



# The Ecological Value of Typical Agricultural Products: An Emergy-Based Life-Cycle Assessment Framework

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### Specialty section:

This article was submitted to  
Environmental Economics and  
Management,  
a section of the journal  
Frontiers in Environmental Science

**Received:** 29 November 2021

**Accepted:** 11 January 2022

**Published:** 18 February 2022

### Citation:

Wang Y, Liu G, Cai Y, Giannetti BF, Agostinho F, Almeida CMVB and Casazza M (2022) The Ecological Value of Typical Agricultural Products: An Emergy-Based Life-Cycle Assessment Framework. *Front. Environ. Sci.* 10:824275. doi: 10.3389/fenvs.2022.824275

Agri-products have an impact on food security, ecology protection, and crucial strategic deployment. With this respect, the economic value of agri-products should be paralleled with a non-monetary assessment of ecological value for humans. This study set up an emergy-based life-cycle assessment (Em-LCA) framework to calculate the ecosystem service (ES) and ecosystem dis-services (EDS) that was applied to six typical crops, exploring the implementation path of the agricultural eco-product value. The results showed the agriculture system mainly depends on non-renewable resources. EDS generated by China's agri-products is higher than the ES provided by them. Nevertheless, there is a low correlation between the current price of agri-products and their greenness, but, economic value presents a rising trend with agri-product greenness increasing. Further to discussing effective approaches to sustainable agriculture, it can be seen that 1) sustainable agriculture will lead to increased greenness, but it is impossible to improve greenness indefinitely. 2) Improving greenness is an effective way to implement ecological value, another way to preserve and raise ecological value is to reduce EDS generation. 3) Reducing energy consumption leads to a decrease in EDS but it is not an appropriate way to achieve sustainable development. These findings provide meaningful suggestions for decision-makers to realize the ecological value of agri-products.

**Keywords:** agriculture ecosystem, ecosystem services, ecosystem dis-services, emergy-based life-cycle assessment, ecological value, value realization

**Abbreviations:** CS, carbon sequestration; Em-LCA, emergy-based life-cycle assessment; ES, ecosystem services; EDS, ecosystem dis-services; FP, food provision; GE, greenhouse gas Emission; GWS, groundwater supply; MR, microclimate regulation; NESV, net ecosystem service value; SE, soil erosion; SWP, soil and water pollution.

## 1 INTRODUCTION

Crop systems provide an important material basis for human survival and development. Rapid population and economic growth are triggering an increase in crop demands, which, in turn, impacts the conversion of natural land for agriculture. Agricultural land covers nearly 40% of the ice-free land on Earth. Studies have forecasted that this expansion will be further accelerated in the next decades (Foley et al., 2011), growing by 18% in 2050 (Tilman et al., 2001). This acceleration impacts adversely on the environment. Preserving the natural system while meeting human demands for food has become a challenge that needs to be faced and solved and the implementation of eco-products is becoming more imperative. An eco-product is an ecosystem product derived from the interaction of biological and human productions (Yang et al., 2014).

An agricultural system not only provides products for human beings but also supports ecosystem services during the process of product growth, as well as some dis-services, such as soil and water pollution (Shah et al., 2019). However, the generation of ecosystem services by agri-products remains often unaccounted for in assessing their value.

There are still some challenges in the realization of eco-products. The first challenge is the definition of eco-products. The definition of eco-product is similar to ecosystem services, emphasizing the relationship between humans and nature (Costanza et al., 2014). Ecosystem services, deriving from 17 ecological function classes, were defined as benefits that human

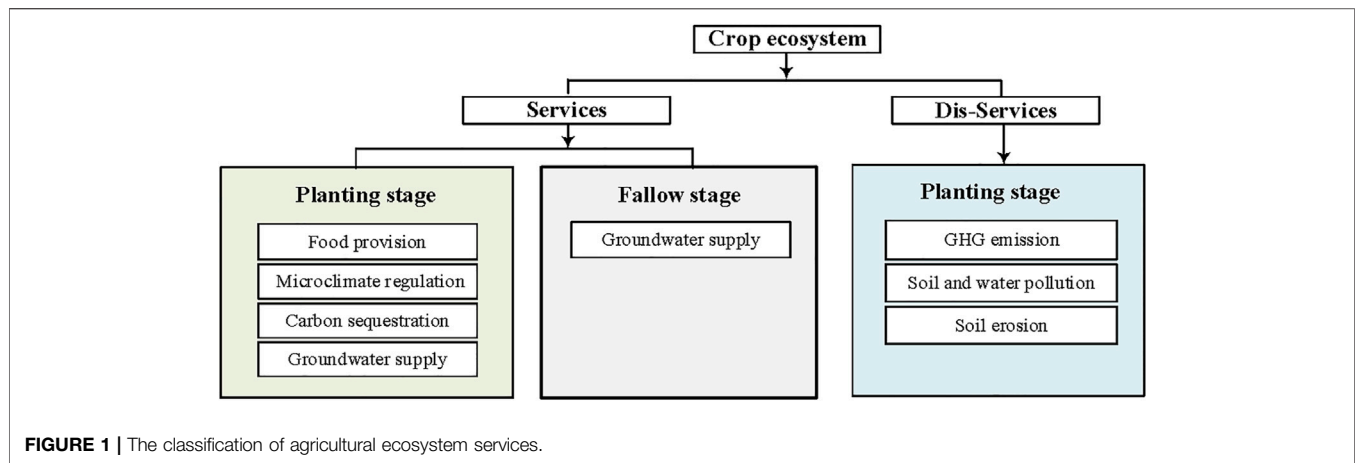
beings derive directly or indirectly from ecological functions (Costanza et al., 1998). De Groot divided ecological functions into four major categories and 25 sub-functions, including provision service, regulation service, habitat service, and information service (De Groot et al., 2002). In the characterization of ecosystem services, humans and ecosystems are considered separate systems.

Applying this approach, an eco-product is an economic product of human society produced by human labor. However, agriculture can combine these two dimensions, since agricultural products are generated by the joint action of humans and nature, exerting an impact on ecosystems and their services. This study defines an agricultural eco-product as an economic product, that can increase human well-being under the joint action of humans and nature.

A second challenge is the accounting and quantification of an ecological value. As noted earlier, our review examined the methods of quantifying the value of eco-products outlined in related literature (Table 1). However, most of the studies tend to reflect a value based on human preference, rather than one based on the natural contribution to agricultural activities (Franzese et al., 2017). The interdependence and interference of ecosystem services complicates the process of accurately capturing the economic value due to the risk of double counting (Van Oijstaeijen et al., 2020). Some theoretical methods and models, such as InVEST modeling often generate errors in the form of overestimation and double accounting, excluding the preservation of natural resources from the core purpose of the accounting process. In addition, current research on agricultural

**TABLE 1 |** Shortlist of methods for quantifying the value of eco-products.

Methods	Objective	References
Theoretical method		
Market price	Assessment of the environmental benefits/costs from habitat creation at Steart to provide evidence to guide optimal outcomes in related projects	Vieira da Silva et al. (2014)
Equivalent factor	The implementation of ecological civilization strategy, including sustainable natural resource management and ecological compensation, also putting forward an urgent requirement for policy making	Xie et al. (2017)
Alternative market price	Monetary value of an ecosystem service determined through the eco-price	Campbell and Tilley (2014)
Shadow pricing	The shadow price generally is greatest for developed nations, which have larger technical scalars and use, less net primary production per unit output	Richmond et al. (2007)
Voluntary payment method	Developing a practical methodology for assessing and valuing ecosystem services relevant for water resource management, considering the links between pressures, ecological status, and ecosystem services	Grizzetti et al. (2016)
Ecological footprint accounting	Using ecological footprint accounting as a biophysical measure for the assessment of ecosystem services	Manjula et al. (2019)
Modelings		
Nature value explorer (NVE)	Demonstrate the impact of various land use scenarios on the value and generation of ecosystem services	De Valck et al. (2019)
i-tree eco	Uses field data from trees and air pollution and meteorological data to quantify environmental effects and value to society	Blair et al. (2017)
Integrated valuation of ecosystem services and tradeoffs (InVEST)	Facilitate quantification of tradeoffs associated with different management choices and identify areas where natural capital investments enhance development and conservation	Arcidiacono et al. (2016)
Benefits estimation tool (B&EST)	Evaluate and monetize the economic, social, and environmental benefits of blue-green infrastructure to support investment decisions and identify stakeholders for potential funding routes	Ashley et al. (2018)
EcoPLAN scenario evaluator (SE)	Evaluate the supply of ecosystem services to alternative scenarios in spatial development projects	Martino and Muenzel, (2018)



ecological value is mainly focused on the impact of agricultural land reduction on ecosystem services (Macfadyen et al., 2012; Marrero et al., 2016; Tang et al., 2018) as well as the relationship between food production and ecosystem services (Gordon et al., 2010; Barral et al., 2020). However, few scholars have discussed the ecological value of agriculture and the realization of the ecological value of agricultural production.

To solve these problems, this study first defined the concept of agricultural eco-products and demarcated agricultural ecosystem services and boundaries. Then we established a non-monetary framework to quantify the ecosystem services and disservices of six typical crop systems in China based on a ternary value theory. An eco-efficiency indicator was adopted to evaluate the eco-efficiency performance of each agri-product. Finally, we further discussed whether the current market mechanism realizes the ecological value of the agri-products and explored the value of agricultural eco-product, and put forward the feasibility of the implementation of ecological value. All of these findings provide effective suggestions for decision-makers to develop sustainable agriculture and realize the value of eco-products.

## 2 METHODS

### 2.1 The Classification of Agricultural Eco-Products

An agricultural eco-product has multi-dimensional features. One is economic, which is the object traded in the market to satisfy the human demand for food (Lu and Campbell, 2009). Another is ecological, being related to certain services provided to human beings (Ma et al., 2021). While economic features depend on agricultural production, ecological features are related to the services provided. These services, according to their functions, are classified into two categories, ecosystem services, and ecosystem dis-services. As shown in **Figure 1**, an agricultural ecosystem service is a benefit that humans get from the ecosystem. Among such processes, photosynthesis is one of the main mechanisms, providing services, such as food supply and carbon sequestration, and local microclimate regulation (Yang et al., 2020). Surface water remaining from plants

absorption can penetrate the ground through soil cracks to recharge groundwater.

In this study, the time interval between two cultivation is a turnover year. Due to the short time of fallowing, crop residues were not enough time to generate corresponding soil nurturing services, so this study was left out.

Ecosystem dis-services are related to products or processes, that can cause harm to the environment during crop growth. For example, these include the use of excessive external resources, such as pesticides and fertilizers, that produce greenhouse gas emissions, as well as residual pesticides and fertilizers, that can cause soil and water pollution (Liu et al., 2021). Concurrently, other factors, such as steep terrain and widespread irrigation, can cause soil erosion. Besides, crop systems are harvested after crop maturity, thus, cultural and educational services are not considered in this study.

### 2.2 Short Review on Methods

Agriculture plays an important role in the economy of China. Being the premise and source of China's economic development, to some extent, agricultural development determines the development of the national economy. As an important product in the foundation of the national economy, the features of agri-product are different from those of other industrial products. For example, the limitation of price reflection. The agri-product price adjusts resource allocation through the price mechanism and promotes a balance between total supply and demand. The price mechanism mainly consists of market prices and policy prices. The price fluctuation of agri-products is directly related to the immediate interests and enthusiasm of agricultural product producers.

Many scholars have studied the price of agri-products, and researchers have mainly focussed on the influencing factors of the price fluctuation of agricultural products, such as macro-policy (Mattila et al., 2010), inflation (Zhang et al., 2014), the impact of trade on agricultural prices (Bekkers et al., 2017), and others (Myers, 2006; Zilberman et al., 2013). Furthermore, some researchers used models to study agri-products price, Fox adopted a spatial equilibrium model to examine the implications of simultaneous equilibrium in three related

markets: retail food, farm output, and marketing service, implications for the viability of simple markup pricing rules, and the determinants of the farmer's share of the food dollar are discussed (Fox, 1953). The equilibrium movement model served to assess the price fluctuation and its transmission of agri-products from the perspective of industrial organization. A two-way price transmission model of agri-product acquisition to food retail link was deduced accordingly (Gardner, 1975). At the same time, new methods are being developed, such as the ARCH model (Engle, 1982) and general equilibrium model (Valdivia et al., 2012). Moreover, studies have examined the impact of consumer behavior on agri-product pricing (Gerbens-Leenes and Nonhebel, 2002). Naseem et al. investigated consumer preferences for various attributes of the rice market in Benin. They empirically analyzed the relationship between the price paid by consumers for their choice of rice and its attributes in the markets using hedonic pricing and discrete choice models of demand (Naseem et al., 2013). Yin et al. surveyed consumers from three cities in China, consequently establishing a logit model to analyze the main factors affecting consumers' choice for organic food. Their result indicated that Chinese consumers' intent to purchase organic food is strongly affected by factors such as income, degree of trust in organic food, degree of acceptance of organic food price, and concern about self-health (Yin et al., 2010). However, a few scholars have studied the ecological value and the pricing of agri-products based on ecological value.

## 2.3 Accounting Method and Analytical Indicators

### 2.3.1 Emergy-Based LCA Analysis

Life cycle thinking recognizes that all product life cycle stages generate environmental impacts that need to be evaluated and, then, reduced (Finnveden et al., 2009). During the past few decades, LCA has become a core element in environmental policy or voluntary actions in various countries (Guinee et al., 2011). This method, however, applies a "consumer-side" approach. Outside the LCA community, another environmental assessment method, emergy evaluation, is gaining international recognition and is increasingly being applied. Emergy was first introduced by Odum in the 1980s and is defined as the sum of the available energy required indirectly and directly to make a product or to provide a service (Odum, 1984). The emergy value of a resource can reflect the amount of past work a natural process uses to produce or regenerate it (Liu et al., 2019). All inputs that enter the systems are converted into emergy by multiplying relevant UEVs (Unit Emergy Value) (Wang et al., 2018). By accounting for the quantity and quality of input flows, keeping track of interactions among system components across scales, emergy provides a suitable systemic framework for assessing the performance and sustainability of processes (Geng et al., 2013). Emergy-based Life-Cycle Analysis (Em-LCA) accounting has been widely used to evaluate environmental impact in different fields (Duan et al., 2011; Gala et al., 2015; Wang et al., 2015). Through the Em-LCA method, various kinds of resources (i.e., energy, materials, information) are converted into a common measurement unit of solar energy equivalents (sej), giving uniform metrics to the system, and

further proceed and are interpreted in terms of direct and potential ecosystems caused by environmental impact (van der Werf et al., 2020).

In LCA practice, labor is most often not accounted for as an energy input (Brown et al., 2012). However, in Em-LCA accounting, labor and services can be involved. The amount of input emergy per reference unit (e.g., energy; currency; information amount) is the unit emergy value (UEV), quantified as solar equivalent joule per unit. As a systematic method, it can be used to evaluate the interplay of economic, social, and environmental systems, aiming to obtain the integrated performance of sustainability (Liu et al., 2019).

**Figure 2** represents a diagram of the crop production system to present emergy processes, storage, and flows. In particular, the diagram represents inflows of sunlight (i.e., solar radiation), wind, rain, and runoff chemical energy produced by irrigating farmland, which are the basic renewable sources included in the accounting of an agricultural production system. These resources are combined into processes, where other inputs are necessary to support the production of crops. Being represented as external circles, their flows are drawn as solid lines. These inputs include the use of fertilizers, pesticides, fuel, human labor, and services. Dashed black lines represent monetary flows. Dashed green lines represent the ecosystem services generated by the crop production system and the red lines represent ecosystem dis-services. Only renewable resources, as a primary input, flow into the system during the fallow period.

Based on the given emergy diagram, matter and energy flows can be divided into renewable resources and purchased resources. The inventory of system components used for the diagram is detailed in **Table 1**. Emergy flows and corresponding UEVs are calculated according to **Eq. 1**:

$$E_i = f_i \times UEV_i \quad i = 1 \dots n \quad (1)$$

where  $E_i$  represents solar emergy (sej),  $f_i$  represents  $i$ th input flow of energy or matters,  $UEV_i$  represents the unit emergy value of the  $i$ th flow.

### 2.3.2 Agricultural Ecosystem Services and Dis-Services Accounting

In the agriculture system, renewable and human inputs together have performed various processes and functions to support services. At the same time, excessive external inputs also caused corresponding ecosystem dis-services. This study quantifies crop ecosystem services and dis-services.

#### 2.3.2.1 Crop Ecosystem Services

##### 1) Food Provision (FP)

Food supply is the agri-products provided by the crop ecosystem. In this paper, we define food supply as the total emergy value input into the crop system. The calculation formula is as follows:

$$E_{FP} = R + \sum_{i=1}^n P(X_i) \quad (2)$$

where  $E_{FP}$  denotes food supply emergy (sej),  $R$  denotes renewable resources (sej), which is the sum of the maximum of sunlight,

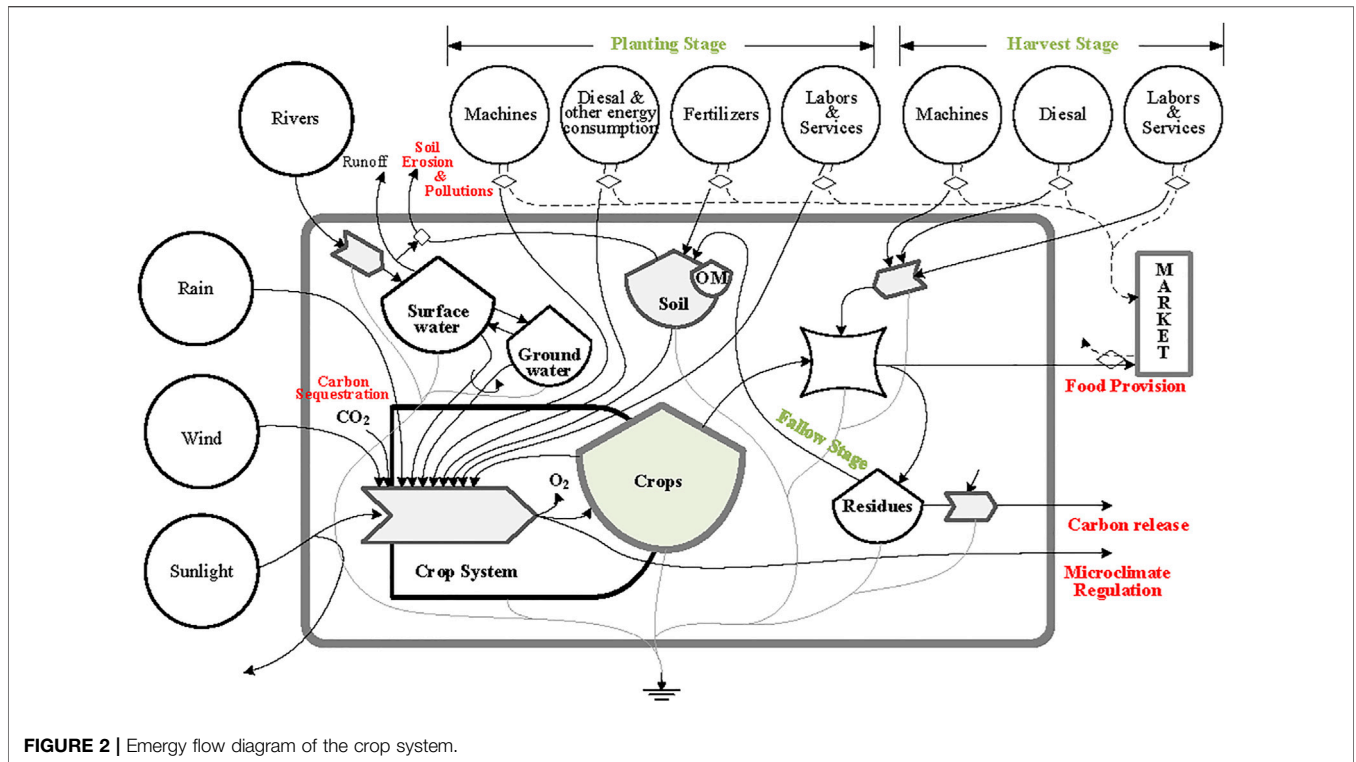


FIGURE 2 | Energy flow diagram of the crop system.

wind, and rain (chemical energy), and Irrigating water,  $P(X_i)$  represents emergy of  $i$ -th purchased resource (sej).

2) Microclimate Regulation (MR)

The crop ecosystem regulates microclimate by increasing humidity and rainfall, and decreasing temperature. The heat quantity absorbed by plants during evaporation equals the increase in humidity and the decrease in temperature in the ecosystem. Thus, the energy required for evaporation can be used to measure the increase in humidity and the decrease in temperature. The formula follows:

$$E_{MR} = \frac{E_{CE}}{1000} \times A \times \rho_w \times (1 - \alpha) \times UEV_{CE} \quad (3)$$

where  $E_{MR}$  represents emergy required by evaporation (sej),  $E_{CE}$  represents farmland evaporation (mm/year),  $\rho_w$  represents water density ( $kg/m^3$ ),  $A$  represents the cultivated area ( $m^2$ )  $\alpha$  represents the percentage of water used for photosynthesis,  $UEV_{CE}$  represents the emergy of surface water (sej/g).

3) Carbon Sequestration (CS)

Carbon sequestration is a process through which atmospheric freely available carbon dioxide ( $CO_2$ ) is captured and stored through a natural process, occurring naturally in plants (photosynthesis) and soil for a long period of time (Granier and Tardieu, 1999). The formula follows:

$$E_{CS} = \frac{CP \times 1 - \delta * C_A}{C_e} \times UEV_{OC} \quad (4)$$

where  $CP$  represents crop yields (g),  $\delta$  represents the water content of part of crop yield (%),  $C_A$  represents the carbon absorption rate (%),  $C_e$  represents the economic coefficient of the crops (%), which is defined as the ratio of the economic yield to the biological yield of a crop,  $UEV_{OC}$  represents the UEV of organic carbon (sej/g).

4) Groundwater Supply (GWS)

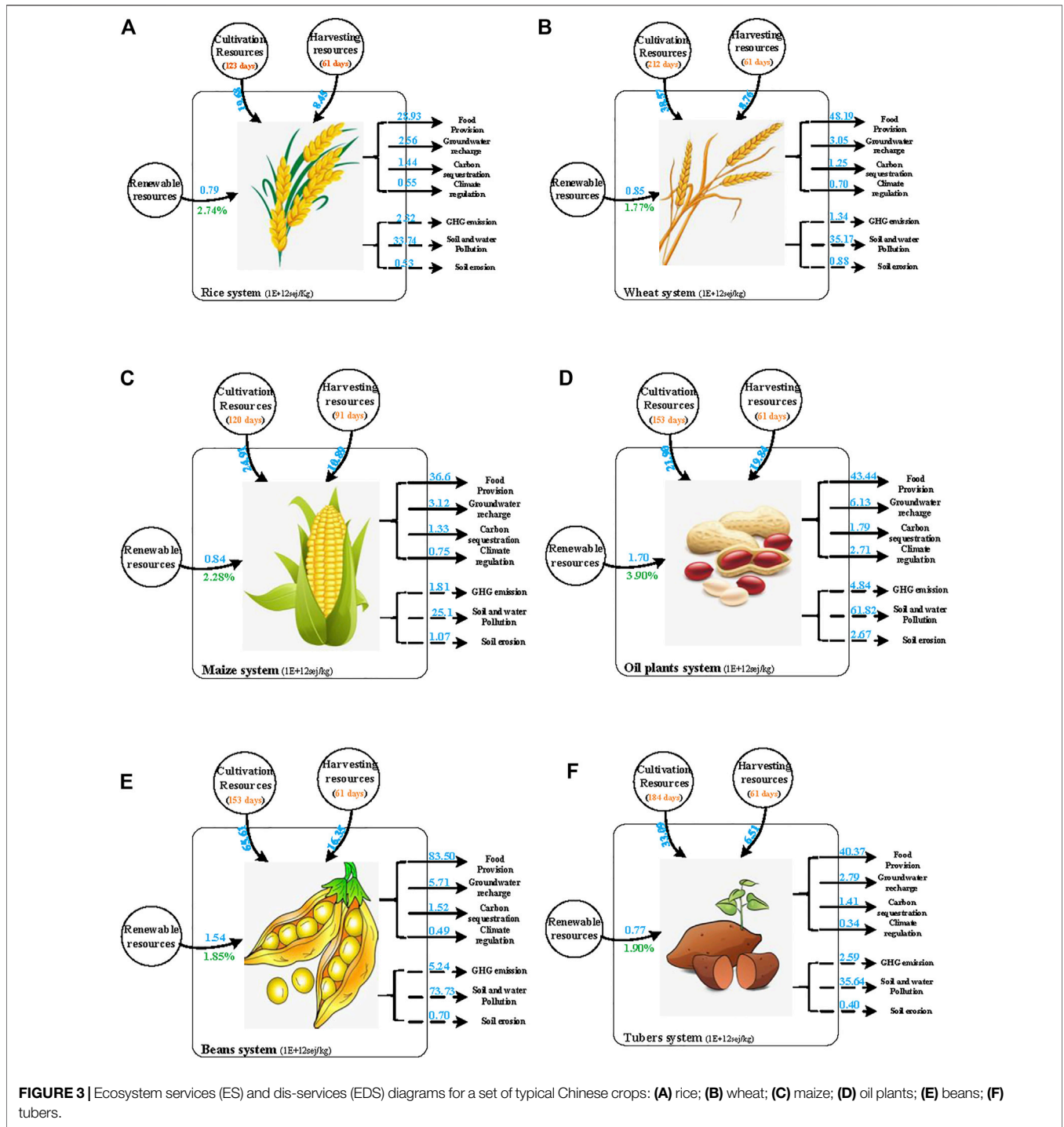
Groundwater recharge refers to the process of absorption by the soil of residual water, left by precipitation and crop irrigation. The calculation formula is:

$$E_{GS} = \frac{(P \times A + I) \times \rho_w}{10000} \times \beta \times G_w \times UEV_w \quad (5)$$

During the fallow period of farmland, because there is no artificial input of irrigation water, the calculation formula changes as follows:

$$E_{GSF} = \frac{(P \times A) \times \rho_w}{1000} \times \beta \times G_w \times UEV_w \quad (6)$$

where  $E_{GS}$  and  $E_{GSF}$  represent the emergy of groundwater supply during the cultivated and fallow period respectively (sej),  $P$  represents precipitation (mm),  $A$  represents the irrigating area ( $m^2$ ),  $I$  represents the volume of irrigating water ( $m^3$ ),  $\rho_w$  represents water density ( $g/cm^3$ ),  $\beta$  represents permeability coefficient (Jiang et al., 2014),  $G_w$  represents Gibbs free energy of water ( $J/g$ ), and  $UEV_w$  represents the UEV of water (sej/J).



### 2.3.2.2 Crop Ecosystem Dis-Services

#### 1) GHG Emission (GE)

GHG emissions mainly come from CO<sub>2</sub>, CH<sub>4</sub>, and N<sub>2</sub>O emissions caused by human inputs human input of chemical fertilizers, pesticides, and diesel. In this study, according to ReCipe 2016, we used human health loss and ecosystem

quality loss to measure dis-service caused by greenhouse gases, the details are as follows:

#### a) Human health loss

$$E_{HL} = \sum M_i \times DALY_i \times \tau_H \tag{7}$$

where  $E_{HL}$  is the emery of human health loss (sej),  $M_i$  is the quantity or mass of the  $i$ -th greenhouse gas released to the environment (kg/year).  $DALY_i$  is the Disability Adjusted Life Years caused by the  $i$ -th greenhouse gas (capita\*year/kg),  $\tau_H$  means the emery per capita (sej/capita).

#### b) Ecosystem quality loss

$$E_{EL} = \sum M_i \times PDF(\%)_i \times E_{BIO} \quad (8)$$

where  $E_{EL}$  is the emery of agriculture ecosystem quality loss (sej),  $M_i$  is the quantity or mass of the  $i$ -th greenhouse pollutants released into the environment (kg/year),  $PDF_i$  means the Potential species extinction ratio caused by the  $i$ -th greenhouse pollutant [(PDF\*year)/kg],  $E_{BIO}$  indicates the UEV of biomass (sej/year).

#### 2) Soil and Water Pollution (SWP)

In agricultural production, people use numerous fertilizers and pesticides to increase crop yield. But excessive use of them leave a large number of pesticides in the soil, causing soil pollution, and affecting the sustainable operation of the agricultural system, with implications for human health through the food chain. Meanwhile, some pesticides flow into the river with runoff, causing water eutrophication and other pollution. In this paper, the loss of human health and ecosystem quality is used to measure soil and water pollution. The calculation formula is the same as (Eqs 7, 8).

#### 3) Soil Erosion (SE)

From an agricultural perspective, soil erosion is defined as “the faster removal of topsoil from land used for agricultural purposes through tillage, wind, water or it is one of the main processes through human influence in critical zones” (Mattila et al., 2010). Soil erosion intensity is measured by hydrologic and topographic features. The formula follows:

$$E_{SE} = SE \times A \times OM \times C \times G \times UEV_E \quad (9)$$

where  $E_{SE}$  is the emery required by soil erosion, SE represents soil erosion (g/km<sup>2</sup>), A represents the cultivated area (km<sup>2</sup>), OM means organic matter content (%) (Zeng et al., 2011), G is the energy conversion coefficient (kcal/g), C means the conservation ration of Joule and Kcal (J/Kcal = 4,186),  $UEV_E$  is the UEV of soil erosion (sej/J).

### 2.3.3 Greenness Assessment

Usually, the definition of greenness refers to surface vegetation coverage (Zhang et al., 2013; Gao et al., 2020). In recent years, some scholars have considered the associated greenness in relation to the production process, which is defined as the degree of environmental impact or environmental friendliness in the production process (Zhong and Chen, 2019). These definitions still suffer from the disadvantage of considering only natural or human systems separately.

In this paper, we consider the role of both natural and human systems, based on Em-LCA analysis, proposing an agri-product

greenness, which is defined as the percentage of renewable resources used to the total resources used. The formula is as follows:

$$R\% = \frac{R}{U} \quad (10)$$

where R represents the emery value of renewable, U represents the emery value of the total resources. The higher this ratio, the more renewable resources the product used, indicating it is more environmentally friendly.

## 2.4 Eco-Efficiency Framework

Even though eco-products have been developed and people want to acquire them, there has been no measurement standard to date. This paper uses the eco-efficiency indicator to measure whether a product is an eco-product. Eco-efficiency is one of leading ideals of sustainable development (Janicke, 2008), which leads to economies, industries, or plants and can create a ‘win-win’ by simultaneously producing economic-business and environmental gains (Porter and Linde, 1999). Eco-efficiency is among the most commonly used concepts and approaches in environmental and ecological economics and international and national environmental policies (Hukkinen, 2003). The traditional Eco-efficiency indicator is the ratio between the cost and the impact generated along the life cycle of a product (Korhonen and Snäkin, 2015).

In this study, we considered the total cost multiplied by emdollar value as life cycle costing. The details can be seen in Appendix S3. Based on this, the eco-efficiency was calculated according to the Eq. 10. The higher the eco-efficiency score, the better the ecological performance achieved

$$EE = \frac{Life\ Cycle\ Costing}{Life\ Cycle\ Assessment} = \frac{Costing*(Em\ ¥)}{Dis - service_i} \quad (10)$$

Where EE is the indicator of eco-efficiency; costing is the cost of materials; Em ¥ is the ratio of Emery and Currency; Dis-service<sub>i</sub> is the  $i$  th dis-service.

## 2.5 Data Resources

In this study, data were collected from different sources including the China Statistic Yearbook 2016, China Rural Statistic Yearbook (2016), and China Water Resources Bulletin (2015). In addition, to verifying the data, some interviews with different stakeholders were conducted, such as National Agricultural product cost-benefit data collection. These additional interviews play an important role in improving the accuracy of data. The planetary emery baseline in this study is 12.1E + 24 sej/yr (Brown and Ulgiati, 2016).

## 3 RESULTS

### 3.1 China's Agro-Product Ecosystem Services and Dis-Services

Figure 3 represents the emery flows of six typical crop systems and the ecosystem services and the dis-services they generated. The results showed that renewable resources had the lowest input in the crops system. Among six typical crops, the oil plants and

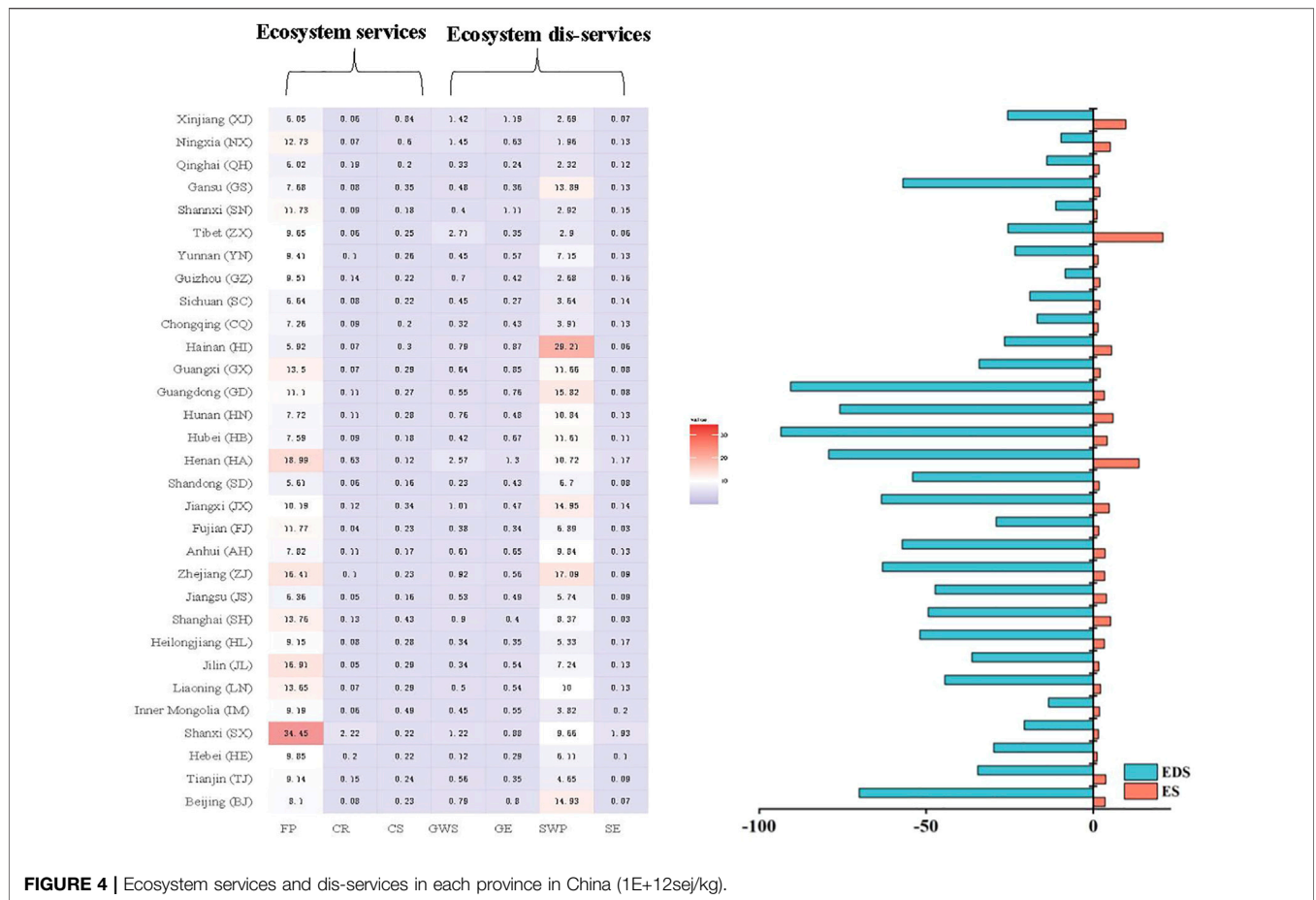


FIGURE 4 | Ecosystem services and dis-services in each province in China (1E+12sej/kg).

tubers process were the largest and lowest renewable inputs respectively, 1.70E+12 sej/kg and 7.7E+11 sej/kg. Human input was divided into cultivating and harvesting periods. In the cultivated stage, the human input in beans was the largest at 6.56E+13 sej/kg, and the oil plants were the highest during the fallow period, which was 1.98E+13 sej/kg.

The R% can reflect the degree of natural resources used and system sustainability. The R% of the typical crops are all lower than 5%, indicating that crops grow more depending on the external resources input that was controlled and dominated by humans. The highest and lowest were oil plants and wheat respectively, at 3.90% and 1.77%.

The ecosystem services provided by the crop system mainly include food supply, carbon sequestration, microclimate regulation, and groundwater recharge. Among them, the food supply service is the highest provided by the crops system. The highest food supply was derived from oil plants, with 8.35E+13 sej/kg, and rice with 2.83e+13 sej/kg, at the bottom. Groundwater recharge indicates that rainfall and irrigation are partially absorbed by crops, while part of the water flows underground through soil and rock cracks to recharge groundwater. Carbon sequestration is the lowest service provided by crops. On the whole, the main ecosystem service is food supply, other services constitute about 10% of the total. Although the crop system produces some ecosystem services to

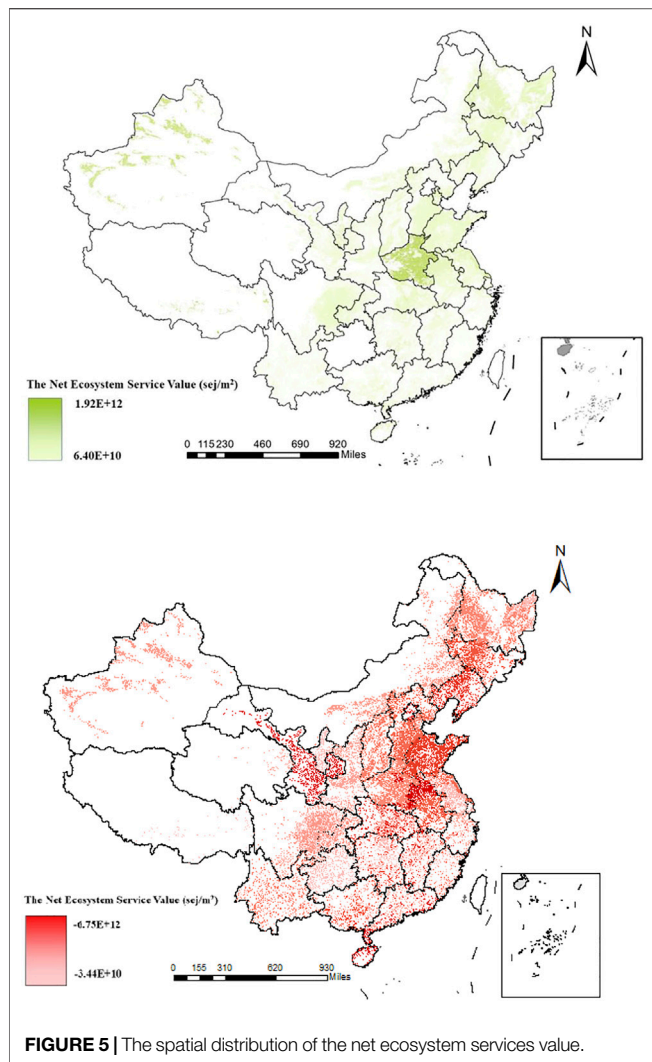
the surrounding environment by its photosynthesis, it makes a less ecological contribution to the environment.

The ecosystem dis-services include GHG emission, human health, and ecological quality loss caused by soil and water pollution and soil erosion. Soil and water pollution are the highest dis-services, the value of this service of rice, wheat, maize, oil plants, beans, and tubers are 3.37E+13 sej/kg, 3.52E+13 sej/kg, 2.51E+13 sej/kg, 6.18E+13 sej/kg, 7.37E+13 sej/kg, 3.56E+13 sej/kg, respectively. GHG emissions are only lower than soil and water pollution, and that of beans and wheat was highest and lowest (5.24E+12 sej/kg and 1.34E+12 sej/kg), respectively. Soil and water pollution are the main ecosystem disservices, followed by the excessive production of crop systems while unscientific, unreasonable use of fertilizers and pesticides, and residues of fertilizers and pesticides can cause soil pollution. This surface runoff can flow into the river, leading to water pollution and producing a large number of ecological services for the ecological environment.

### 3.2 Spatial Distribution of Ecosystem Services and Dis-Services in China

Figure 4 synthesizes the results of crop ecosystem services and dis-services for the food supply service. Shanxi had the largest service.





An agricultural province with sufficient agricultural cultivation resources and conditions, Shanxi has more than 10,000 hectares of cultivated land but little food supply service per hectare, indicating that the agricultural development of this province has not fully used cultivated land resources. On the contrary, although the cultivated area of Shanghai is only 345.6 thousand hectares, just higher than Beijing and Tibet, its grain yield per area is 7042 kg/ha, only lower than Jilin, which indicated that due to the limited area, Shanghai needs to obtain a higher yield from less planting area to meet social and market demands. For the microclimate regulation service, Shanxi is still the highest province and Shanxi is the lowest province. In the northwest region of China (Shanxi, Gansu, Qinghai, Ningxia, Xinjiang), due to higher temperatures, farmland has larger evapotranspiration compared to the region where the temperature is moderate, which led to the microclimate regulation service increasing.

Xinjiang and Jiangsu are the highest and lowest provinces in carbon sequestration services, respectively. Compared with the northern region, the southern region processes abundant rainfall,

thus, except for the moisture absorbed by plants, there is still more water seeping into the ground to recharge groundwater.

For the ecosystem dis-service, Xinjiang is the province with the highest GHG emission service from crop systems among 31 provinces,  $1.19\text{E}+12$  sej/kg, the main reason is that it has a unique total power of agricultural machinery ( $2.3148\text{E}+7$  kwh), which comes from the massive use of fossil fuels in the planting process. Due to the widespread use of pesticides and fertilizers per area in Beijing, a large number of pesticide residues lead have led to high soil and water pollution. The soil erosion service in Zhejiang province is the most serious among the 31 provinces, mainly because the terrain is complicated, mountains and hills occupy 70.4% of the land area, and the terrain slopes from southwest to northeast, which led to more serious soil erosion.

To avoid double accounting, the net ecosystem services (NES) is the sum of the maximum ecosystem services expected for food supply and ecosystem dis-services (Yang et al., 2018). In **Figure 4**, it can be seen that the ecosystem dis-services generated in the production process of the vast majority of crop systems were much higher than the ecosystem services brought by them, by about 10 times. Hainan ( $1.16\text{E}+13$  sej/kg) had the highest ecosystem services in the 31 provinces (about 10 times that of Ningxia), which mainly comes from the soil and water pollution service, the use of fertilizers in Hainan made it one of the highest of the 31 provinces, at approximately 4.71 g per farmland area. Ningxia had only one over ten, 0.21 g, residues of pesticides causing water and soil pollution. Henan supported a high level of ecosystem services with abundant cultivated conditions, with an agricultural sown area of 14,425 thousand hectares, the highest in 31 provinces, and rainfall and land conditions that are suitable for crop cultivation.

**Figure 5** represents a map of the spatial distribution of net ecosystem services value. The net ecosystem service value was mainly concentrated in Hebei, Shandong, Henan in Northern China. The main reason is that these provinces have rich land resources. The cultivated land there occupied 21% of the total arable land in China. This widely cultivated area increases the profits of the three provinces. The agricultural output accounts for 22.5% of the national output. Based on the characteristics of ecosystem services and dis-services, the 31 provinces can be classified into three categories: low service and high dis-service, Middle service and middle dis-service, and High service and low dis-service. Hainan, Beijing, Gansu, and Zhejiang are in the Low service and high dis-service group, Hainan is the highest amount of fertilizers per unit area among all provinces ( $4.71\text{ g/m}^2$ ). While Beijing has the highest mechanical power using per unit area ( $1.77\text{ kwh/ha}$ ). The terrain of Zhejiang has a decreasing trend from south to north, mainly due to it having hilly mountains. Henan, Xinjiang, Ningxia, and Tibet are in the High service and low dis-service category. Henan provides the highest ecosystem service because it has rich farming conditions. The agricultural planting area is about 14.425 million hectares, which is the highest of the 31 provinces, and the fertilizers used per unit area in Ningxia  $0.21\text{ g/m}^2$ , which is only 1/20 of Hainan. Tibet is more focused on the development of other industries, and the arable area is just higher than that of Beijing and Shanghai. Less agricultural cultivation may bring fewer dis-services. The other provinces are in the Middle service and middle dis-service category.

**TABLE 2 |** Energy flows and corresponding unit energy values (UEVs).

No	Items		Units	UEVs (sej/unit)	References
	Cultivation Stage	Fallow stage			
Renewable resources					
1	Sunlight	Sunlight	J <sup>a</sup>	1.00E+00	Brown and Ulgiati (2016)
2	Wind	Wind	J <sup>b</sup>	7.90E+02	Brown and Ulgiati (2016)
3	Rain (chemical energy)	Rain (chemical energy)	J <sup>c</sup>	7.01E+03	Brown and Ulgiati (2016)
4	Irrigating water	—	J <sup>d</sup>	1.28E+04	Brown and Ulgiati (2016)
Purchased resources					
Planting stage					
5	Irrigating water consumption energy	—	J <sup>e</sup>	1.74E+05	Brown and Ulgiati, (2016)
6	Human labor	—	J <sup>f</sup>	5.96E+04	Brown and Ulgiati, (2016)
7	Machines	—	G	—	—
	Steel and iron	—	G	2.40E+09	Brown and Ulgiati, (2004b)
	Aluminum	—	G	5.87E+08	Odum, (2000)
	Rubber and plastic materials	—	G	5.46E+09	Odum, (2000)
	Copper	—	G	2.55E+09	Brown and Ulgiati, (2004a)
8	Diesel	—	J <sup>g</sup>	1.81E+05	Ghisellini et al. (2014)
9	Nitrogen fertilizer	—	G	5.64E+07	Ghisellini et al. (2014)
10	Phosphate fertilizer	—	G	6.91E+06	Ghisellini et al. (2014)
11	Potash fertilizer	—	G	5.76E+06	Ghisellini et al. (2014)
12	Compound fertilizer	—	G	5.18E+07	Ghisellini et al. (2014)
13	Pesticides	—	G	3.65E+06	Ghisellini et al. (2014)
14	Plastic mulch	—	G	1.20E+07	Ghisellini et al. (2014)
15	Services	—	¥ <sup>h</sup>	4.37E+11	Collected from NEAD database
Harvest stage					
16	Human labor	—	J <sup>f</sup>	5.96E+04	Brown and Ulgiati, (2016)
17	Machines	—	G	—	—
	Steel and Iron	—	G	2.40E+09	Brown and Ulgiati, (2004b)
	Aluminum	—	G	5.87E+08	Odum, (2000)
	Rubber and plastic materials	—	G	5.46E+09	Odum, (2000)
	Copper	—	G	2.55E+09	Brown and Ulgiati, (2004a)
18	Diesel	—	J <sup>g</sup>	1.81E+05	Ghisellini et al. (2014)
19	Services	—	¥ <sup>h</sup>	4.37E+11	Collected from NEAD database
Ecosystem service					
20	Food provision	—	—	—	—
21	Microclimate regulation	—	g	3.31E+04	Collected from NEAD database
22	Carbon sequestration	—	g	5.09E+07	Collected from NEAD database
23	Groundwater recharge	Groundwater recharge	J	1.06E+05	Collected from NEAD database
Ecosystem dis-service					
24	GHG emission	—	kg	5.95E+15	Collected from NEAD database
25	Soil and water pollution	—	kg	5.95E+15	Collected from NEAD database
26	Soil erosion	—	G	5.16E+04	Collected from NEAD database

<sup>a</sup>Sunlight = area × (1-albedo) × solar radiation energy × Carnot efficiency, Albedo = 0.7, Carnot efficiency = 0.93.

<sup>b</sup>Wind = 0.5 × arable land × air density × Land wind stress drag coefficient × (average wind speed/0.6)<sup>3</sup> × time, Air density = 1.29 kg/m<sup>3</sup>, Land wind stress drag coefficient = 1.64E-03.

<sup>c</sup>Rain (chemistry energy) = arable land × precipitation × evaporation rate × water density × Gibbs free energy of water, evaporation rate = 0.75, Gibbs free energy of water = 472 J/g, water density = 1E+6 kg/m<sup>3</sup>.

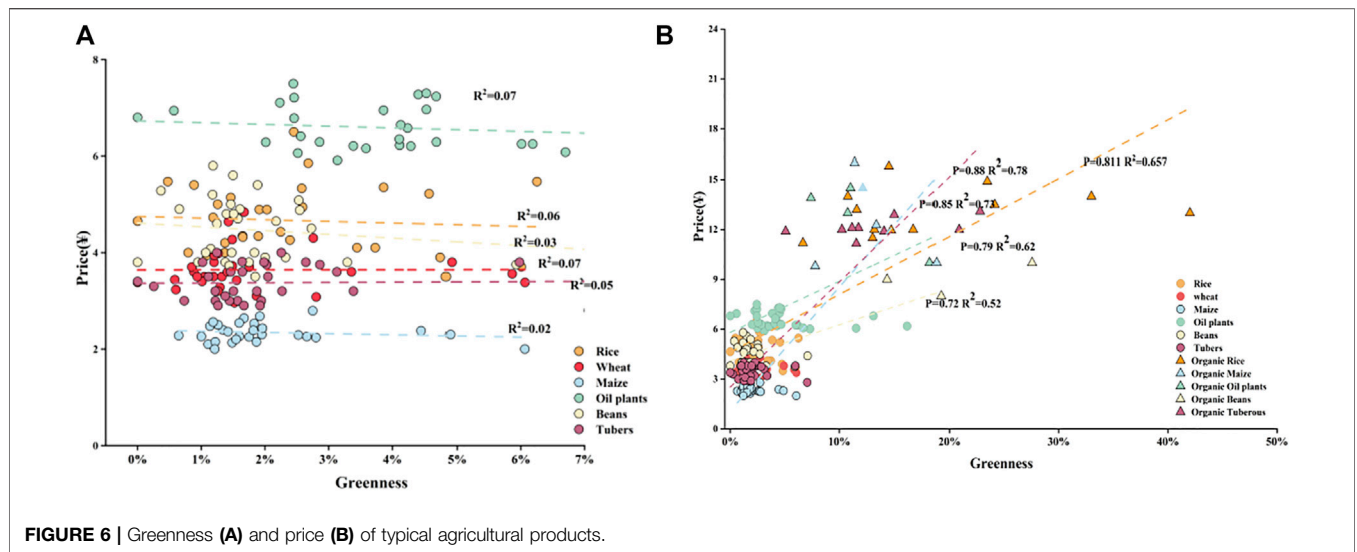
<sup>d</sup>Irrigating water = The total used × runoff coefficient × water density × Gibbs free energy of river, runoff coefficient = 0.15, Gibbs free energy of river = 4.7 J/g.

<sup>e</sup>Irrigating water energy consumption = The total use of water × draw water flows × power × rate of fuel consumption. Water flows = 40 m<sup>3</sup>/h, power = 6.3 kw, rate of fuels consumption = 281 g/kwh.

<sup>f</sup>Human labor = the number of labors × daily work hours × days × energy cost per hour(J/kcal), daily work hours = 8 h, energy cost per hour = 125 kcal/h, J/kcal = 419.

<sup>g</sup>Diesel = the total used × energy content per kg, energy content per kg = 5.15E + 07 J/kg.

<sup>h</sup>Services = arable land × Cost per unit area.



**TABLE 3 |** The greenness (R%) and average annual price (¥/kg) of typical agricultural products in different provinces.

	Grain	Price	Wheat	Price	Maize	Price	Oil plants	Price	Beans	Price	Tubers	Price
	R%		R%		R%		R%		R%		R%	
Beijing	1.91%	4.89	1.30%	3.28	2.75%	2.79	6.19%	6.25	2.53%	5.08	2.64%	3.80
Tianjin	3.86%	5.35	1.49%	3.73	1.92%	2.68	4.41%	7.28	1.47%	5.00	1.51%	3.20
Hebei	1.19%	4.73	0.60%	3.23	0.65%	2.28	0.57%	6.94	0.37%	5.28	0.26%	3.30
Shanxi	0.48%	5.47	0.59%	3.44	1.11%	2.10	2.23%	7.11	0.66%	4.90	0.74%	3.00
Inner Mongolia	6.25%	5.47	1.20%	3.80	1.49%	2.13	3.39%	6.21	1.50%	5.60	1.57%	3.00
Liaoning	1.26%	5.00	1.33%	3.50	2.53%	2.29	4.11%	6.22	1.61%	4.90	1.67%	2.90
Jilin	1.09%	3.94	1.05%	3.50	2.66%	2.26	3.14%	5.91	1.38%	3.80	1.45%	3.00
Heilongjiang	1.18%	4.00	0.88%	3.60	1.87%	2.15	2.52%	6.06	1.44%	3.73	1.22%	3.20
Shanghai	2.39%	4.26	1.87%	3.10	1.34%	2.40	2.46%	7.21	1.58%	4.70	1.65%	3.60
Jiangsu	2.68%	5.85	2.81%	3.08	1.60%	2.27	4.29%	6.20	1.89%	5.40	1.94%	3.00
Zhejiang	1.90%	4.34	1.01%	3.40	1.00%	2.26	6.01%	6.25	1.15%	4.08	1.12%	3.50
Anhui	2.59%	4.94	3.36%	3.60	1.95%	2.30	4.24%	6.58	2.55%	4.88	1.22%	3.00
Fujian	1.46%	5.14	1.19%	3.50	1.19%	2.52	2.01%	6.29	1.40%	4.80	1.46%	3.60
Jiangxi	6.01%	3.70	1.67%	4.84	1.67%	2.64	7.32%	6.02	2.00%	3.90	2.05%	3.50
Shandong	0.89%	5.40	1.56%	3.43	1.42%	2.36	2.86%	6.29	1.18%	5.20	1.25%	4.00
Henan	2.25%	4.43	5.87%	3.56	4.45%	2.38	11.54%	6.06	2.33%	3.90	2.27%	3.20
Hubei	2.03%	4.89	1.43%	4.64	1.14%	2.48	4.53%	6.97	1.19%	5.80	1.26%	2.90
Hunan	4.75%	3.90	1.76%	3.70	1.75%	2.25	6.70%	6.08	2.17%	4.65	2.26%	4.00
Guangdong	3.73%	4.10	1.27%	3.20	1.27%	2.50	4.69%	7.24	1.48%	4.00	1.87%	3.20
Guangxi	3.45%	4.10	1.27%	3.98	1.83%	2.53	3.59%	6.16	1.51%	4.80	1.64%	3.81
Hainan	4.83%	3.50	0.00%	3.38	-	2.63	4.53%	7.30	2.73%	4.50	3.13%	3.60
Chongqing	1.37%	4.20	0.85%	3.70	1.19%	2.56	2.45%	7.50	1.07%	4.00	2.03%	3.75
Sichuan	1.65%	4.35	1.49%	4.27	1.60%	2.54	3.86%	6.95	1.75%	3.80	1.99%	3.80
Guizhou	1.65%	4.32	1.41%	3.60	1.96%	2.43	4.11%	6.35	1.84%	4.00	2.86%	3.75
Yunnan	1.37%	4.00	0.94%	3.50	1.82%	2.39	2.56%	6.41	1.25%	4.60	1.38%	3.10
Tibet	5.66%	—	6.07%	3.38	6.06%	2.00	16.21%	6.19	7.09%	4.40	7.07%	2.80
Shannxi	0.80%	4.00	1.18%	4.00	1.22%	2.15	2.46%	6.79	0.95%	3.80	1.02%	3.80
Gansu	2.45%	6.50	1.52%	2.96	1.55%	2.20	4.13%	6.65	1.85%	3.50	1.92%	2.90
Qinghai	0.00%	4.65	1.21%	3.94	1.21%	2.00	0.00%	6.80	0.00%	3.80	0.00%	3.40
Ningxia	2.58%	5.33	2.76%	4.30	2.80%	2.24	4.69%	6.29	3.29%	3.80	3.39%	3.20
Xinjiang	4.58%	5.22	4.92%	3.80	4.90%	2.30	13.12%	6.80	5.93%	3.75	5.98%	3.80

### 3.3 Correlation Analysis of Greenness and Market Price

At present, agri-products have been priced in the market, however, as we do not know whether there is a correlation between current

agri-product market prices and their greenness we further explored this situation. Table 2 shows the current agri-product price and greenness (R%). The details of the calculation process can be seen in the Appendix. By analyzing the correlation between the agri-

**TABLE 4 |** The eco-efficiency (EE) of each crop in 31 provinces.

	Grain			Wheat			Maize		
	Ge	SWP	SE	Ge	SWP	SE	Ge	SWP	SE
Beijing	0.95	0.08	2,108.84	6.02	0.17	16.60	4.23	0.19	4.98
Tianjin	5.83	0.46	66.62	7.73	0.37	7.69	5.25	0.41	4.31
Hebei	6.72	0.33	197.36	8.75	0.27	5.91	5.99	0.30	4.65
Shanxi	9.27	0.79	21,055.02	14.44	0.65	17.88	6.89	0.64	7.92
Inner mongolia	5.14	0.80	159.99	7.99	0.66	18.32	4.64	0.72	3.34
Liaoning	3.00	0.17	11.51	4.65	0.14	916.73	2.71	0.15	2.16
Jilin	2.49	0.20	8.38	3.90	0.17	15,832.05	2.24	0.18	1.51
Heilongjiang	4.51	0.32	4.93	6.84	0.26	178.72	4.06	0.29	2.40
Shanghai	5.58	0.28	8.13	8.59	0.23	143,866.77	5.03	0.25	210.70
Jiangsu	2.02	0.18	4.16	3.15	0.15	3.43	1.82	0.17	18.19
Zhejiang	2.80	0.10	4.30	4.30	0.08	32.19	2.53	0.09	45.85
Anhui	2.89	0.20	6.23	4.48	0.16	4.64	2.60	0.18	14.24
Fujian	4.25	0.22	9.92	6.09	0.18	3,052.86	3.25	0.20	137.06
Jiangxi	3.40	0.12	2.04	5.12	0.10	456.57	3.05	0.11	202.40
Shandong	1.79	0.12	98.52	2.78	0.10	2.47	1.62	0.11	3.25
Henan	0.15	0.02	2.12	2.37	0.16	0.22	1.38	0.17	0.38
Hubei	2.14	0.13	4,524.06	3.31	0.11	7.41	1.92	0.12	12.98
Hunan	2.62	0.19	2.27	3.93	0.10	259.85	2.35	0.11	24.14
Guangdong	1.48	0.08	2.95	2.22	0.06	5,072.06	1.33	0.07	28.08
Guangxi	2.88	0.23	5.62	4.29	0.19	1791.31	2.59	0.21	16.16
Hainan	1.86	0.06	10.89	—	—	—	—	—	—
Chongqing	2.99	0.36	5.43	4.67	0.29	43.89	2.70	0.32	7.15
Sichuan	4.10	0.40	6.92	6.24	0.33	10.08	3.69	0.36	8.86
Guizhou	8.28	1.42	17.36	12.80	1.16	38.60	7.49	1.28	13.85
Yunnan	4.68	0.42	12.95	7.20	0.34	27.82	4.22	0.38	8.73
Tibet	16.04	2.02	1,181.86	24.70	1.66	23.99	14.46	1.82	213.09
Shannxi	1.70	0.68	43.16	2.63	0.55	4.00	1.53	0.61	4.15
Gansu	9.90	0.28	2,981.72	15.16	0.23	13.82	8.92	0.25	11.93
Qinghai	—	—	—	44.72	2.66	35.96	25.69	2.93	126.98
Ningxia	13.50	4.64	101.56	21.07	3.80	50.44	12.17	4.19	22.54
Xinjiang	10.89	2.35	441.36	16.90	1.92	19.30	9.82	2.12	27.38
—	<b>Oli plants</b>			<b>Beans</b>			<b>Tubers</b>		
	<b>GE</b>	<b>SWP</b>	<b>SE</b>	<b>GE</b>	<b>SWP</b>	<b>SE</b>	<b>GE</b>	<b>SWP</b>	<b>SE</b>
Beijing	4.51	0.20	192.53	2.64	0.12	57.74	3.55	0.16	227.44
Tianjin	5.62	0.44	756.58	3.27	0.26	91.41	4.40	0.34	774.57
Hebei	6.40	0.32	34.76	3.75	0.19	61.11	4.99	0.25	53.18
Shanxi	71.72	8.62	11.57	5.20	0.44	25.95	7.00	0.60	58.81
Inner mongolia	4.94	0.77	13.25	2.89	0.45	10.28	3.88	0.61	18.57
Liaoning	2.88	0.16	21.07	1.68	0.10	30.73	2.27	0.13	57.24
Jilin	2.39	0.20	22.72	1.40	0.11	12.58	1.88	0.15	67.66
Heilongjiang	4.33	0.31	157.26	2.53	0.18	3.52	3.40	0.24	54.59
Shanghai	5.34	0.27	146.49	3.13	0.16	114.36	4.21	0.21	666.57
Jiangsu	1.94	0.18	18.38	1.13	0.10	16.76	1.52	0.14	129.83
Zhejiang	2.72	0.09	23.19	1.57	0.06	13.71	2.12	0.07	21.71
Anhui	2.77	0.19	17.29	1.62	0.11	8.74	2.17	0.15	74.91
Fujian	4.07	0.21	63.07	2.38	0.12	50.17	3.20	0.17	23.06
Jiangxi	3.26	0.11	8.82	1.90	0.07	23.08	2.56	0.09	34.94
Shandong	1.72	0.12	14.48	1.01	0.07	42.20	1.35	0.09	38.10
Henan	1.48	0.18	0.83	0.86	0.11	1.89	1.16	0.15	2.97
Hubei	2.05	0.13	6.23	1.20	0.07	37.60	1.61	0.10	23.53
Hunan	2.50	0.12	6.19	1.46	0.07	32.55	1.97	0.09	26.24
Guangdong	1.42	0.07	14.23	0.83	0.04	38.77	1.12	0.06	11.98
Guangxi	2.76	0.22	43.06	1.61	0.13	41.01	2.17	0.18	30.73
Hainan	4.20	0.12	77.94	1.66	0.05	587.11	3.30	0.10	86.06
Chongqing	2.87	0.34	11.58	1.68	0.20	8.71	2.26	0.27	3.86
Sichuan	3.93	0.38	10.17	3,853.27	0.50	15.63	3.09	0.30	8.17
Guizhou	7.97	1.36	19.02	4.66	0.79	19.99	6.27	1.07	9.37
Yunnan	4.49	0.40	39.58	2.62	0.23	15.01	3.53	0.32	16.52
Tibet	15.45	1.94	42.84	9.00	1.14	117.06	12.11	1.53	803.02
Shannxi	1.63	0.65	17.00	0.95	0.38	15.84	1.28	0.51	12.04
Gansu	9.51	0.27	40.17	5.56	0.16	43.76	7.47	0.21	15.23
Qinghai	27.48	3.11	49.25	15.99	1.82	81.12	21.51	2.45	32.46
Ningxia	12.94	4.45	49.92	7.57	2.61	150.71	10.19	3.51	33.41
Xinjiang	1.83	2.25	128.31	6.12	1.32	228.72	3.39	0.73	—

**TABLE 5** | The renewable inputs of each province and agri-products.

Items	Grain	Wheat	Maize	Oil plants	Beans	Tubers	Total	Percentage (%)
Beijing	1.2E + 18	1.3E + 20	4.3E + 20	6.9E + 18	2.0E + 19	6.6E + 18	5.1E + 23	0.12
Tianjin	1.2E + 20	8.0E + 20	1.6E + 21	4.4E + 18	3.9E + 19	6.3E + 18	2.1E + 22	12.18
Hebei	5.6E + 20	1.4E + 22	2.5E + 22	2.3E + 21	8.1E + 20	2.1E + 21	5.5E + 24	0.83
Shanxi	6.9E + 18	3.3E + 21	8.1E + 21	3.8E + 21	1.2E + 21	7.2E + 20	1.3E + 25	0.13
Innermongolia	4.5E + 20	3.0E + 21	1.7E + 22	2.9E + 21	2.8E + 21	2.1E + 21	6.1E + 25	0.05
Liaoning	3.4E + 21	1.9E + 20	1.5E + 22	9.1E + 20	5.4E + 20	3.9E + 20	2.1E + 24	0.98
Jilin	4.4E + 21	1.6E + 20	2.0E + 22	8.6E + 20	1.2E + 21	3.0E + 20	5.7E + 24	0.47
Heilongjiang	1.8E + 22	5.6E + 20	3.0E + 22	3.1E + 20	1.0E + 22	9.0E + 20	1.4E + 25	0.42
Shanghai	9.7E + 20	4.2E + 20	3.2E + 19	4.4E + 19	3.3E + 19	7.6E + 18	1.5E + 22	10.09
Jiangsu	1.3E + 22	1.2E + 22	2.5E + 21	1.6E + 21	1.4E + 21	2.4E + 20	5.0E + 23	6.14
Zhejiang	1.1E + 22	1.1E + 21	8.6E + 20	5.1E + 20	1.7E + 21	1.4E + 21	2.0E + 24	0.82
Anhui	1.1E + 22	1.0E + 22	3.7E + 21	2.4E + 21	2.9E + 21	7.7E + 20	2.4E + 24	1.32
Fujian	4.8E + 21	1.4E + 19	2.8E + 20	5.3E + 20	3.9E + 20	1.2E + 21	7.9E + 24	0.09
Jiangxi	2.1E + 22	7.0E + 19	1.7E + 20	2.4E + 21	7.6E + 20	6.7E + 20	7.3E + 24	0.34
Shandong	7.0E + 20	2.1E + 22	1.8E + 22	2.4E + 21	6.9E + 20	1.0E + 21	1.3E + 24	3.47
Henan	8.5E + 21	6.4E + 22	4.1E + 22	6.9E + 21	4.6E + 21	4.0E + 21	3.8E + 24	3.42
Hubei	1.2E + 22	5.4E + 21	3.3E + 21	4.8E + 21	5.7E + 20	1.2E + 21	7.1E + 24	0.38
Hunan	2.2E + 22	1.6E + 20	1.6E + 21	4.6E + 21	5.8E + 20	9.7E + 20	1.2E + 25	0.25
Guangdong	1.2E + 22	1.5E + 19	1.0E + 21	1.2E + 21	3.8E + 20	1.6E + 21	1.9E + 24	0.85
Guangxi	1.1E + 22	5.5E + 19	3.2E + 21	7.8E + 20	6.3E + 20	1.1E + 21	1.4E + 25	0.12
Hainan	2.5E + 21	0.0E + 00	0.0E + 00	1.5E + 20	3.1E + 19	4.3E + 20	1.5E + 23	2.04
Chongqing	3.5E + 21	3.3E + 20	2.2E + 21	9.5E + 20	8.7E + 20	2.7E + 21	5.0E + 24	0.21
Sichuan	1.0E + 22	5.2E + 21	6.4E + 21	4.0E + 21	1.8E + 21	4.5E + 21	1.4E + 26	0.02
Guizhou	3.2E + 21	1.1E + 21	3.3E + 21	1.8E + 21	1.1E + 21	3.1E + 21	6.0E + 25	0.02
Yunnan	6.5E + 21	2.3E + 21	7.9E + 21	1.1E + 21	2.3E + 21	2.8E + 21	2.0E + 26	0.01
Tibet	6.5E + 18	2.3E + 20	2.9E + 19	9.0E + 19	2.9E + 19	5.8E + 18	4.6E + 26	0.00
Shanxi	8.1E + 20	6.7E + 21	7.0E + 21	9.9E + 20	9.6E + 20	1.7E + 21	2.2E + 25	0.08
Gansu	2.5E + 19	4.1E + 21	5.1E + 21	1.0E + 21	7.0E + 20	2.7E + 21	5.5E + 25	0.02
Qinghai	0.0E + 00	4.6E + 20	1.4E + 20	2.5E + 20	1.1E + 20	3.8E + 20	1.7E + 26	0.00
Ningxia	4.8E + 20	7.5E + 20	1.8E + 21	4.6E + 20	1.4E + 20	8.2E + 20	6.3E + 24	0.07
Xinjiang	4.2E + 20	7.2E + 21	5.5E + 21	7.6E + 20	3.5E + 20	1.4E + 20	6.5E + 25	0.02

product price and greenness of each province, it can be seen in **Figure 6A** that, under the market equilibrium of agri-products in China, the price of typical agri-products is relatively stable and has a low correlation with the greenness of products ( $R^2 < 0.1$ ), the price of agri-products is more determined by market demand. If the greenness of the agri-products is considered, as shown in **Figure 6B**, the results show that the price of agri-products increases with the increase of greenness, and the correlation between them is high ( $p > 0.75$ ,  $R^2 > 0.5$ ). Meanwhile, various agri-product price increase range is different, indicating that the improvement of the degree to which they are green is one of the important reasons for improving the price of agri-products, which is also one of the directions that could help us further realize the value of agri-products.

### 3.4 Eco-Efficiency Indicator for Each Agri-Products

Based on the total cost as well as Em-LCA results, the eco-efficiency scores of each crop were calculated for each dis-service according to **Eq. 10**. The corresponding results are presented in **Tables 3, 4**, the higher the score in each category, the better the eco-efficiency performance achieved. The soil erosion related eco-efficiency of Shanghai and Shanxi are, in particular, far higher than other

provinces, mainly caused by the slope of the terrain. Soil and water pollution had the lowest eco-efficiency due to the excessive amount of fertilizers and pesticides used. Compared to six typical crops, grain and oil plants are the largest and lowest performing in terms of eco-efficiency, respectively, which puts more pressure on the ecology and requires the adjustment of the crop planting process. The wheat cultivation in Jilin and Shanghai, with high eco-efficiency scores, were triggered by lower cultivation conditions. The cultivated area of wheat in Jilin is 0.3 thousand hectares that smaller than Beijing (20.8 thousand hectares). Furthermore, in sum, the eco-efficiency in the eastern region is higher than that of the western region. The main reason for this is that the agricultural planting process is more efficient with a high degree of mechanization.

## 4 DISCUSSION

### 4.1 The Value of Ecosystem Services and Dis-Services for Typical Crop Systems

In this study, an emergy-based Life Cycle Analysis (Em-LCA) was established to quantify the ecosystem services and dis-services for the typical crop system. The results showed that the R% of the typical crop system in China was less than 5%, demonstrating that

**TABLE 6 |** The natural resources and maximum proportion of theoretical renewable resources.

Items	The total water resources (m <sup>3</sup> )	The total sown area (m <sup>2</sup> )	The maximum theoretical R% (%)
Beijing	2.68E + 09	2.19E + 09	16.8
Tianjin	1.28E + 09	4.37E + 09	2.1
Hebei	1.35E + 10	6.53E + 10	1.2
Shanxi	9.40E + 09	4.06E + 10	2.2
Innermongolia	5.37E + 10	9.24E + 10	6.3
Liaoning	1.79E + 10	4.98E + 10	3.7
Jilin	3.31E + 10	7.00E + 10	5.2
Heilongjiang	8.14E + 10	1.59E + 11	5.5
Shanghai	6.41E + 09	1.90E + 09	23.1
Jiangsu	5.82E + 10	4.57E + 10	10.3
Zhejiang	1.41E + 11	1.98E + 10	41.2
Anhui	9.14E + 10	5.87E + 10	15.7
Fujian	1.33E + 11	1.34E + 10	59.5
Jiangxi	2.00E + 11	3.08E + 10	40.4
Shandong	1.68E + 10	7.61E + 10	1.7
Henan	2.87E + 10	8.11E + 10	1.0
Hubei	1.02E + 11	5.26E + 10	18.0
Hunan	1.92E + 11	4.15E + 10	31.7
Guangdong	1.93E + 11	2.62E + 10	48.1
Guangxi	2.43E + 11	4.40E + 10	52.5
Hainan	1.98E + 10	7.26E + 09	29.4
Chongqing	4.56E + 10	2.43E + 10	19.4
Sichuan	2.22E + 11	6.73E + 10	27.5
Guizhou	1.15E + 11	4.54E + 10	32.2
Yunnan	1.87E + 11	6.21E + 10	33.0
Tibet	3.85E + 11	4.43E + 09	97.5
Shannxi	3.33E + 10	4.00E + 10	7.6
Gansu	1.65E + 10	5.37E + 10	4.5
Qinghai	5.89E + 10	5.88E + 09	61.6
Ningxia	9.20E + 08	1.29E + 10	0.8
Xinjiang	9.30E + 10	5.19E + 10	18.5

the growth of the current crops was dominated by humans. Compared with Italy's agricultural system (R% equals 29%) (Ghisellini et al., 2014), China's agriculture is still on the path to sustainable development, and more measures need to be taken to improve sustainability.

Food supply service was the largest ecosystem service provided by the crop systems, which contributed about 90% of the total ecosystem services. The highest dis-service was the soil and water pollution service. The dis-service of crop systems was much higher than the other services, indicating that crop systems have a huge potential impact on the environment from an ecological perspective. The highest region was mainly concentrated in northern China, with rich land resources.

## 4.2 Impact of Greenness on Sustainable Agriculture

Agri-products quality affects the physical and mental health of consumers and received more and more attention from society and government, more traditional agri-products are transformed into organic or green agri-products through the improvement of greenness. In this study, we assume that certain external resource input levels reached that of developed countries, such as mechanical efficiency, irrigation regime. But that only changes improvement of the resources used efficiency, the cultivation

pattern remains the same. This could be one way to achieve sustainable agriculture, nevertheless, simply increasing the efficiency of resource utilization does not meet the requirement of sustainable agriculture. In our opinion, sustainable agriculture is not only achieved through the long-time resources used, but also the synergy between nature, ecology, society, and maximizing agricultural production. Sustainable agriculture will naturally lead to greenness increasing. For example, farmers who adopt circular agriculture can improve greenness and meet food demands. Su et al. evaluate the overall performance of traditional rice systems, integrated farming, and non-point production system. The results indicate that economic benefits increase by 2.32–2.35 times and the agricultural non-point source pollution decreases by 10.21%–59.01% in comparison with rice monoculture, and that the R% will reach 45% (Su et al., 2020a).

Greenness in this study is defined as the rate of renewable inputs to the total input. However, with respect to each province, only a small part of renewable inputs are used for agricultural production. **Table 5** lists the renewable resource input of each province and agri-products, it can be seen that the percentage of the renewable inputs of agri-products to the total renewable inputs is lower than 1%, except for Shanghai, Jiangsu, Anhui, Shandong, Henan, and Hainan, indicating that the use of renewable resources in agriculture is relatively low and that renewable resources are not used fully. Meanwhile, the relation

**TABLE 7** | Ecosystem service value of different ecosystem.

Items	Agriculture	Agricultural disservice	Forest	Shrub	Grassland	Marsh	Lake	Reservoir	River	Rate (%)
Beijing	3.48	70.03	1.45	2.44	2.52	0.70	—	1.04	0.42	29
Tianjin	3.72	34.51	1.12	1.67	3.22	0.65	0.52	1.38	0.77	28
Hebei	1.17	29.82	1.12	2.03	4.55	0.21	0.69	0.77	0.45	11
Shanxi	1.58	20.68	1.36	2.34	2.42	0.69	1.03	0.89	0.64	14
Inner Mongolia	1.84	13.43	1.18	1.75	1.50	0.20	1.33	0.58	0.45	21
Liaoning	2.14	44.44	1.21	1.97	2.47	0.29	0.23	0.70	0.31	23
Jilin	1.67	36.32	1.23	2.15	2.51	0.43	0.87	0.37	0.21	18
Heilongjiang	3.31	51.84	1.19	2.30	3.04	0.18	1.21	0.38	0.50	27
Shanghai	5.13	49.41	0.92	2.32	1.38	1.95	0.89	1.21	2.41	32
Jiangsu	3.93	47.36	1.25	1.89	2.94	0.64	2.02	0.62	1.53	27
Zhejiang	3.46	63.14	1.47	2.47	3.94	0.64	0.66	0.76	1.76	23
Anhui	3.55	57.16	1.23	2.27	2.83	0.40	1.69	0.48	1.00	26
Fujian	1.62	29.09	1.30	2.35	3.70	1.31	0.38	0.80	0.61	13
Jiangxi	4.81	63.37	1.28	2.32	3.37	1.14	1.69	0.50	0.72	30
Shandong	1.74	54.04	1.06	1.88	2.27	0.54	1.07	0.69	0.61	18
Henan	13.73	79.18	1.16	1.96	2.25	0.19	0.18	0.76	0.25	67
Hubei	4.12	93.49	1.26	2.34	3.71	0.41	1.04	0.31	1.28	28
Hunan	5.94	75.89	1.29	2.31	3.69	0.56	1.34	0.40	1.03	36
Guangdong	3.27	90.59	1.31	2.17	3.52	0.74	0.51	0.80	1.04	24
Guangxi	2.06	34.13	1.30	2.31	3.46	0.43	0.33	0.46	0.46	19
Hainan	5.48	26.58	1.58	2.49	3.36	0.32	0.37	0.66	0.61	37
Chongqing	1.41	16.82	1.22	2.29	3.33	0.00	0.23	0.29	0.57	15
Sichuan	1.93	19	1.26	2.20	2.36	1.20	0.46	0.26	0.30	19
Guizhou	1.96	8.44	1.61	2.38	3.92	0.00	0.86	0.37	0.31	17
Yunnan	1.47	23.45	1.68	2.55	4.06	0.90	1.71	0.27	0.27	11
Tibet	20.83	25.55	1.53	1.82	0.85	0.98	2.25	1.82	1.11	67
Shanxi	1.15	11.24	1.33	2.16	2.50	0.24	0.33	0.53	0.50	13
Gansu	1.92	56.93	1.25	2.09	1.51	0.86	1.08	1.36	0.62	18
Qinghai	1.75	13.92	1.51	2.33	1.56	0.98	2.32	2.30	0.79	13
Ningxia	5.08	9.66	0.95	1.11	1.23	0.49	0.70	0.46	0.33	49
Xinjiang	9.77	25.6	1.20	0.97	1.62	0.87	2.34	1.28	1.27	51

of Greenness and agricultural yield, due to lack of corresponding experience data cannot directly ensure the relation of greenness to production. However, some researchers have proven that appropriately increasing the use of renewable resources attributes to yield improvement (Faramarzi et al., 2010). Despite this, agri-products currently depend more on non-renewable resources, which means that agriculture is still based on “potatoes made of oil”. Thus, increasing Greenness in agriculture is another way to achieve sustainable agriculture.

Simultaneously, there are physical limits to greenness, and it is impossible to increase greenness without limit. **Table 6** presents the natural resources and the maximum proportion of theoretical renewable resources in the current planting pattern. The calculation detail can be seen in Appendix, showing that, in Tianjin, Hebei Shanxi, Inner Mongolia, Liaoning, Jilin Heilongjiang, and Ningxia, the rate of renewable resources is relatively low, indicating that the amount of renewable resources available for agricultural development is relatively small. The reason for this is that the agricultural water consumption in these provinces is higher than total local water resources, regardless of the transfer of water from other places. On the contrary, the rate of maximum renewable resources in Tibet can reach 97.5%, but that is under ideal conditions, and not the case in reality. Thus, improving the renewable resource input can increase greenness, but there is a physical limit as it only changes the cultivation

mode, and developing a circular mode is better for realizing the sustainable development of agriculture.

### 4.3 Impact of Greenness Enhancement on Ecosystem Services

This study calculates the ecosystem services and dis-services of China’s crop system. The results show that the ecosystem dis-services produced by the agricultural production process in China’s agricultural system are higher than the ecosystem service. The particularity of agriculture needs to further explore whether the accounting of overall ecosystem services should consider agricultural ecosystem services, according to the calculation of other ecosystem ecological services by Qing Yang et al. (2019), Yang et al. (2019), Yang et al. (2020), as seen in **Table 7**, compared to other ecosystem services, the contribution rate of crop systems is about 25%, with Henan province taking the highest proportion. Thus, we can conclude that the agricultural ecosystem should be considered when calculating overall ecosystem services.

However, the ecosystem services produced by crop systems are higher than that of other ecosystems. It is important to develop solutions for the challenging issue of maintaining ecosystem services while reducing ecosystem dis-services. Improving greenness is an effective way to achieve this goal. According to previous results, the dis-services mainly come from fertilizers and

**TABLE 8** | The ecosystem service value of different ecosystems in energy consumption reduction scenarios.

	<u>Grain</u>	<u>EDS</u>	<u>Wheat</u>	<u>EDS</u>	<u>Maize</u>	<u>EDS</u>	<u>Oil plants</u>	<u>EDS</u>	<u>Beans</u>	<u>EDS</u>	<u>Tubers</u>	<u>EDS</u>
	<u>ES</u>		<u>ES</u>		<u>ES</u>		<u>ES</u>		<u>ES</u>		<u>ES</u>	
Beijing	0.13	17.71	0.32	6.16	0.47	6.43	0.14	6.43	0.18	18.05	0.18	4.10
Tianjin	0.33	2.54	0.33	2.69	0.48	2.88	0.04	2.88	0.06	16.32	0.15	1.99
Hebei	0.31	3.18	0.28	3.36	0.39	3.47	0.26	3.47	0.50	2.09	0.06	1.67
Shanxi	0.19	2.77	0.14	2.89	0.35	3.50	0.97	3.50	1.44	4.88	0.01	0.45
Inner mongolia	0.18	1.50	0.13	1.56	0.19	1.95	0.18	1.95	0.29	2.21	0.07	0.91
Liaoning	0.22	4.81	0.15	4.73	0.36	5.22	0.43	5.22	0.60	6.68	0.05	1.40
Jilin	0.22	3.79	0.11	3.69	0.35	4.32	0.12	4.32	0.20	15.25	0.06	1.00
Heilongjiang	0.18	2.44	0.08	2.26	0.24	2.63	0.00	2.63	0.01	28.22	0.28	5.26
Shanghai	0.49	4.50	0.48	4.32	0.32	4.39	0.43	4.39	0.55	19.02	0.05	0.76
Jiangsu	0.35	3.58	0.45	3.58	0.23	3.53	0.36	3.53	0.52	20.23	0.02	0.39
Zhejiang	0.55	8.39	0.32	8.19	0.31	8.26	0.35	8.26	0.46	9.75	0.28	6.96
Anhui	0.32	4.31	0.42	4.33	0.23	4.30	0.19	4.30	0.29	27.38	0.02	0.77
Fujian	0.18	3.36	0.12	3.28	0.13	3.35	0.19	3.35	0.30	1.14	0.35	7.21
Jiangxi	1.07	5.97	0.19	5.57	0.20	5.63	1.83	5.63	2.37	6.36	0.05	1.12
Shandong	0.21	4.59	0.21	4.81	0.19	4.87	0.58	4.87	1.31	3.14	0.06	1.40
Henan	0.45	3.37	2.53	5.68	1.82	4.83	4.50	4.83	6.54	3.92	0.15	0.74
Hubei	0.29	5.06	0.21	5.16	0.16	5.22	2.65	5.22	4.17	2.41	0.02	1.08
Hunan	0.67	3.35	0.16	4.67	0.21	4.75	3.33	4.75	4.58	2.84	0.04	0.88
Guangdong	0.64	8.17	0.13	7.92	0.19	8.06	1.17	8.06	1.84	1.85	0.23	7.56
Guangxi	0.53	4.31	0.12	4.11	0.27	4.27	0.29	4.27	0.44	2.35	0.20	4.67
Hainan	0.93	36.82	0.00	0.00	0.00	0.00	1.76	0.00	2.42	2.18	0.86	27.24
Chongqing	0.19	1.73	0.09	0.14	0.16	1.88	0.16	1.88	0.28	0.61	0.53	4.57
Sichuan	0.20	2.05	0.18	0.09	0.20	2.21	0.51	2.21	0.82	0.36	0.19	2.16
Guizhou	0.16	0.85	0.15	0.07	0.24	0.99	0.38	0.99	0.57	0.33	0.44	1.62
Yunnan	0.19	2.75	0.13	0.06	0.29	2.96	0.08	2.96	0.13	2.35	0.32	5.44
Tibet	0.35	1.45	1.00	0.36	0.97	1.52	4.61	1.52	5.29	7.74	0.04	0.06
Shannxi	0.20	1.13	0.18	0.18	0.18	1.43	0.17	1.43	0.30	0.72	0.12	1.45
Gansu	0.18	6.15	0.18	0.14	0.19	6.37	0.30	6.37	0.48	1.61	0.36	13.11
Qinghai	0.00	0.00	0.17	0.20	0.18	1.26	0.78	1.26	1.81	0.37	0.11	0.83
Ningxia	0.21	0.74	0.38	0.13	0.40	0.97	1.03	0.97	1.27	0.14	0.87	2.04
Xinjiang	0.26	1.57	0.70	0.19	0.69	1.81	2.07	1.81	2.39	4.07	0.09	0.55

fossil energy. An improvement in greenness means that the use of external resources in the production process will be reduced, and at the same time, the dis-service will be reduced. For ecosystem services, the service provided by the agricultural ecosystem mainly depends on plant photosynthesis and the physical and chemical properties of the soil, so the improvement in greenness does not necessarily lead to an improvement of ecosystem services. Instead, more effective use of cultivated land is needed. Within a reasonable range, maximizing the planting of crops in a certain planting area is one method of improving ecosystem services.

### 4.3 Impact of Energy Consumption on Ecosystem Services

While the agriculture system achieves the yields that humans demand, it often brings energy consumption, which causes the dis-services generated. Agricultural energy consumption mainly comes from irrigating water and mechanical farming. Thus, improving irrigation and mechanical use efficiency will lead to reductions in energy consumption. **Table 8** shows the energy use efficiency of China's agriculture and that of other developed countries, comparing ecosystem services and dis-services. The results show that ecosystem services and dis-services decrease in all provinces. Reasonable reduction in

energy consumption will cause ecosystem dis-services to decrease but ecosystem services will also be reduced at the same time. Although this method is beneficial to the environment and ecology, the yields may not meet human needs, Enhancing energy use efficiency is not a suitable way of achieving sustainable agriculture. Based on this, some scholars have proposed the concept of organic agriculture. Organic agriculture refers to a farming system that enhances soil fertility through maximizing the efficient use of resources while foregoing the use of agrochemicals, as well as that of many synthetic compounds, which are used as food additives (Siegmeier and Moeller, 2013). Organic agriculture relies on a number of farming practices based on ecological cycles, and aims at minimizing the environmental impact of the food industry, preserving the long-term sustainability of soil, and reducing the use of non-renewable resources (Gomiero et al., 2011). Organic agriculture proposes a pathway to realizing sustainable agriculture and reconciling the relationship between nature, society, and the economy.

### 4.4 Policy Implication

It is necessary to find solutions to develop sustainable agriculture that balance ecology and production. This study presents several suggestions.



- 1) The production of the agricultural system was mainly dominated by fertilizers and pesticides which are major sources of pollution. Thus, the government should implement a series of policies to strengthen the management of pesticides and fertilizers. First, improving the ability of pesticides and fertilizers to guarantee food security and ensuring the quality and safety of agricultural production through the formulation and implementation of policies (Zheng et al., 2020). Second, promoting rational positioning and coordinated development of the pesticide industry in various regions. Vigorously enhancing industrial agglomeration, accelerating the concentration of pesticide enterprises in professional parks or chemical industry clusters, reducing production dispersion, and reducing point source pollution (Zulfiqar and Thapa, 2017).
- 2) Improving energy efficiency and the use of local renewable resources. The intensive use of fossil fuels caused an increase in local ecological pressure. Thus, it is crucial to optimize local energy structures by encouraging more renewable and clean energy sources (such as solar power, wind power, and geothermal power) and improving energy efficiency by promoting more energy efficient technologies and equipment (Lou et al., 2015). Meanwhile, farming skills that can reduce energy use should be taught to agricultural workers to make more efficient use of energy.
- 3) Circular agriculture should be developed. Circulating agriculture is a comprehensive management model that organically links planting, animal husbandry, fishery, and processing industries. Su et al. presented an emergy assessment of three Chinese agricultural farming categories, including traditional cropping systems, integrated ecoagricultural framing systems (i.e., rich-fish and rich-duck), and the currently booming NGP activities (i.e., nursery plantation, pond fish farming, vegetable production, and duck rearing), which demonstrate considerable differences among the seven investigated systems, with the R% of integrated rice-fish (54.66%) being the highest and the R% of pond fish farming (5.53%) being the lowest (Su et al., 2020b). A virtual cycle of the overall ecological chain can be formed to propose feasible schemes to solve agricultural pollution problems and save agricultural resources while improving the output effect of agricultural products and realizing a balanced development of ecology and economy.

#### 4.5 Limitations and Future Research

There are some limitations to this study. The data are mainly from the China Statistical Yearbook, China Rural Statistical Yearbook, and other relevant literature. More results could be considered due to the availability of data, due to biodiversity loss, and accurate data not being available, meaning some calculations were not carried out. Therefore, more data should be obtained in future studies, and the ecosystem services and dis-service between organic agriculture, traditional agriculture, and circular agriculture should be compared.

## 5 CONCLUSION

This research proposed an Em-LCA analysis framework to account for the ecosystem services and dis-services of six typical crop systems. Ecosystem services include food supply, local microclimate regulation, carbon sequestration, and groundwater recharge, and ecosystem dis-services include GHG emissions, water and soil pollution, and soil erosion. The results showed that the R% of the six typical crops in China are all less than 5%, and their development relies more on external resources, causing more ecosystem dis-service generation. Although ecosystem services are also produced, they account for only approximately one-tenth of the ecological services. From the perspective of spatial distribution, the provinces with the highest net ecosystem service value are mainly concentrated in places with more cultivated land resources, such as Henan, Shandong, and Hebei. In addition, this study found that the current market price of agricultural leather has a low correlation with the greenness of the product. Agriculture is a semi-artificial ecosystem, and the more external resources are invested, the more yields can meet the needs of human society and provide more benefits. However, greenness cannot be improved indefinitely. At the present stage of social and economic development, secondary and tertiary industries need more resources to promote social progress. Agriculture has fewer renewable resources to use and needs to maintain food security and the risk factors of agricultural waste and by-products (Donner et al., 2021), which represent major challenges for sustainable agriculture. Furthermore, compared to reducing energy consumption without changing farming practices, organic farming is a suitable way to increase ecological value. Nevertheless, part of the income obtained by agricultural products can compensate for the dis-services brought by the production process of products, such as greenhouse gases, etc., and reduce the dis-services by appropriately subsidizing forest and wetland ecosystems, which might be one way to realize the value of eco-products. This study analyzes the current crop system in China from an ecological perspective, and interpreted its impact on the ecological environment, providing a method of accounting for the value of agricultural eco-products.

## DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Material**, further inquiries can be directed to the corresponding author.

## AUTHOR CONTRIBUTIONS

GL was responsible for overall project supervision, conceptualization, data curation and project management; YW, GL, YC, and MC contributed to methodology development, conducted validation, and contributed to the writing of early drafts and final draft review and editing; BG, FA, and CA were instrumental in formal analysis of data.

## FUNDING

This study is supported by the National Natural Science Foundation (No. 52070021) and the 111 Project (No. B17005).

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## SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fenvs.2022.824275/full#supplementary-material>

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