil crops was 30.70 PJ in 2018, accounting for 84.0% of that in 2000. In Hebei Province, the exergy of peanut dominated the oil crops, and the ratio in oil crops declined with fluctuations, accounting for 89.25% of the total oil crops in 2000 and 78.94% in 2018. Although the production of rape seed, sunflower seed and flaxseed increased 1.45, 2.03 and 2.46 times in 2018, respectively, their influence was still limited. The production of sesame shrank to 9.84% from 2000 to 2018, accounting for 0.19% of the exergetic value of oil crops in 2018. Much more than the exergy of cotton and fiber (3.92 PJ), sugar crops (4.71 PJ) and tobacco (0.03 PJ) in 2018, that of the fruits increased to 1.99 times over 2000 levels with fluctuations, reaching 40.63 PJ, 25.94 PJ and 25.61 PJ in 2016, 2017 and 2018, respectively, as shown in Fig. 4(c).

Crop residues are the inevitable by-products of the cropping. The crop/ crop residues ratios for cotton, peanut, rice, wheat, maize, soybean, tubers, rapeseed, sesame, beet, and vegetables were estimated to be 9.2, 0.8, 0.9, 1.1, 1.2, 1.6, 0.5, 1.5, 2.2, 0.08 and 0.1, respectively (Zhang et al., 2019). The straw yield amounted to 707.78 PJ in 2018, accounting for 57.87% of the total yield of the cropping subsystem, and the proportion was relatively stable keeping around 55.94% in these

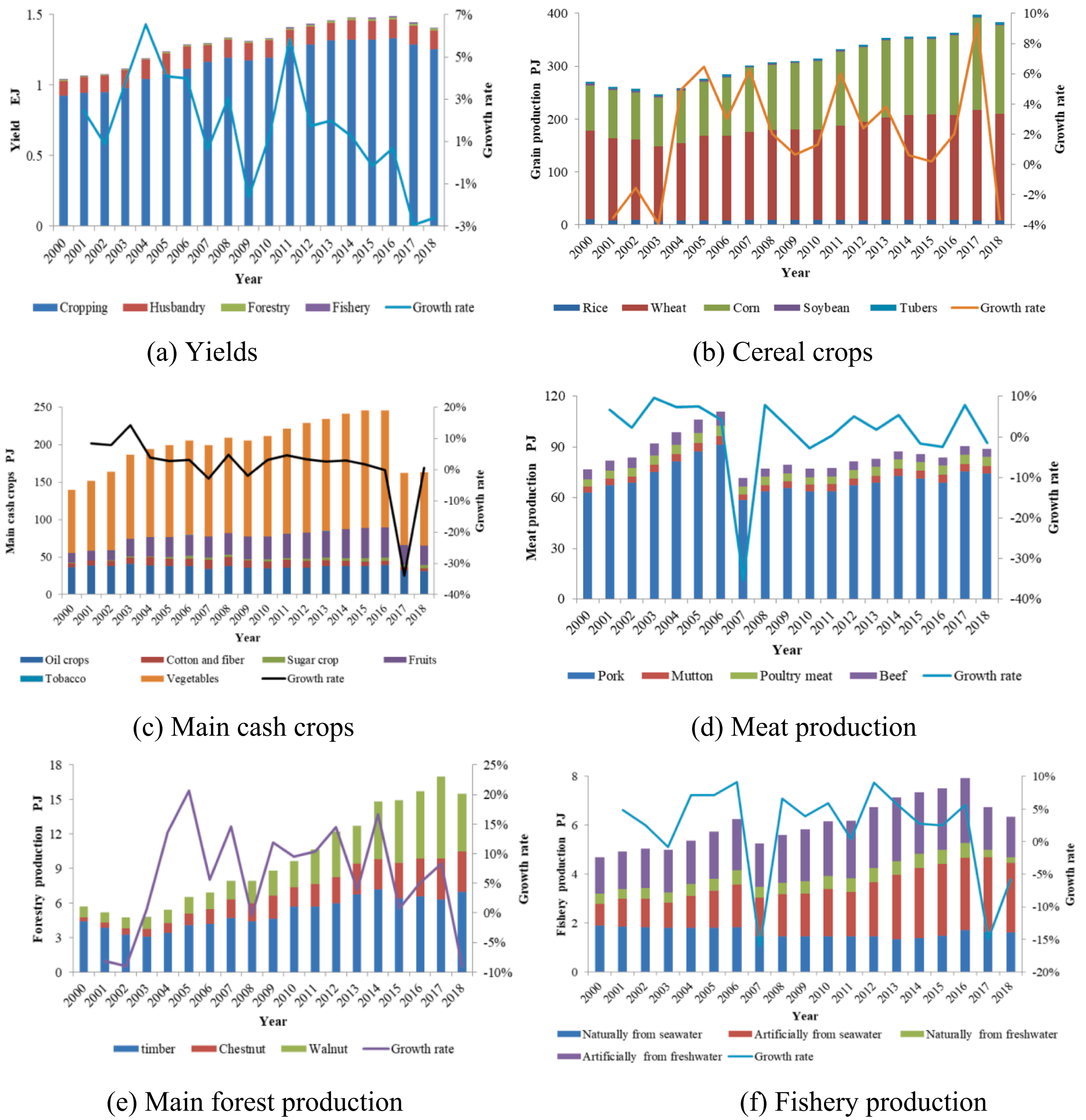


Fig. 4. Yield of agricultural products.

years. The crop straws from maize and wheat accounted for 70.11% and 79.80% of the total amount, respectively, in 2000 and 2018.

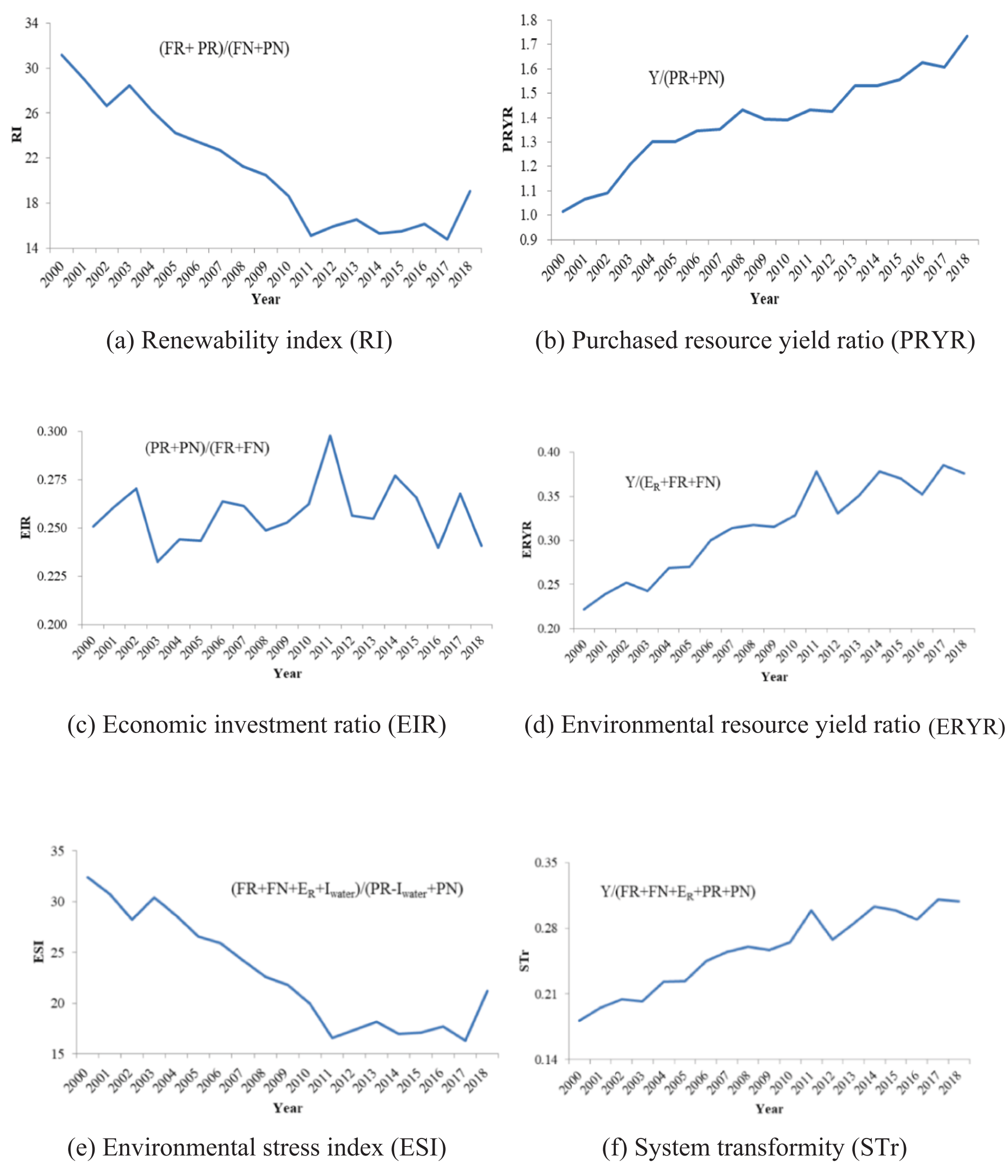
Livestock production was relatively stable during this time. Stockbreeding products mainly include meat, milk, eggs and wool. Meat (pork, mutton, poultry meat and beef) dominated the stockbreeding products in the period, increasing by 15.98% from 2000 to 2018, with the growth rate abruptly declining 35.25% in 2007, as shown in Fig. 4 (d). The highest yields of pork, mutton, poultry meat and beef were 91.43 PJ, 4.99 PJ, 6.45 PJ and 7.91 PJ, respectively, all of which appeared in 2006. After 2006, the yield of meats was not as high as before. Pork accounted for approximately 83% of the total meat yield. Beef occupied the second position, accounting for 7.46% of the total meat yield in 2000 to 6.19% in 2011, and occupied the third position, accounting for 5.96% and 5.57% of the total meat yield in 2012 and 2018, respectively. Poultry meat kept the third position from 2000 to 2011 and became the second one in the rest period. Mutton ranked last, keeping around the ratio of 4.5%. Milk yield steeply increased from 2000 to 2007, the growth rate reaching 44.56% in 2003, and the production reached 24.72 PJ in 2008 from 4.13 PJ in 2000. However, the milk yield did not expand after 2008 due to the consequences of a scandal over problem milk. Confidence in dairy products was more negatively influenced. Egg production was stable and kept approximately 22PJ in these 19 years in Hebei Province.

Main forest products in Hebei Province contain wood, chestnut and walnut, as shown in Fig. 4(e). The results showed a marked development of chestnut and walnut, increasing 10.83 and 5.26 times, respectively. Wood had the largest exergetic amount, except in 2017, accounting for 77.67% in 2000 and 45.20% in 2018 of the total forest yield. The shares of chestnut and walnut grew from 5.71% and 16.61% in 2000to 22.71% and 32.09%, respectively, in 2018.

Similar to meat production, the growth rate of aquatic production declined 16.07% in 2007 also in Hebei Province, as shown in Fig. 4(f). Fishery production became dependent on artificial farming, and the ratio of artificially cultured products to naturally grown products increased to 2.43 in 2018 from 1.03 in 2000. The products from seawater aquaculture maintained the leading position, with its share in the total products increasing from 59.55% to 70.07%. The production of marine aquiculture in exergy increased from 4.70 PJ in 2000 to 6.36 PJ in 2018. Naturally grown products from freshwater were the least among the four fisheries productions. Meanwhile, the yields from sea fishing were more stable than those from freshwater fishing, although sea fishing had less production.

3.3. Indicator assessment

Six indicators representing the biophysical features and the temporal variations in the agricultural sector in Hebei Province based on the exergy flux are shown in Fig. 5 from a historical point. Since the growing depletion of nonrenewable resources and decreasing amount of irrigation water, the renewability index declined from 31.17 in 2000 to19.08 in 2018 with some setbacks, as shown in Fig. 5(a), implying the enlarging dependence on the non-renewable resource input for the agriculture system. The PRYR meaning the yield of per unit purchase investment increased from 1.02 in 2000 to 1.74 in 2018, although it decreased in some years as shown in Fig. 5 (b). The purchased economic input was always less than the agricultural yield and the gap increased over the study period. The values of EIR fluctuated between 0.232 in 2003 and 0.298 in 2011 over the period, indicating that the purchased inputs were always far lower than the environment resource inputs, as shown in Fig. 5 (c). As shown in Fig. 5 (d), the values of ERYR enhanced from 0.22 in 2000 to 0.38 in 2018. Both waste emissions and their shares in environmental resource inputs decreased in the evaluation period. The growth rate of the yield was faster than that of the environmental



(a) Renewability index (RI) (b) Purchased resource yield ratio (PRYR)
(c) Economic investment ratio (EIR) (d) Environmental resource yield ratio (ERYR)
(e) Environmental stress index (ESI) (f) System transformity (STr)

Fig. 5. Exergy-based indicators evaluation.

resource inputs. This result shows that the yield depended less on free environmental resources. The contribution of environmental resources greatly exceeded the purchased contribution. The ESI decreased from 32.42 in 2000 to 21.17 in 2018, implying that agriculture was being transformed from traditional to modern modes, relying on economic investments, as shown in Fig. 5(e). The environmental impact per unit of the purchased economic input decreased. Notable changes occurred in the system transformity, from 0.18 in 2000 to 0.31 in 2018, and the agricultural sector became more ecologically efficient than before, as shown in Fig. 5(f).

In 2000, to produce 100 units of yield, 96.61 units of purchased resources were needed, including 14.30 units of purchased nonrenewable resources, 391.55 units of free natural resources, 1.77 units of labor, 0.0013 units of capital and 59.07 units of environmental impacts. In comparison, in 2018, to produce 100 units of yield, approximately 57.42 units of purchased investment were needed, including 14.12 units of purchased nonrenewable resources into the sector, 238.86 units of free natural resource input, 0.21 units of labor, 0.00014 units of capital and 26.30 units of environmental emissions. Clearly, the natural ecosystem made the greatest contribution to agriculture, much more than the other factors. Irrigation water occupying most of the purchased resources was significantly reduced over this time. In addition, the exergy of waste emissions was higher than that of the non-renewable resource input and the difference decreased. In summary, the agricultural resource conversion efficiency in Hebei Province improved over the study period.

4. Discussion

It is essential to comprehend the pattern and variation in agricultural production for sustainable and healthy development of the agricultural sector. Extended exergy accounting manifests the operation of agriculture in Hebei Province' depends on renewable resource inputs from nature. Land resources are important factors in agricultural production. Hebei Province contains less than the average cultivated area per capita in China. The expansion of urbanization and infrastructure consumed considerable arable land. Given the shortage of arable land with other industries, the land supply became one of important constraints to improve agricultural production. The Hebei Province government has released a policy to protect arable land and develop intensive farms (DNRH, 2022).

Supplying water is an essential factor in the process of agricultural production (Elliott et al., 2014). In Hebei Province, irrigation water contributed 98.11% of the purchased renewable investment on average from 2000 to 2018. In 2018, the per capita water resources in the province were only 11.01% of that in China; meanwhile, precipitation was concentrated during a short period of time. A few groundwater funnel areas have appeared in Hebei Province because of the overexploitation of water resources. With fewer per capita water resources than China as a whole, Hebei Province adjusted the grain planting structure and reduced the production of high-water cost crops. In 2018, the yield proportions of rice, wheat, maize, soybean and tubers in Hebei Province were 2.2%, 52.7%, 43.6%, 0.3% and 1.3%, respectively, from the exergy view. The proportions were 44.3%, 24.2%, 29.3%, 1.0% and 1.3%, respectively, in China. Regarding the shortage of water resources, the aquatic production from freshwater was keeping 1.90PJ from 2000 to 2018 with some fluctuations, with the naturally from freshwater declining from 0.41PJ to 0.24PJ while the artificially from freshwater increasing slightly from 1.49PJ to 1.66PJ. The growth rate of freshwater production of naturally and artificially fell obviously 23.0% and 15.7% in 2007, and 52.4% and 33.9% in 2017, respectively. Clearly, water supply constrains the development of cropping and fishery in Hebei Province. Some effective measures have been proposed to save water resources, such as drip irrigation and pipeline irrigation techniques (Zhang et al., 2013). Moreover, the South-to-North Water Diversion Project greatly improved the situation of water resources in Hebei Province.

Being an ecological economic system, the booming agriculture benefited from the investment of purchased nonrenewable resources, which were prime measure to ensure production yield and efficiency, reducing the labor force. The indicators also expressed that the agricultural yield depended on purchased resource inputs. Sustained investment can guarantee agricultural production; However, it is difficult to increase productivity proportionally. Thereafter, changes in the transition to intensive agriculture are likely to focus on the increasing efficiencies of different resources.

Environmental emissions in agricultural activities and carrying capacity have been considered (Zhang and Chen, 2014a). Machinery and chemical products used in agriculture generate large amounts of environmental emissions, as shown in the exergy of waste emissions. The exergy of waste emissions was higher than that of non-renewable resource inputs, although the estimates in this study may underestimate the environmental emissions from agriculture in Hebei Province. Lots of GHG emissions come from agriculture in China (Zhang and Chen, 2014b), and as an important agricultural producer, Hebei Province generates considerable amounts of GHGs. In addition, the production of agricultural necessities such as fertilizer, pesticide, and plastic mulch causes emissions also.

The dietary habits and living standards of inhabitants also affect food production directly. The consumption of animal-based foods significantly increased in both urban and rural households. The per capita consumption of meat, poultry and related products increased from 27 kg and 8 kg in 2000 to 33.06 kg and 22.84 kg in 2018 in urban and rural households, respectively, with pork accounting for the largest share of meat consumed with its proportion declining. The per capita amount of milk and dairy products consumed by urban and rural residents also increased, from 11.87 kg and 0.22 kg to 21.51 kg and 7.47 kg, respectively. In contrast, the per capita grain consumption by residents reduced from 215.88 kg to 138.63 kg in rural areas compared to the expansion from 94.53 kg to 122.95 kg in urban areas during the study period. There were urban–rural differences in the consumption of animal-based foods. With the advancement of urbanization in Hebei Province, there is still room for improvement in the consumption of animal-based foods. Therefore, expanding demand for animal-based foods will consume more resources and generate more emissions (Yue et al., 2017). In Hebei Province, the contradiction between the supply and demand of agricultural products will continue to exist and become prominent in the background of promoted consumption.

Obviously, there is still room to increase agricultural production, as well as to reduce resource consumption and types of emissions. In the future, as a water-scarce area, Hebei Province may shift the policy direction towards the planting of crops that consume less water under the premise of ensuring grain production. Large quantities of crop residues could be utilized as fertilizer, fodder or industrial raw materials (Sun et al., 2021). On this basis, the forage level was improved and more animal-based foods were produced. A balanced dietary structure and reduction in food waste could lead to less pollution (Yue et al., 2017).

Table 2 lists the dynamic trends of agricultural indicators in China and Hebei Province from 2000 to 2015 at an interval of 5 years, considering the previous paper (Zhang et al., 2019). We found the same change trend between China and Hebei Province. The environmental stress index (ESI) and renewability index (RI) values decreased, and system transformity (STr), purchased resource yield ratio (PRYR), and environmental resource yield ratio (ERYR) increased to some extent; the economic investment ratio (EIR) was stable. Moreover, the indicators for China were inferior to those for Hebei Province. For example, the renewability index in China declined to 63.59% from 2000 to 2015, while that of Hebei Province reached 49.76%, showing that agriculture in Hebei Province is more modernized than that in China as a whole.

5. Concluding remarks

Extended exergy accounting (EEA) selects suitable parameters and

Table 2
Comparison of the agriculture indices in China and Hebei Province.

Index		China				Hebei Province			
		2000	2005	2010	2015	2000	2005	2010	2015
Renewability index	(RI)	57.62	46.54	40.76	36.64	31.17	24.23	18.64	15.51
Purchased resource yield ratio	(PRYR)	0.69	0.87	0.84	0.92	1.02	1.30	1.39	1.56
Exergy investment ratio	(EIR)	0.13	0.13	0.14	0.15	0.25	0.24	0.26	0.27
Environmental resource to yield ratio	(ERYR)	0.09	0.11	0.11	0.13	0.22	0.27	0.33	0.37
Environmental resource index	(ESI)	56.92	50.07	43.98	37.77	32.42	26.59	19.92	17.09
System transformity	(STr)	0.08	0.10	0.10	0.11	0.18	0.22	0.27	0.30

introduces capital and labor flows. Accounting has certain deficiencies in capital operation, labor expenditure, and environmental remediation. Different from former studies quantifying labor in monetary terms, this study defines the extended exergetic content of labor through the exchange of labor and goods (Meng et al., 2022). Capital in reality is not just labor wages. The accounting method for capital and labor does not account for situations such as monetary overspending, which may lead to uncertainty for capital flows. The resources exergy analysis is based on the second law thermodynamics, while exergoeconomics is basically a "parallel" cost assignment process considering the supply chain of economy that is not following the thermodynamic rules (Rocco et al., 2014).The emission accounting method could not estimate the toxicity of various pollutant discharges from a long-range time and space. Moever, the application of exergy has its weakness to uncover the real environmental impacts (Dewulf et al., 2008).

It is not wise to increase agricultural yields at the expense of the environment. A reasonable approach is to produce sustainable agricultural products by improving resource efficiency and reducing emissions. As a water-scarce area in China and with a higher population density than China as a whole, Hebei Province faces the challenge to generate more agricultural products under the constraints of resource and environmental capacity. In this paper, extended exergy accounting and indicators were employed to evaluate the thermodynamic presentation of agriculture in Hebei Province from 2000 to 2018, including kinds of inputs and yields. In summary, agricultural system is shifting from self-reliance to a greater dependence on energy costs, with lower renewability and environmental stress, higher non-renewable resource consumption, economic investment ratio and environmental emissions, reflecting that it is more modernized than that of the country as a whole. The purchased resource yield ratio, environmental resource yield ratio and system transformity reflected the increased resource depletion efficiency and agricultural production. Although the purchased non-renewable inputs were becoming essential, the sector depended on natural ecosystem resources still. Extended exergy accounting unifying different resources from the sustainability perspective proved to be a reliable tool to evaluate the resources, the environment and performance of agriculture in Hebei Province, which may provide a reference for conserving resources, reducing environmental impacts, and designing suitable agricultural practices in other areas or provinces.

CRediT authorship contribution statement

Hai Qi: Writing – original draft, Writing – review & editing. **Zhiliang Dong:** Methodology. **Xinshang You:** Supervision, Funding acquisition. **Yu Li:** Supervision, Formal analysis. **Yiran Zhao:** Supervision. **Xiaotian Sun:** Supervision.

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.

Data availability

I have shared the link to my data at the Attach file step

Acknowledgements

This study has been supported by The National Social Science Fund of China (Grant no. 17BGL202), Natural Science Foundation of Hebei Province (G2020208002), S&T Program of Hebei (22557616D).

References

Ahamed, J.U., Saidur, R., Masjuki, H.H., Mekhilef, S., Ali, M.B., Furqon, M.H., 2011. An application of energy and exergy analysis in agricultural sector of Malaysia. Energy Policy 39, 7922–7929.
Ahmadi, M.M., Keyhani, A., Rosen, M.A., Lam, S.S., Pan, J., Tabatabaei, M., Aghbashlo, M., 2022. Towards sustainable net-zero districts using the extended exergy accounting concept. Renew. Energy 197, 747–764.
Ayres, R.U., Ayres, L.W., Warr, B., 2003. Exergy, power and work in the US economy, 1900–1998. Energy 28, 219–273.
Biondi, A., 2022. A contribution to the search for a thermodynamics-based sustainability indicator: Extended Exergy Analysis of the Italian system (1990–2012) and comparison with other indicators. Energy 244, 123100.
Bligh, D.C., Ismet Ugursal, V., 2012. Extended exergy analysis of the economy of Nova Scotia, Canada. Energy 44, 878–890.
Brockway, P.E., Steinberger, J.K., Barrett, J.R., Foxon, T.J., 2015. Understanding China's past and future energy demand: An exergy efficiency and decomposition analysis. Appl. Energy 155, 892–903.
Bühler, F., Nguyen, T.-V., Elmegaard, B., 2016. Energy and exergy analyses of the Danish industry sector. Appl. Energy 184, 1447–1459.
Calvo, G., Valero, A., Valero, A., 2016. Material flow analysis for Europe: An exergoecological approach. Ecol. Ind. 60, 603–610.
Carmona, L.G., Whiting, K., Wiedenhofer, D., Krausmann, F., Sousa, T., 2021. Resource use and economic development: an exergy perspective on energy and material flows and stocks from. Resour. Conserv. Recycl. 165, 105226, 1900 to 2010.
Cay, 2001–2019.. China Agriculture Yearbook. China Statistical Publishing House, Beijing.
Cesy, 2001–2019.. China Energy Statistical Yearbook. China Statistical Publishing House, Beijing.
Cfy, 2001–2019.. China Forestry Yearbook. China Statistical Publishing House, Beijing.
Chen, B., Chen, G.Q., 2006. Exergy analysis for resource conversion of the Chinese Society 1993 under the material product system. Energy 31, 1115–1150.
Chen, B., Chen, G.Q., 2007a. Resource analysis of the Chinese society 1980–2002 based on exergy - Part 4: Fishery and rangeland. Energy Policy 35, 2079–2086.
Chen, B., Chen, G.Q., 2007b. Resource analysis of the Chinese society 1980–2002 based on exergy—Part 3: Agricultural products. Energy Policy 35, 2065–2078.
Chen, B., Chen, G.Q., Yang, Z.F., 2006. Exergy-based resource accounting for China. Ecol. Model. 196, 313–328.
Chen, G.Q., Chen, B., 2009. Extended-exergy analysis of the Chinese society. Energy 34, 1127–1144.
Chen, B., Dai, J., Sciubba, E., 2014. Ecological accounting for China based on extended exergy. Renew. Sustain. Energy Rev. 37, 334–347.
Chen, G.Q., Qi, Z.H., 2007. Systems account of societal exergy utilization: China 2003. Ecol. Model. 208, 102–118.
Chen, G.Q., Zhang, B., 2010. Greenhouse gas emissions in China 2007: Inventory and input–output analysis. Energy Policy 38, 6180–6193.
Chen, G.Q., Jiang, M.M., Yang, Z.F., Chen, B., Ji, X., Zhou, J.B., 2009. Exergetic assessment for ecological economic system: Chinese agriculture. Ecol. Model. 220, 397–410.
Clsy, 2001–2019.. China Labor statistical Yearbook. China Statistics Publishing House, Beijing.
CSY, 2001-2019. China Statistical Yearbook Beijing: China Statistics Publishing House.
Dai, J., Fath, B., Chen, B., 2012. Constructing a network of the social-economic consumption system of China using extended exergy analysis. Renew. Sustain. Energy Rev. 16, 4796–4808.
Dai, J., Chen, B., Sciubba, E., 2014. Extended exergy based ecological accounting for the transportation sector in China. Renew. Sustain. Energy Rev. 32, 229–237.

Deng, X., Gibson, J., Wang, P., 2017. Relationship between landscape diversity and crop production: a case study in the Hebei Province of China based on multi-source data integration. J. Clean. Prod. 142, 985–992.

Dewulf, J., Van Langenhove, H., Muys, B., Bruers, S., Bakshi, B.R., Grubb, G.F., Paulus, D. M., Sciubba, E., 2008. Exergy: Its Potential and Limitations in Environmental Science and Technology. Environ. Sci. Tech. 42, 2221–2232.

Dincer, I., Hussain, M.M., Al-Zaharnah, I., 2004a. Analysis of sectoral energy and exergy use of Saudi Arabia. Int. J. Energy Res. 28, 205–243.

Dincer, I., Hussain, M.M., Al-Zaharnah, I., 2004b. Energy and exergy use in public and private sector of Saudi Arabia. Energy Policy 32, 1615–1624.

Dincer, I., Hussain, M.M., Al-Zaharnah, I., 2004c. Energy and exergy utilization in transportation sector of Saudi Arabia. Appl. Therm. Eng. 24, 525–538.

Dincer, I., Hussain, M.M., Al-Zaharnah, I., 2005. Energy and exergy utilization in agricultural sector of Saudi Arabia. Energy Policy 33, 1461–1467.

DNRH, 2022. Regulations of Hebei Province on Land Administration. Department of Natural Resources of Hebei province (Oceanic Administration).

Ediger, V.Ş., Çamdalı, Ü., 2007. Energy and exergy efficiencies in Turkish transportation sector, 1988–2004. Energy Policy 35, 1238–1244.

Elliott, J., Deryng, D., Müller, C., Frieler, K., Konzmann, M., Gerten, D., Glotter, M., Flörke, M., Wada, Y., Best, N., Eisner, S., Fekete, B.M., Folberth, C., Foster, I., Gosling, S.N., Haddeland, I., Khabarov, N., Ludwig, F., Masaki, Y., Olin, S., Rosenzweig, C., Ruane, A.C., Satoh, Y., Schmid, E., Stacke, T., Tang, Q., Wisser, D., 2014. Constraints and potentials of future irrigation water availability on agricultural production under climate change. Proceedings of the National Academy of Sciences 111, 3239-3244.

Ertesvåg, I.S., 2005. Energy, exergy, and extended-exergy analysis of the Norwegian society 2000. Energy 30, 649–675.

Ertesvåg, I.S., Mielnik, M., 2000. Exergy analysis of the Norwegian society. Energy 25, 957–973.

Gabriel Carmona, L., Whiting, K., Valero, A., Valero, A., 2015. Colombian mineral resources: An analysis from a Thermodynamic Second Law perspective. Resour. Policy 45, 23–28.

Gasparatos, A., El-Haram, M., Horner, M., 2009. Assessing the sustainability of the UK society using thermodynamic concepts: Part 2. Renew. Sustain. Energy Rev. 13, 956–970.

Heun, M.K., Brockway, P.E., 2019. Meeting 2030 primary energy and economic growth goals: Mission impossible? Appl. Energy 251, 112697.

Hey, 2001–2019.. Hebei Economic Yearbook. China Statistical Publishing House, Beijing.

Huang, X., Feng, C., Qin, J., Wang, X., Zhang, T., 2022. Measuring China's agricultural green total factor productivity and its drivers during 1998–2019. Sci. Total Environ. 829, 154477.

Jaber, J.O., Al-Ghandoor, A., Sawalha, S.A., 2008. Energy analysis and exergy utilization in the transportation sector of Jordan. Energy Policy 36, 2995–3000.

Jadhao, S.B., Pandit, A.B., Bakshi, B.R., 2017. The evolving metabolism of a developing economy: India's exergy flows over four decades. Appl. Energy 206, 851–857.

Ji, X., Chen, G.Q., 2006. Exergy analysis of energy utilization in the transportation sector in China. Energy Policy 34, 1709–1719.

Koroneos, C.J., Nanaki, E.A., 2008. Energy and exergy utilization assessment of the Greek transport sector. Resour. Conserv. Recycl. 52, 700–706.

Koroneos, C.J., Nanaki, E.A., Xydis, G.A., 2011. Exergy analysis of the energy use in Greece. Energy Policy 39, 2475–2481.

Li, T., Wang, A., Xing, W., Li, Y., Zhou, Y., 2019. Assessing mineral extraction and trade in China from 1992 to 2015: A comparison of material flow analysis and exergoecological approach. Resour. Policy 63, 101460.

Li, Z., Zhou, Y., Li, K., Xiao, H., Cai, Y., 2021. The spatial effects of city-level water-energy nexus: A case study of Hebei Province, China. J. Clean. Product. 310, 127497.

Meng, Z., Jin, P., Wu, X., Zhang, B., Gao, J., 2022. An improved extended exergy accounting method for assessing the sustainability of the Chinese society. J. Clean. Prod. 354, 131739.

Mosquim, R.F., Keutenedjian Mady, C.E., 2021. Design, performance trends, and exergy efficiency of the Brazilian passenger vehicle fleet: 1970–2020. J. Clean. Prod. 290, 125788.

Nakicenovic, N., Gilli, P.V., Kurz, R., 1996. Regional and global exergy and energy efficiencies. Energy 21, 223–237.

Nielsen, S.N., Jørgensen, S.E., 2015. Sustainability analysis of a society based on exergy studies – a case study of the island of Samsø (Denmark). J. Clean. Prod. 96, 12–29.

Pacheco-Rojas, D.A., Leon-De-Los-Santos, G., MartÍN-Del-Campo, C., 2022. Exergy analysis of the Mexican energy sector. Sustainable Energy Technol. Assess. 53, 102540.

Palacios, J.-L., Calvo, G., Valero, A., Valero, A., 2018. The cost of mineral depletion in Latin America: An exergoecology view. Resour. Policy 59, 117–124.

Piao, S., Ciais, P., Huang, Y., Shen, Z., Peng, S., Li, J., Zhou, L., Liu, H., Ma, Y., Ding, Y., Friedlingstein, P., Liu, C., Tan, K., Yu, Y., Zhang, T., Fang, J., 2010. The impacts of climate change on water resources and agriculture in China. Nature 467, 43–51.

Qi, H., Dong, Z., Dong, S., Sun, X., Zhao, Y., Li, Y., 2021. Extended exergy accounting for smelting and pressing of metals industry in China. Resour. Policy 74, 102267.

Rocco, M.V., Colombo, E., Sciubba, E., 2014. Advances in exergy analysis: a novel assessment of the Extended Exergy Accounting method. Appl. Energy 113, 1405–1420.

Saidur, R., Sattar, M.A., Masjuki, H.H., Abdessalam, H., Shahruan, B.S., 2007. Energy and exergy analysis at the utility and commercial sectors of Malaysia. Energy Policy 35, 1956–1966.

Sciubba, E., 2011. A revised calculation of the econometric factors α- and β for the Extended Exergy Accounting method. Ecol. Model. 222, 1060–1066.

Seckin, C., Sciubba, E., Bayulken, A.R., 2012. An application of the extended exergy accounting method to the Turkish society, year 2006. Energy 40, 151–163.

Seckin, C., Sciubba, E., Bayulken, A.R., 2013. Extended exergy analysis of Turkish transportation sector. J. Clean. Prod. 47, 422–436.

Sun, H., Wang, E., Li, X., Cui, X., Guo, J., Dong, R., 2021. Potential biomethane production from crop residues in China: Contributions to carbon neutrality. Renew. Sustain. Energy Rev. 148, 111360.

Szargut, J., Ziębik, A., Stanek, W., 2002. Depletion of the non-renewable natural exergy resources as a measure of the ecological cost. Energ. Conver. Manage. 43, 1149–1163.

Tan, L.M., Arbabi, H., Brockway, P.E., Densley Tingley, D., Mayfield, M., 2019. An ecological-thermodynamic approach to urban metabolism: Measuring resource utilization with open system network effectiveness analysis. Appl. Energy 254, 113618.

Utlu, Z., Hepbasli, A., 2005. Analysis of energy and exergy use of the Turkish residential-commercial sector. Build. Environ. 40, 641–655.

Utlu, Z., Hepbasli, A., 2007. A review on analyzing and evaluating the energy utilization efficiency of countries. Renew. Sustain. Energy Rev. 11, 1–29.

Valero, A., Carpintero, Ó., Valero, A., Calvo, G., 2014. How to account for mineral depletion. The exergy and economic mineral balance of Spain as a case study. Ecol. Ind. 46, 548–559.

Wall, G., Sciubba, E., Naso, V., 1994. EXERGY USE IN THE ITALIAN SOCIETY. Energy 19, 1267–1274.

Wall, 1977. Exergy —a useful concept within resource accounting. Research Report . Göteborg, Sweden: Institute of Theoretical Physics, 77–42.

Warr, B.S., Ayres, R.U., 2010. Evidence of causality between the quantity and quality of energy consumption and economic growth. Energy 35, 1688–1693.

Warr, B., Schandl, H., Ayres, R.U., 2008. Long term trends in resource exergy consumption and useful work supplies in the UK, 1900 to 2000. Ecol. Econ. 68, 126–140.

Xie, L., Xue, Q., Yuan, Z., 2019. Composition and spatial difference of agro-industry carbon footprint in Hebei province, North China. Ecol. Ind. 97, 141–149.

Yang, J., Chen, B., 2014. Extended exergy-based sustainability accounting of a household biogas project in rural China. Energy Policy 68, 264–272.

Yue, Q., Xu, X., Hillier, J., Cheng, K., Pan, G., 2017. Mitigating greenhouse gas emissions in agriculture: From farm production to food consumption. J. Clean. Prod. 149, 1011–1019.

Zhang, B., Chen, G.Q., 2010. Physical sustainability assessment for the China society: Exergy-based systems account for resources use and environmental emissions. Renew. Sustain. Energy Rev. 14, 1527–1545.

Zhang, B., Chen, G.Q., 2014a. China's CH_4 and CO_2 emissions: Bottom-up estimation and comparative analysis. Ecol. Ind. 47, 112–122.

Zhang, B., Chen, G.Q., 2014b. Methane emissions in China 2007. Renew. Sustain. Energy Rev. 30, 886–902.

Zhang, B., Chen, G.Q., Xia, X.H., Li, S.C., Chen, Z.M., Ji, X., 2012. Environmental emissions by Chinese industry: Exergy-based unifying assessment. Energy Policy 45, 490–501.

Zhang, B., Meng, Z., Zhang, L., Sun, X., Hayat, T., Alsaedi, A., Ahmad, B., 2018. Exergy-based systems account of national resource utilization: China 2012. Resour. Conserv. Recycl. 132, 324–338.

Zhang, B., Jin, P., Qiao, H., Hayat, T., Alsaedi, A., Ahmad, B., 2019. Exergy analysis of Chinese agriculture. Ecol. Ind. 105, 279–291.

Zhang, Q.-T., Xia, Q., Liu, C.C.K., Geng, S., 2013. Technologies for Efficient Use of Irrigation Water and Energy in China. J. Integr. Agric. 12, 1363–1370.

Zhang, X.-H., Zhang, R., Wu, J., Zhang, Y.-Z., Lin, L.-L., Deng, S.-H., Li, L., Yang, G., Yu, X.-Y., Qi, H., Peng, H., 2016. An emergy evaluation of the sustainability of Chinese crop production system during 2000–2010. Ecol. Ind. 60, 622–633.

Zhou, S.Y., Zhang, B., Cai, Z.F., 2010. Emergy analysis of a farm biogas project in China: A biophysical perspective of agricultural ecological engineering. Commun. Nonlinear Sci. Numer. Simul. 15, 1408–1418.