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Trends in the economic return on energy use and energy use efficiency in China's crop production

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ABSTRACT

This study examines trends in energy input and output in China's crop production. Trends are also observed in energy use efficiency and economic return on energy use from 1991 to 2012. The results indicate that energy input increased from 3647.1 PJ to 7919.5 PJ and energy output increased from 7222.0 PJ to 10954.0 PJ between 1991 and 2012. Given the growth in the sowing area, energy input and output per unit of area sown also increased during this period. Energy use efficiency was estimated at 1.98 in 1991 and 1.38 in 2012, with an average annual decrease of 1.69%. The economic return on crop production in China increased from 1991 to 2012 whereas agricultural labor input decreased; consequently, the economic return on energy use, sowing area, and labor all increased stably. Given a larger growth rate and higher production of high-value and low-energy crops when compared with low-value and high-energy crops, an increase in the economic return on energy use occurred but so did a decline in energy use efficiency. This phenomenon indicates the need to increase investments in technological development and technological innovation, adopt new policies to optimize China's crop production structure, and establish sustainable production systems.

1. Introduction

Crop production depends on energy inputs, and the efficient use of resources is a key part of efficient and sustainable production [1]. Recently, however, energy use in agriculture has been increasing in response to a growing population, limited supply of arable land, and desire for higher standards of living [2]. Continuous demand for increasing food production has resulted in intensive use of diesel, electricity, human labor, farm machinery, fertilizers, pesticides, and agricultural plastics-based energy resources in both developed and developing countries [3].

In transitioning countries such as China, agricultural growth is essential for promoting economic development and meeting the ever-growing demands of a growing population. Indeed, China must feed 20% of the global population using approximately 5% of the planet's water resources and 7% of its arable land [4]. Thus, China has spared no effort in pursuing national food security as a means of advancing economic development and maintaining social stability. Consequently, the output of grain increased from 277.1 million tons (MT) in 1978 to 552.7 MT in 2013; the output of beans increased from 12.5 MT in 1991 to 16.0 MT in 2013; tuber crop production increased from 9.8 MT in 1949 to 33.3 MT in 2013; cotton production climbed from 0.4 MT in 1949 to 6.3 MT in 2013; oilseed production increased from 2.6 MT in 1949 to 35.2 MT in 2013; sugar beet output increased from 2.9 MT in 1949 to 137.5 MT in 2013; tea production increased from 0.3 MT in 1978 to 1.9 MT in 2013; tobacco production increased from 0.5 MT in 1970 to 3.4 MT in 2013; vegetable production climbed from 204.1 MT in 1991 to 735.1 MT in 2013; and fruit output increased from 21.8 MT in 1991 to 250.9 MT in 2013 [5–7]. Meanwhile, during the period 1978–2012, the nominal economic return on crop production increased at an average annual growth rate of 9.3%, whereas the real economic return (REcR) (based on 1978 constant prices) on crop production increased at an average annual growth rate of 3.9% [8]. This marked achievement can largely be attributed to growth in agronomic inputs, namely, the use of chemical fertilizers, electricity, and total agricultural machinery power, which increased by factors of 5.68, 32.33, and 7.82, respectively, from 1978 to 2013. Meanwhile, the consumption of diesel, pesticides, and agricultural plastic film increased by factors of 1.43, 1.36, and 2.83, respectively, from 1991 to 2012 [5,7,8]. However, intensive energy input can harm public health and the environment. For example, overuse of chemical fertilizers often results in decreased economic return on crop production [9], significant acidification of major croplands [10], greenhouse gas emissions [11], and damage to water quality and aquatic ecosystems [12].

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Energy input in agriculture is very intensive and directly and indirectly uses large quantities of energy. Therefore, the availability of natural resources has rapidly decreased, whereas the level of contamination has increased. Energy input has been discussed given its effect on carbon emissions [13–15], biological diversity [16,17], and human health [18,19]. The best way to lessen the environmental threat posed by energy use is to increase energy use efficiency (EUE). The efficient use of energy in agriculture helps increase production and productivity, provides financial savings, minimizes negative environmental impacts, helps protect natural resources, and promotes the sustainable development of agricultural ecosystems [20,21]. Agriculture and energy have very close relationship: agriculture both produces and consumes energy, and agriculture and energy use are complementary and mutually affect one another [22,23].

Energy analysis of agricultural production systems is a promising approach to study and investigate trends in energy input, EUE, and long-term sustainability [24,25]. In recent decades, China has made remarkable strides toward increasing crop production and enhancing food security. Furthermore, the Chinese government has introduced a series of polices to adjust its crop production. From 1985 to 1998, the Chinese government attempted to promote the marketing of agricultural products [26]. Subsequently, the central government withdrew from managing national cereal production and storage from 1999 to 2003 [27] and started to encourage crop production by introducing the first nationwide direct subsidies for farmers in 2004, including subsidized seed and machinery purchases, and increased spending on rural infrastructure. The policy was very important in reducing agricultural production costs, increasing food farmers' income and promoting food production [28]. Another visible measure was the elimination of agricultural taxes in 2006 [29], China has had an agricultural tax throughout its recorded history. Typically, Chinese farmers were assessed an agricultural tax on the basis of each family's allotted land area and historical average price and yield before 2006 [30]. Patterns and trends in crop production were studied within particular social and economic environments; however, given the availability and quality of the statistical data and the level of concern for yields as opposed to energy, no study has yet evaluated patterns and trends in energy input, energy output, and EUE in China's agriculture sector from 1991 to 2012.

Many studies have undertaken an energy and economic analysis to examine energy output-input relationships and to investigate the processes involved with production of certain crops, such as wheat, cotton, beans, and potatoes in India [31–33], wheat, maize, and beans in Italy [34], rice and wheat in Bangladesh [35–37], cotton, sugar beet, and apricots in Turkey [38–40], and rice in Iran [41], the Philippines [42], and China [43]. In addition, several studies have focused on EUE in crop production systems in India [20,44], Turkey [45], and Greece [46].

As such, this study aims to investigate the interactions among energy input, energy output, EUE, and economic output in China's crop production system. Using a series of indicators, we seek to reveal the relationships between them and to: (1) analyze levels and trends in energy input and output in China's crop production system from 1991 to 2012; (2) identify the trend in economic return on energy use within this system in the study period; and (3) evaluate trends in EUE, energy productivity (EP), and net energy(NE) in China's crop production.

2. Materials and methods

2.1. Data

The analysis focuses on calculating the amount of inputs used for the production of agricultural crops and crop yields per year from 1991 to 2012. The investigation starts in 1991 with the availability of national-level data on input amounts. The data used were obtained from the China Statistical Yearbook [47], the China Agricultural Yearbook [5], the China Agriculture Statistical Report [6], the New China's agricultural statistics for 60 years [7], and the databases of National Bureau of Statistics (NBS) [8] and Ministry of Agriculture (MOA) [48]. The study also benefited from previous research and studies on energy analysis in agriculture.

2.2. Data analysis methods

The energy input in crop production system was divided into direct and indirect energy [49]. Direct energy includes diesel, electricity, and human labor [50], whereas indirect energy consists of the energy embedded in the manufacturing processes for farm machinery, fertilizers, pesticides, and agricultural plastic film [51]. Energy requirements in agriculture could also be divided into two groups, renewable and nonrenewable. In terms of the renewability of electricity, the electricity used in China's crop production mainly comes from hydroelectric and thermal sources. The shares of hydroelectricity and thermal electricity in electricity production were 20% and 80%, respectively, during the study period [47]. Nonrenewable energy includes diesel, thermal electricity, and energy consumed to manufacture farm machinery, fertilizers, pesticides, and agricultural plastic film, whereas renewable energy consists of human labor and hydroelectricity [52]. Energy output is calculated from statistics on the total production of cereals, beans, tubers, cotton, oilseeds, sugar beet, tea, hemp, tobacco, vegetables, and fruits (including all major crops grown in China). To calculate energy input, output and other energy indicators, the data were converted into energy input and output levels using equivalent energy values for each commodity. Table 1 provides the energy equivalents for inputs and outputs.

2.3. Key indicators

Energy systems drive the development of crop production systems, and crop production can also provide raw materials for energy production. Thus, many researchers have explored the relationship between the energy system and the crop production system [45], with some indicators adopted to investigate the relationship. These indicators serve two different purposes: structural indicators aim at clarifying the management and conversion of inputs into outputs for a given crop or cropping system, and efficiency indicators aim at evaluating the

Table 1
Energy equivalents for different inputs and outputs in crop production.

Item	Unit	Energy equivalent MJ Unit^{-1}	Reference
Inputs			
Nitrogen (N)	kg	66.14	[70,71]
Phosphorus (P_2O_5)	kg	12.44	[70,71]
Potassium (K_2O)	kg	11.15	[72]
Compound fertilizer	kg	12.83	[73]
Human labor	h	2.20	[73]
Diesel	L	56.31	[74,75]
Pesticide	kg	303.80	[76]
Electricity	kWh	3.60	[77]
Plastic film	kg	79.00	[78]
Machinery	kW	4.93	[73]
Outputs			
Cereals and pulses	kg	14.70	[45]
Oilseed	kg	25.00	[45]
Sugar beet	kg	5.04	[45]
Beans	kg	14.70	[79]
Tubers	kg	3.60	[45]
Cotton	kg	11.80	[45]
Vegetables	kg	0.80	[45]
Fruits	kg	1.90	[45]
Tobacco	kg	0.80	[45]
Hemp	kg	18.50	[80]
Tea	kg	0.80	[45]

Table 2
Energy use efficiency related indicators in crop production.

Item	Abbreviation	Unit	Calculation	Note	Reference
Energy input per unit sowing area	EIPA	GJ ha^{-1}	Energy input/Sowing area		
Energy output per unit sowing area	EOPA	GJ ha^{-1}	Energy output/Sowing area		
Energy use efficiency	EUE		Energy output/Energy input		[81–84]
Net energy	NE	PJ	Energy output-Energy input		[84,85]
Energy productivity	EP	kg GJ^{-1}	Crop production/Energy input		[86]
Energy output per unit labor	EOPL	GJ $labor^{-1}$	Energy output/Labor force in crop production		
Nominal economic return in crop production	NEcR	Yuan			
Real economic return in crop production	REcR	Yuan		Taken inflation into consideration, 1978 was selected as the base year, GDP was set to 100 Yuan in 1978	[87]
Nominal economic return on energy use	NEcRE	Yuan GJ^{-1}	NEcR in crop production / Energy input		
Real economic return on energy use	REcRE	Yuan GJ^{-1}	REcR in crop production / Energy input	To eliminate the impact of inflation on economic return	[87]
Nominal economic returns per unit sowing area	NEcRA	Yuan ha^{-1}	NEcR in crop production/Sowing area		
Real economic return per unit sowing area	REcRA	Yuan ha^{-1}	REcR in crop production/Sowing area	To eliminate the impact of inflation on economic return	[87]
Nominal economic return per unit labor	NEcRL	Yuan $labor^{-1}$	NEcR in crop production/Labor force in crop production		
Real economic return per unit labor	REcRL	Yuan $labor^{-1}$	REcR in crop production/Labor force in crop production	To eliminate the impact of inflation on economic return	[87]

efficiency of transforming input energy into outputs [53]. Thus we adopted some EUE-related indicators to depict patterns and trends in energy consumption, energy output, and EUE in China's crop production. Furthermore, the economic return, energy input, output, and other indicators were calculated annually for the crop production system. Table 2 provides the procedures that were followed.

3. Results

3.1. Energy input

Total energy input increased from 3647.1 PJ in 1991 to 7919.5 PJ in 2012, with an average annual increase of 3.76% during the study period (Fig. 1(A)). For the direct energy categories, energy inputs of diesel oil and electricity increased at average annual growth rates of 4.32% and 1.27% (Fig. 1(B)), respectively. However, the energy consumed through labor decreased from 1073.1 PJ in 1991 to 848.5 PJ in 2012, with an average annual decline of 1.11%. Considering the indirect energy categories, energy inputs through farm machinery, fertilizers, pesticides, and agricultural plastic film increased at average annual growth rates of 9.77%, 2.22%, 4.17%, and 6.44%, respectively (Fig. 1(B)). The share of total energy input consumed in the form of labor decreased from 28.2% in 1991 to 10.4% in 2012. Thus, the results imply that the development of China's crop production decreased human energy input but increased the level of mechanization and the use of energy-intensive inputs.

Indirect energy input increased from 1659.8 PJ in 1991 to 2987.9 PJ in 2012, at an average annual growth rate of 2.84%. Meanwhile, direct energy input increased from 1987.3 PJ in 1991 to 4931.7 PJ in 2012, with an average annual growth rate of 4.42%. The share of total energy input that was direct energy increased from 54.5% in 1991 to 62.2% in 2012. Thus, an increase of 8 percentage points occurred in the ratio of direct energy input to total energy input, with the increase in total energy input being primarily driven by growth in the use of direct energy (Fig. 1(C)).

Nonrenewable energy input increased by a factor of 1.61, and from 68.7% to 82.5% as a percentage of the total energy input, during the investigation period (Fig. 1(D)). This result indicates that China's crop production became increasingly dependent on nonrenewable energy, the input of which increased from 2504.7 PJ in 1991 to 6530.4 PJ in 2012, at an average annual growth rate of 4.67%. The average annual growth rate of renewable energy was only 0.94%, suggesting that the energy use structure may need to be adjusted.

3.2. Energy input per unit sowing area

Energy input per unit sowing area (EIPA) increased from 24.7 GJ ha^{-1} in 1991 to 47.1 GJ ha^{-1} in 2012, at an average annual growth rate of 3.11% (Fig. 2(A)). The energy input in the form of different agricultural supplies excluding labor increased significantly during this time, with electricity and farm machinery having the highest annual growth rates, followed by agricultural plastic film, diesel oil, pesticides, and fertilizers (Fig. 2(B)).

The direct EIPA increased at an average annual growth rate of 3.77%, from 13.5 GJ ha^{-1} in 1991 to 21.3 GJ ha^{-1} in 2012, whereas the indirect EIPA increased from 11.3 GJ ha^{-1} in 1991 to 17.8 GJ ha^{-1} in 2012 (Fig. 2(C)). Furthermore, the ratio of nonrenewable EIPA to total EIPA increased from 68.7% to 82.5%, at an average annual increase of 4.01%. Meanwhile, renewable EIPA only increased from 7.7 GJ ha^{-1} to 8.3 GJ ha^{-1} during the period, at an average annual growth rate of 0.30% (Fig. 2(D)).

3.3. Energy output and energy output per unit sowing area

Given the increased energy input for China's crop production, energy output also increased gradually, from 7222.0 PJ in 1991 to

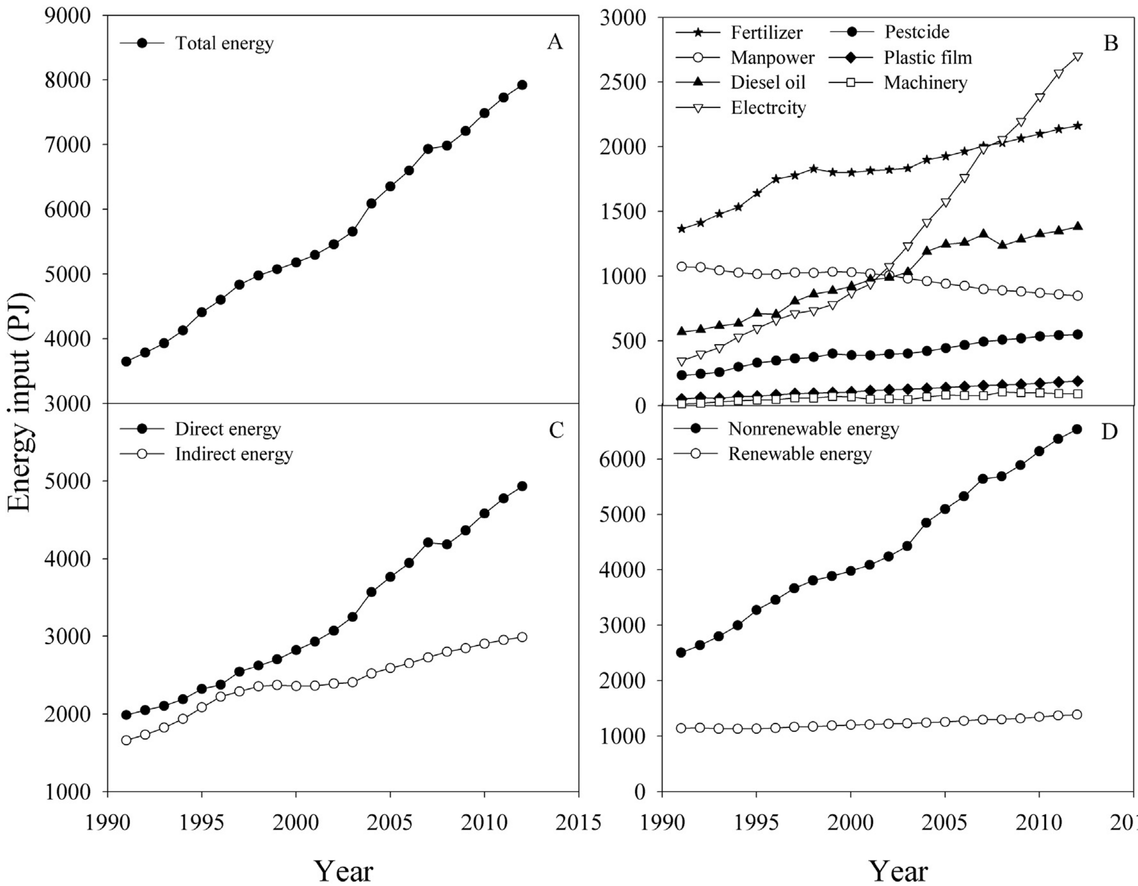

Fig. 1. Trends in (A) total energy input, (B) different categories of energy inputs, (C) direct and indirect energy inputs, and (D) nonrenewable and renewable energy inputs (PJ) in China's crop production, 1991–2012.

10,954.0 PJ in 2012 (Fig. 3(A)), at an average annual growth rate of 2.00%. The energy output increased from 1991 to 1998, declined from 1999 to 2003, and then continued to increase from 2004. Energy output per unit sowing area (EOPA), indicating the system's energy output intensity attributable to energy use, increased from 49.0 GJ ha^{-1} in 1991 to 65.1 GJ ha^{-1} in 2012, at an average annual growth rate of 1.36% (Fig. 3(B)).

3.4. Energy use efficiency and related parameters

In this study, EUE, also referred to as the energy output-input ratio, was calculated using the energy consumption associated with the use of diesel oil, electricity, human labor, farm machinery, fertilizers, pesticides, and agricultural plastic film for crop production and its byproducts. As Table 3 shows, EUE declined from 1.98 in 1991 to 1.38 in 2012, at an average annual decrease of 1.69%. Furthermore, EUE sharply declined, at an average annual decrease of 2.46% during the period 1991–2007, and changed little from 2008 to 2012.

Net energy (NE) decreased from 3574.9 PJ in 1991 to 3034.4 PJ in 2012, at an average annual decrease of 0.78% (Table 3). From 1991–2007, the NE rapidly declined at an average rate of 2.75% per year; subsequently, the NE showed a slowly increasing trend. Energy productivity (EP) fluctuated throughout the period 1991–2012 (Table 3), and the average EP was 212.5 kg GJ^{-1}. The results indicate that no significant change occurred in the amount of energy input to achieve a given amount of crop production, as expressed per unit of weight.

During the period studied, the size of the labor force in crop production decreased by 20.9%, at an average annual decrease of 1.11%. Given this decrease and the increase in energy output, energy output per unit labor (EOPL) increased from 21.1 GJ $labor^{-1}$ to 40.5 GJ $labor^{-1}$ from 1991 to 2012, with an average annual increase of 3.15% (Table 3). This result suggests that the productivity of China's crop production system rapidly increased during this period.

3.5. Economic output and economic return on energy use

As Table 4 shows, the nominal economic return (NEcR) on China's crop production increased from 498.1×10^9 Yuan to 4694.1×10^9 Yuan, at an average annual growth rate of 11.27% during the investigation period. To eliminate the impact of inflation on economic return, a real economic return (REcR) index was used, and 1978 was selected as the base year, as suggested by the NBS (i.e., gross domestic product was set to 100 Yuan in 1978). This index of REcR on China's crop production increased from 80.3 Yuan to 231.3 Yuan, at an average annual growth rate of 5.17% during the study period (Table 5).

The nominal economic return on energy use (NEcRE) in crop production increased from 136.6 Yuan GJ^{-1} in 1991 to 592.7 Yuan GJ^{-1} in 2012, at an average annual growth rate of 7.24%. NEcRE was relatively stable from 1996 to 2003 (Table 4). These results suggest that the NEcRE in China's crop production system increased gradually, except for the period 1996–2013. The real economic return on energy use (REcRE) allows for an evaluation of the trend in the real economic output of energy consumption after eliminating the effects of inflation. The trend (rather than the value) in the REcRE reflects the actual situation more realistically than dose NEcRE. The REcRE increased at an average annual growth rate of 1.35% during the study period (Table 5). From 1991 to 1993, the REcRE decreased slightly, and then increased until 1996; subsequently, REcRE fluctuated between 1997 and 2002, and then increased from 2003. Overall, REcRE in China's crop production increased from 1991 to 2012, as the economic output and economic return on energy

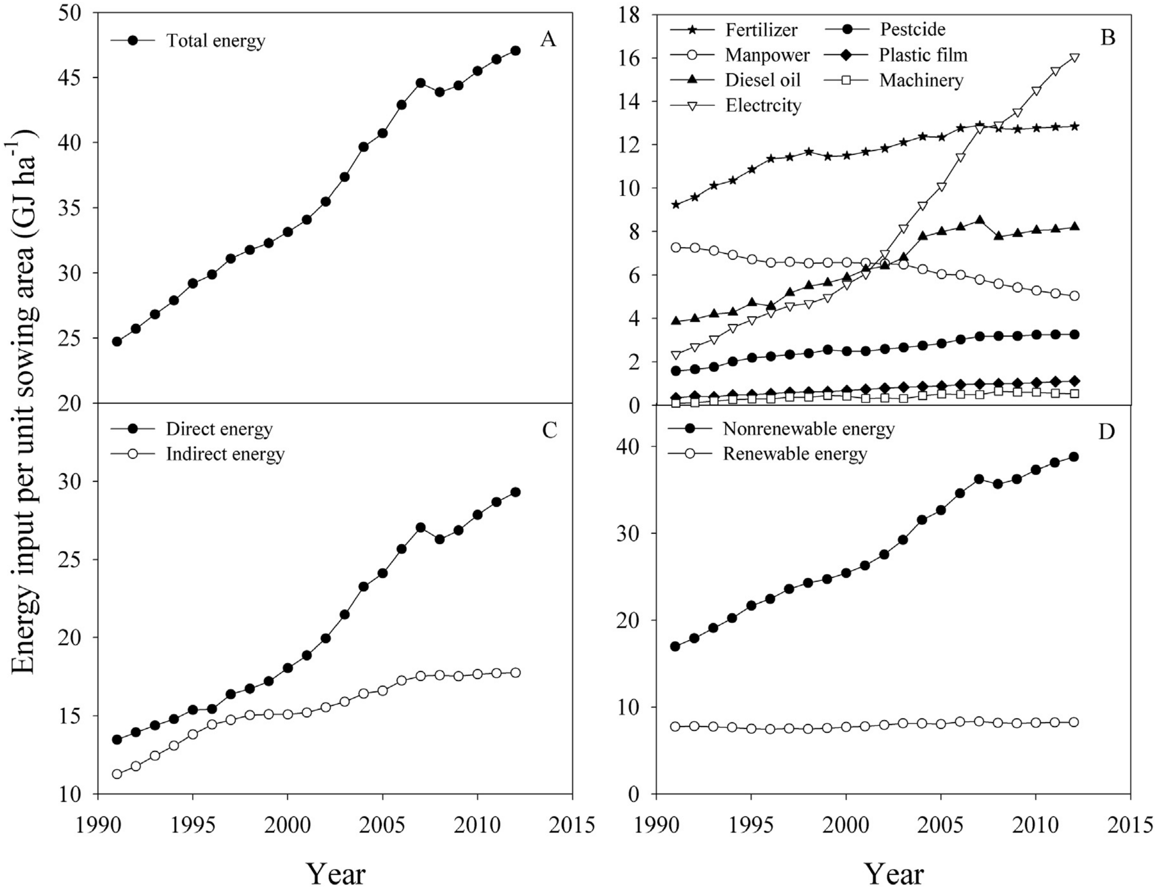

Fig. 2. Trends in (A) total energy input per unit sowing area, (B) different categories of energy inputs per unit sowing area, (C) direct and indirect energy inputs per unit sowing area, and (D) nonrenewable and renewable energy inputs per unit sowing area (GJ ha^{-1}) in China's crop production, 1991–2012.

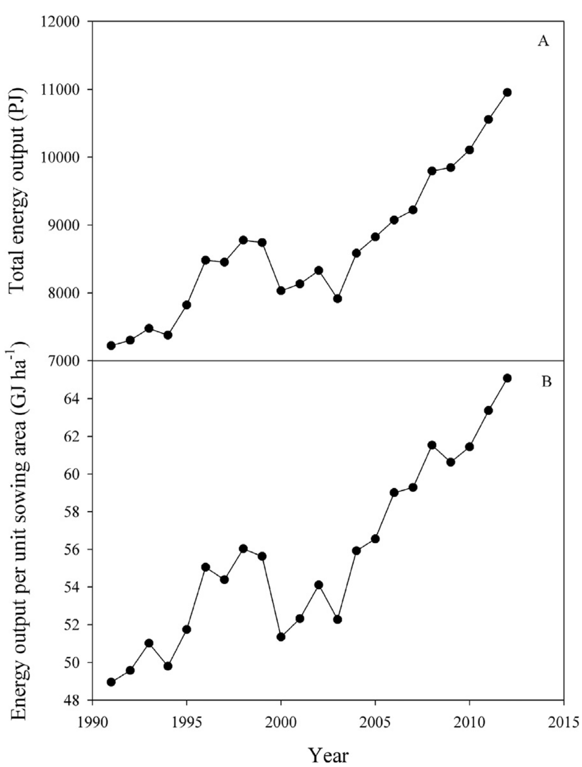

Fig. 3. Trends in (A) energy output (PJ) and (B) energy output per unit sowing area (GJ ha^{-1}) in China's crop production, 1991–2012.

Table 3
The energy use efficiency (EUE), net energy (NE), energy productivity (EP), and energy output per unit labor (EOPL) in China's crop production from 1991 to 2012.

Year	EUE	NE PJ	EP kg GJ^{-1}	EOPL GJ labor^{-1}
1991	1.98	3574.9	211.6	21.1
1992	1.93	3515.9	198.1	21.4
1993	1.90	3546.7	201.1	22.5
1994	1.79	3248.4	191.5	22.6
1995	1.77	3411.2	198.8	24.2
1996	1.84	3878.8	219.1	26.3
1997	1.75	3619.9	221.2	25.9
1998	1.76	3799.9	227.5	26.9
1999	1.72	3667.6	226.1	26.6
2000	1.55	2849.8	202.0	24.5
2001	1.54	2837.5	225.9	25.1
2002	1.53	2869.6	232.7	26.0
2003	1.40	2258.7	221.0	25.3
2004	1.41	2496.5	215.3	28.1
2005	1.39	2472.0	211.8	29.4
2006	1.38	2476.3	204.9	30.8
2007	1.33	2287.6	202.9	32.2
2008	1.40	2812.8	213.2	34.5
2009	1.37	2638.1	210.7	35.1
2010	1.35	2622.5	210.4	36.5
2011	1.37	2826.5	213.3	38.6
2012	1.38	3034.4	217.2	40.5

use increased in tandem with the intensive input of agricultural supplies.

The nominal economic return per unit sowing area (NEcRA) increased from 3376.9 Yuan ha^{-1} to 27,886.6 Yuan ha^{-1}, at an annual growth rate of 10.58%. The real economic return per unit sowing area

Table 4
The nominal economic return (NEcR), nominal economic return on energy use (NEcRE), nominal economic return per unit sowing area (NEcRA), and nominal economic return per unit labor (NEcRL) in China's crop production from 1991 to 2012.

Year	NEcR $\times10^9$ Yuan	NEcRE Yuan GJ^{-1}	NEcRA Yuan ha^{-1}	NEcRL Yuan $labor^{-1}$
1991	498.1	136.6	3376.9	1457.1
1992	539.8	142.6	3665.9	1585.9
1993	636.6	162.1	4344.9	1914.1
1994	871.8	211.2	5886.8	2666.7
1995	1123.8	254.8	7436.5	3475.6
1996	1307.3	284.2	8488.1	4052.4
1997	1344.2	278.1	8650.0	4113.5
1998	1374.3	276.2	8774.9	4212.3
1999	1410.7	278.0	8976.0	4286.2
2000	1387.4	267.8	8872.0	4230.1
2001	1446.3	273.1	9305.4	4456.8
2002	1493.2	273.5	9701.6	4667.5
2003	1487.0	263.0	9823.8	4757.0
2004	1813.8	298.0	11,817.6	5928.3
2005	1961.3	308.8	12,570.5	6543.1
2006	2152.2	326.2	13,996.3	7315.9
2007	2465.8	355.6	15,855.1	8609.5
2008	2804.4	401.6	17,616.6	9887.4
2009	3061.1	424.7	18,849.0	10,907.1
2010	3694.1	493.5	22,455.2	13,338.7
2011	4198.9	543.4	25,206.9	15,349.3
2012	4694.0	592.7	27,886.6	17,364.6

Table 5
The real economic return (REcR), real economic return on energy use (REcRE), real economic return per unit sowing area (REcRA), and real economic return per unit labor (REcRL) in China's crop production from 1991 to 2012.

Year	REcR Yuan	REcRE Yuan GJ^{-1}	REcRA $\times10^{-9}$ Yuan ha^{-1}	REcRL $\times10^{-9}$ Yuan $labor^{-1}$
1991	80.3	2.20	544.4	234.9
1992	80.2	2.12	544.7	235.6
1993	81.5	2.07	556.2	245.1
1994	90.8	2.20	613.2	277.8
1995	102.0	2.31	675.0	315.5
1996	110.7	2.41	718.8	343.2
1997	110.6	2.29	711.9	338.5
1998	113.9	2.29	727.2	349.1
1999	119.3	2.35	759.2	362.5
2000	114.9	2.22	734.6	350.2
2001	118.2	2.23	760.5	364.2
2002	122.4	2.24	795.0	382.5
2003	118.8	2.10	785.1	380.2
2004	137.2	2.25	893.6	448.3
2005	144.5	2.27	926.1	482.0
2006	154.6	2.34	1005.7	525.7
2007	157.7	2.27	1014.2	550.7
2008	165.8	2.37	1041.5	584.6
2009	183.5	2.55	1129.9	653.8
2010	204.9	2.74	1245.7	739.9
2011	212.0	2.74	1272.6	774.9
2012	231.3	2.92	1374.1	855.6

(REcRA) increased from 544.4×10^{-9} Yuan ha^{-1} in 1991 to 1374.1×10^{-9} Yuan ha^{-1} in 2012, at an average annual growth rate of 4.51% (Table 4). After considering the decline in labor in China's crop production, the nominal economic return per unit labor (NEcRL) increased from 1457.1 Yuan $labor^{-1}$ in 1991 to 17,364.6 Yuan $labor^{-1}$ in 2012, at an average annual increase rate of 12.52%. during this period, the real economic return per unit labor (REcRL) increased at an average annual growth rate only of 6.35% (Table 5).

In summary, energy input and output increased stably with growth in China's crop production from 1991 to 2012. Given the increase in sowing area, the energy input and output per unit sowing area also increased over time. EUE declined from 1991 to 2012, and EP changed little. The NE and EOPL showed steady increases. The economic return on energy use, sowing area, and labor all showed steady growth. However, the increasing trend in economic return on energy use was accompanied by a decline in the EUE of China's crop production.

4. Discussion

The data used in this study were mainly taken from the databases and publications of the MOA and the NBS, and the quality of the data improved significantly with the development of legal norms and procedures governing China's statistical work [54]. Thus, in this study, we obtained several interesting results using such uniquely rich data.

This study focused on the evaluation of energy input, output and use efficiency in China's crop production; therefore, we defined the cropland as the boundary of the energy analysis [55,56], and solar energy was not considered in total energy input. Furthermore, solar energy alone is such a significant amount that its consideration in the energy analysis would mask any other energy inputs previously referred [57]. Our analysis of EUE in China's crop production revealed that, given higher growth in energy input than energy output, EUE declined tremendously. During this study period, the energy consumed by China's crop production systems was mainly in the form of direct energy. Before 2002, direct energy input was primarily composed of labor; subsequently, electricity became the main component. The share of electricity in total direct energy input increased from 17.4% to 54.8%, whereas the share of labor decreased from 54.0% to 17.2% (the share of diesel oil was stable at 30.7% during the investigation period). The decline in the ratio of labor to total energy input may have resulted from the agricultural mechanization effort led by the Chinese government that started in 1978 [58], when the MOA and Ministry of Finance subsidized the purchase of agricultural machinery [59]. Meanwhile, the shares of pesticide, plastic film, and agricultural machinery in total energy input increased from 1991 to 2012 because of a sharp increase in the use of these products [60,61].

EP fluctuated between 1991 and 2012, indicating that the production output intensity of the system from the energy consumption of crop production remained relatively stable. Meanwhile, the NEcRE, which reflects the nominal economic return per unit of energy used in crop production, increased at an average annual growth rate of 7.24%. Considering inflation, the REcRE also increased during the study period, but at a slower annual growth rate of 1.35%. Therefore, the NEcRE and REcRE both indicated that the economic return on energy use in China's crop production indeed increased from 1991 to 2012.

As claimed by MOA, China's grain output increased by 99.5% from 1978 to 2013 (from 277.1 MT to 552.7 MT), whereas vegetable output climbed from 204.1 MT in 1991 to 735.1 MT in 2013, and fruit output increased from 21.8 MT in 1991 to 250.9 MT in 2013 [5–7]. The energy content per unit weight of grain was higher than that of vegetables and fruits [45]; however, the market price per unit weight of grain was lower than vegetables and fruits [62]. According to market price and energy content per unit weight, crops can be divided into low-value and high-energy crops, such as cereals, beans, hemp, and potatoes, and high-value and low-energy crops, including cotton, oilseeds, vegetables, fruits, sugar beet, tea, and tobacco. In recent decades, China has achieved significant progress in the farming of high-value and low-energy crops attributable to changes in diet and economic structure [63]. Low-value and high-energy crop production increased from 436.2 MT in 1991 to 589.8 MT in 2012, with an average annual growth rate of 1.45%. The amount of high-value and low-energy crops increased from 335.7 MT in 1991 to 1130.7 MT in 2012, with an average annual growth rate of 5.95% (Fig. 4). The significant difference in the amount between high-value and low-energy crops and low-value and high-energy crops resulted in a slow increase in energy output and sharp growth in economic return, thus, leading to an increase in economic return on energy use but decreased EUE.

China's crop production has experienced several different development stages during the study period in terms of the growth rate of

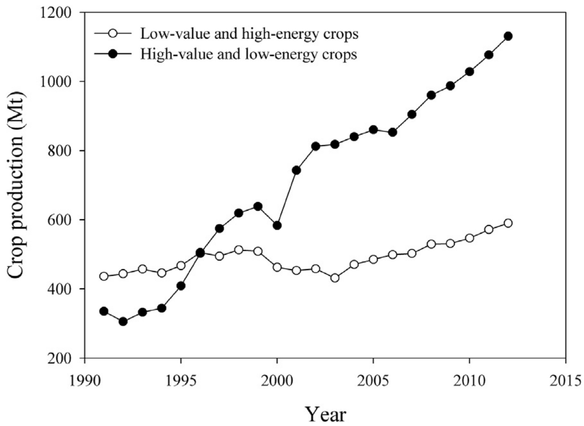

Fig. 4. Trends in high-value and low-energy crop production and low-value and high-energy crop production (MT) in China, 1991–2012.

energy input and crop production efficiency. The first stage is high rate and high efficiency farming practiced between 1991 and 1998. In this stage, the average annual growth rates of total energy input and EIPA were 3.96% and 3.18%, respectively, both lower than the average annual growth rate of crop production (4.90%). The second period is high rate and low efficiency farming practiced from 1999 to 2006. During this time, growth rates of total energy input (3.33%) and EIPA (3.62%) maintained high values, that were higher than that of crop production. The third period is low rate and high efficiency farming practiced from 2007 to 2012. During this time, the average annual growth rate of crop production was 3.41%, which was much higher than that of total energy input (2.24%) and EIPA (0.90%). However, as suggested by many researchers, China's crop production during the past decades followed a clear progression: from low input and low yield to high input and high yield [64]. Meanwhile, both total energy input and EIPA maintained steady growth, and EUE showed a steady decline. Hence, achieving a higher EUE with less energy input and lower environment cost might be an important approach to developing a sustainable crop production system.

During the investigation period, energy consumption in the form of fertilizer, pesticide, diesel, and electricity sustained rapid growth. In general, energy input from fertilizer and pesticide accounted for 40.3% of total energy use. However, the applications of fertilizer and pesticide were much higher than the minimum required for maximum crop growth. Further increases in fertilizer and pesticide application onto the cropland are unlikely to be effective at increasing crop production [65]. Moreover, the excessive use of fertilizer and pesticide in various forms might reduce the economic return from crop production, significantly acidify major croplands [10], increase greenhouse gas emissions [11], and damage water quality and aquatic ecosystems [12]. Future crop production increases that rely on increased fertilizer and pesticide inputs could result in more serious environmental pollution and economic losses. Therefore, decreasing fertilizer and pesticide use in crop production with effective fertilizer, disease, and pest management practices could be very helpful in reducing energy input, preventing natural resource degradation, and protecting the environment. The significant amount of energy input from diesel and electricity was mainly the result of mechanization and irrigation in crop production. Thus, the development of irrigation infrastructure and improvements in mechanical efficiency by increasing investment and technological innovation can make sense in reducing energy waste and energy input, and can achieve higher EUE.

China's crop production remains [66] in a transition period and will be in one for the foreseeable future. Energy balance plays a vital role in Chinese agriculture amid the development of sustainable agriculture, particularly during this transition period, because crop production is also closely related to global and regional environmental problems. Sustainable agricultural development seeks to maintain self-sufficiency, employment, and rural area income, while protecting natural resources and the environment [67]. To enhance the efficiency of energy use, the energy balance, and the level of harmony in the energy consumption system, the Chinese government should further increase the level of agricultural mechanization [68] and promote the development and use of renewable energy in crop production [69], thus seeking to achieve a reasonable crop production structure and sustainable crop production system. Because effective crop production must be supported by technological development and technological innovation, increasing investment in technical research and development is important to promote the advancement of mechanical efficiency, renewable energy, and infrastructure construction, as well as to adjust the crop production structure. Within this framework, energy analysis is essential to indicate the improvements that will lead to more efficient and environmentally friendly production systems.

5. Concluding remarks

A set of indicator systems based on energy, economic return, and production is proposed to examine the trends in energy input and output, energy use efficiency, and economic return on energy in China's crop production from 1991 to 2012. The results indicate that energy input and output increased as did energy input and output per unit of area sown. Given a higher growth rate than earlier and the production of high-value and low-energy crops relative to low-value and high-energy crops, economic return on energy use increased but energy use efficiency decreased. The results of this study indicate that there exists a need to increase investments in technological development and technological innovation, and adopt new policies to optimize China's crop production structure, and establish sustainable production systems.

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