Agro-ecological compensation of watershed based on emergy

Yicheng Fu, Xia Du, Benqing Ruan, Laisheng Liu and Jian Zhang

ABSTRACT

The paper aims at providing a framework to calculate the agro-eco-compensation standard based on the systems agro-ecological concept of embodied energy as emergy. We have proposed a calculation system of eco-compensation standard for sustainable agricultural development based on the convertibility between emergy and price. According to our calculation, the total energy of agricultural production in Yongding River Basin was 3.45 E + 16 Sej/ha (the unit emergy value, expressed in solar emergy joules per unit) in terms of the renewable resources, nonrenewable resources, material inputs, and service costs. The energy of renewable and nonrenewable resources was 1.59 E + 16 and 1.86E + 16 Sej/ha, respectively. The ESI (environmental sustainability index) of the study area was 0.1056, indicating that its agricultural production was in a seriously unsustainable condition. To realize the sustainable agricultural production in the watershed, the downstream governments should pay $21.81 M (¥135 million) approximately to upstream governments for water and soil conservation. The results of the present study suggested that the emergy-based calculation method of agro-eco-compensation standard is feasible to a certain degree.

Key words | agricultural production, agro-eco-compensation, emergy, Yongding River Basin

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INTRODUCTION

Agro-eco-service values are indirectly reflected by the surrounding eco-environment (this refers to all living and non-living things around us, within which we live and work), investment, and habitat. As a complex ecosystem, the indirect service value of the agro-ecosystem is beneficial to its enhancement (Yuan & Cao 2007). For example, the paddy field ecosystem has a significant role in temperature regulation and air quality improvement (Li *et al.* 2005). Although competitive water utilization and wide application of pesticides and chemical fertilizers can promote stable and efficient agricultural production, it reduces the protein content of crops and increases the probability of food pollution (Giannetti *et al.* 2011).

The objectives of agro-eco-compensation are to protect and maintain sustainable ecosystem services. Eco-compensation is an environmental economic policy to protect the environment and promote harmony between humanity and nature. The agro-eco-compensation includes two kinds of understandings (Benayas & Bullock 2012), namely compensation for agricultural ecology (focus on keeping the integrity of the agricultural ecosystem) and eco-compensation for agriculture (with a focus on preventing the destruction of the eco-environment during agricultural production). Various models of the management mechanisms of agro-eco-compensation have been constructed based on the regional characteristics of agricultural production (Liron *et al.* 2011). To compensate farmers for their losses caused by environmental protection, the EU implemented agro-eco-compensation in the forms of subsidies for agricultural environment protection and compensation for environment-limited areas (Laterra *et al.* 2012). To realize a coordinated development of agricultural ecology and regional economy, Wu *et al.* (2014) employed a set of emergy indicators to quantify the sustainability of an ecosystem. Emergy is the amount of available energy of one type (usually solar), that is directly or indirectly required to generate a given output flow or storage of energy or matter. The unit of emergy is the emjoule or emergy joule. In most cases, farmers were not sufficiently compensated because their capital investment and losses of developmental opportunity are unequal to their contribution to the agricultural economy and ecosystem service (Fu *et al.*

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2012). The current eco-compensation standard is calculated based on the willingness to pay, but the influences of carrier changes, time or risk factors on the implementation of the compensation standard are not considered. Odum & Odum (1996) developed the idea that energy provides a common basis for integrating economic and ecological sciences, by using energy language to study open systems. As an effective means to study the agro-eco-service input-output correlation, the emergy approach is an environmental accounting methodology that can be used to assess natural inflows and services within a system. The method is an embodied energy analysis that uses solar energy as reference, to assess the impact of human activity on ecosystems.

Emergy analysis has been widely employed to evaluate the resources consumed by various systems at different temporal and regional scales. We proposed the agro-eco-compensation standard for watershed systems based on emergy analysis in the present study. Some scholars have carried out integrated methodological studies in agro-eco-projects (Wu *et al.* 2013a, 2013b; Yang & Chen 2014), biomass energy production systems (Cavalett & Ortega 2010; Zhang & Long 2010), and emergy-based decision-supporting systems in agricultural services analysis (Rydberg *et al.* 2007; Pulselli *et al.* 2011). Zhang *et al.* (2016) used emergy analysis to explore the comprehensive performance of crop production and economic benefit, environmental pressure and sustainability in China from 2000 to 2010. Emergy analysis with corresponding indices and ratios has been proved to be an effective tool to understand agro-eco-services value flows. At present, the agro-eco-emergy assessment processes of most studies are currently in the form of reviews. By considering the different components of the agro-ecosystem, the emergy assessment method of integrated eco-society and ecological production systems was studied less. The system is used to support the generation of one unit of economic product (expressed in monetary terms), also one unit of direct labor applied to a process. During this process, the emergy-money ratio (emergy/total income of the residential unit) and emergy intensity (emergy/total habitable area in the residential unit's dwellings) is difficult to calculate. To evaluate the ecological endowment embodied in human agricultural production, the direct and indirect fluxes originated from the boundary can be well traced by proper eco-society coupling databases (Han *et al.* 2014). Eco-endowment is an important indicator to describe regional eco-diversity, which can be well traced by proper intensity data. Eco-boundaries contain a mixture of species from the two adjacent ecosystems. Adjacent ecosystems are connected via flows of energy, material and organisms across ecosystem boundaries, and eco-fluxes can exert strong influences on the fertility and productivity of ecosystems (Shao & Chen 2016). A set of indicators have been proposed by emergy analysis to illustrate the efficacy, sustainability, environmental costs and benefits, as well as the interaction between nature and human society of the production systems.

In this paper, the compensation standards for sustainable agricultural development were determined according to corresponding correlation, by calculating the energy of agro-eco-services. Agro-eco-compensation is also an effective way to solve conflicts between farming and ecological destruction. We proposed the emergy analysis-based study system as the agro-eco-compensation standard. The aim of the study is to propose a calculation system of eco-compensation standard for sustainable agricultural development, based on the convertibility between emergy and monetary payments. The basic structure of this paper is as follows: 1. Introduction, the background and theoretical significance of agro-eco-compensation standard, and energy study in this paper; 2. Materials and methods, which includes Study area, Emergy analysis, Methodology, and Basic data; 3. Results and Discussion, which contains Calculation result (Input of R, N, M, and S); 4. Conclusions.

MATERIALS AND METHODS

Study area

Yongding River is one of the seven major river systems in the Haihe River Basin, is located at $E112^\circ$–$117^\circ45'$ and $N39^\circ$–$41^\circ20'$. The two tributaries, Sanggan River and Yang River in the upstream of Yongding River, are integrated together in Zhuguan Village, Huailai County, Hebei Province. In the paper, the upper watershed of Guanting Reservoir (Datong and Suzhou in Shanxi Province and Zhangjiakou in Hebei Province) is selected as the study area (Figure 1). The study area is located at the upstream of Yongding River. The developed local agricultural production leads to high consumption of chemical fertilizers and agricultural nonpoint source pollution. In this paper, based on the theory of emergy analysis, the agro-eco-compensation standard is determined by calculating the agricultural production cost and agro-ecological value. The service values and protection costs of the non-arable terrestrial lands have been introduced by Fu *et al.* (2011).

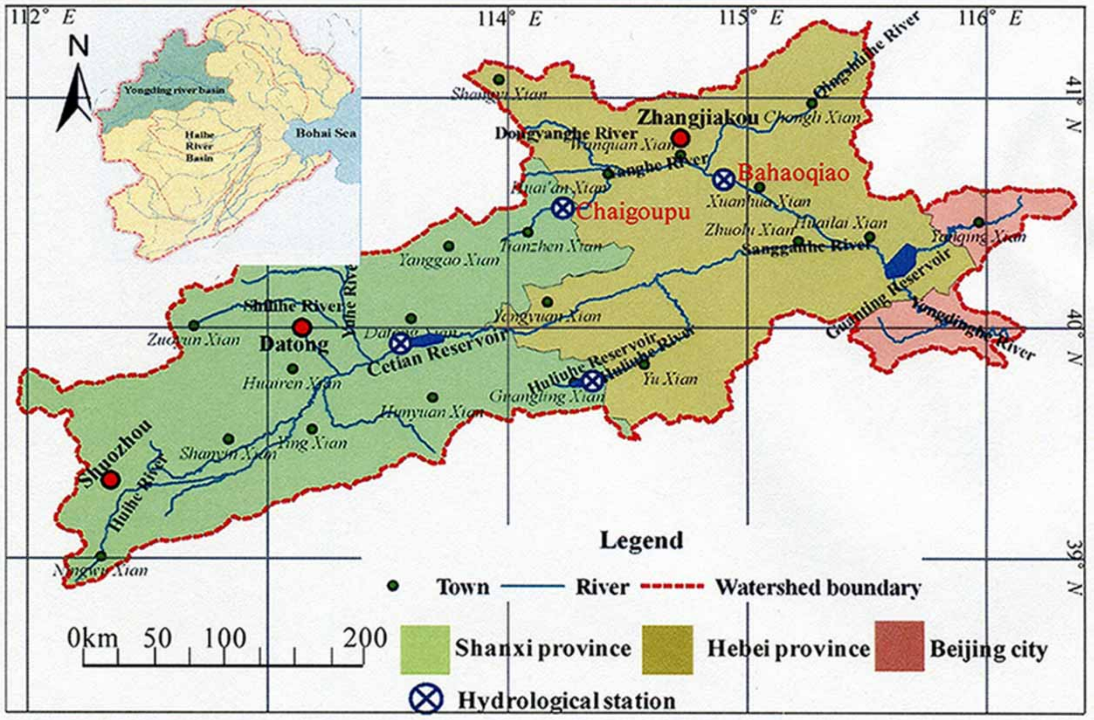

Figure 1 | The geographical location of the Yongding River Basin.

Emergy analysis

In the calculation of agro-ecological compensation standard, the core is to determine the amount of compensation, which can reflect the values, costs and benefits of agro-ecosystem services and be accepted by farmers and governmental departments. In emergy analysis, with solar energy as a benchmark, various non-comparable values or products are converted into measurable economic data. The analysis method can effectively avoid the interference caused by market price fluctuation and the uncertainty in the underlying data of ecosystem services. The economic prosperity is not only dependent on the contribution from the goods and services valued in money, but also relied on the environmental protection costs (Yang *et al.* 2010). A policy priority on an energy source with little if any net energy return, which contributes to climate change rather than alleviating the problem, and which contributes to several other serious environmental problems. The value of environmental and human activity within a system are a common basis (Odum & Odum 1996). The solar emergy of products and services can be calculated by multiplying the amount of energy by transformity (Emergy investment per unit process output of available energy, transformity may be used as an energy-scaling factor for the hierarchies of the universe including information (Odum 1988)), the amount of mass by specific emergy, and money by emergy per unit money. Therefore, natural contributions and economic contributions required to produce agricultural yields can be quantified and compared, based on a common basis of solar energy (solar em joules is solar emergy, which is abbreviated seJ). Calculating emergy techniques allow direct comparison of competitive species, industries, or technologies using standard methods of linear algebra (Amaral *et al.* 2016). It is a noneconomic method for determining relative value based on the quality-normalized available energy of all kinds required for the production or service within any system. To give a complete assessment of eco-economic sustainability, the evaluation of emergy is already an ecological economic assessment itself. Watershed agro-eco-compensation, which is difficult to be valued in economic market: (1) the embodied energy analysis and emergy analysis are difficult to evaluate the whole production chain, including cropping, transportation, extraction, and final production; (2) the specific emergy to money ratios of all the input flows to the concerned processes is difficult to calculate (Fu *et al.* 2012; Zhang *et al.* 2016). By applying the concept of emergy to eco-compensation that integrates nature and society, farmland management can realize the economic and environmental sustainability. Wang *et al.* (2017) used a wheat-maize double-cropping system fertilized by different sources of recycled biomass in the North China Plain to account for the emergy of recycled agricultural biomass. In the theory of emergy, various inputs, storages, outputs, and other energy forms of agro-ecological system can be converted into comparable emergy. By converting the economic value into the emergy per unit product, the compensation standard could be calculated for different inputs and agro-ecological service products (Yi *et al.* 2010).

Methodology

In the paper, natural resources, agricultural products, and economic inputs for environment-friendly agricultural production were converted into emergy flows. Emergy accounting includes the free environmental resources, which are often ignored, and accounts for the energy and materials that flow into/out of the watershed in the form of solar energy. For a regional ecosystem, the energy input contains the imported, gathered, constrained and extracted commodities, while the output contains the exported products and materials (Chen & Chen 2009). In short, inputs of agro-ecosystems are classified into three types: (1) renewable resources in the watershed (R), such as sunlight, rainfall, wind, surface runoff, hydraulic projects, nutrients (nitrogen, phosphorus, potassium, and calcium), and biomass; (2) non-renewable resources in the watershed (N), net loss of topsoil due to soil erosion; (3) economic inputs of environment-friendly production (F) in the watershed, which consists of services (S), such as labor, management and maintenance and services, purchased nonrenewable materials (M), such as mechanical equipment, fuels, electricity, and other materials. The outputs of this system (Y) primarily include wheat, corn, soybean, cotton, peanut, vegetable, fruit, etc. F is provided by the market or economic flows (Ortega *et al.* 2002).

The EYR indicator is defined as the ratio of the purchased energy that is fed back from the external system to the sum of free environmental energy inputs. The smaller the ratio, the lower the economic cost. ELR is the ratio of the total non-renewable energy flows to the energy of the total renewable inputs. ELR indicates the load on the environment, and the lower the ratio, the lower the environmental pressure. ESI takes both ecological and economic compatibility into account, which evaluates the sustainability of a process or system. The larger the ESI, the higher the sustainability of a system. The Energy Efficiency Rate (EER) represents the conversion relationship between energies and values during the transaction of agro-eco-service values. As a conversion factor, EER reflects the quantitative value of energy. The larger the EER, the more solar energy is required to produce the resource, product or service of interest, and the higher their position in the energy hierarchy (Odum 1988; Odum & Odum 1996). Odum and his colleague have calculated the EER of various products and services. Detailed references for calculating emergy values can be found in Odum & Odum 1996. Energy assessment can provide the basis for the combined ecological and economic assessment according to emergy price calculation (Em$). The parameters used in emergy calculation are provided in Table 1.

Based on the energy assessment theory of the agro-ecosystem, we first calculated the energy of products and service functions of the agro-ecosystems in the study area, and then determined the agro-eco-compensation standard according to the conversion coefficient between energy and the market values as well economic inputs of agricultural products. To obtain accurate results, we considered the previous

Table 1 | Energy calculation indices

Symbols	Descriptions	Equations
EYR	Energy yield ratio: the ratio of the energy of the output ($Y = R + N + F$) to the energy of input (F) (Odum & Odum 1996).	$\mathrm{EYR} = Y/F$
ELR	Environmental loading ratio: the ratio of non-renewable energy ($N + F$) to renewable energy (R) (Ulgiati & Brown 1998). It is an indicator of the pressure on the ecosystem due to production activity (Brown & Ulgiati 1997).	$\mathrm{ELR} = (N + F)/R$
ESI	Environmental sustainability index: to obtain the highest yield ratio at the lowest environmental loading.	$\mathrm{ESI} = \mathrm{EYR}/\mathrm{ELR}$
EMR	Energy ratio: energy supporting the economy of a country (Y) to its gross domestic product (GDP).	$\mathrm{EMR} = Y/\mathrm{GDP}$
EER	Energy exchange ratio: which gives the extent of the relative trade advantage of one partner over another.	$\mathrm{EER} = Y/\mathrm{EMR}$
Em$	Emprice: the energy received in the product for each dollar paid for the product	Em$ = GDP. EYR

Y is the total emergy; N, F, and R are non-renewable resources, which are provided by the market and related to fluxes that account for economy, and renewable resources, Sej; GDP is gross domestic product, ¥10,000. In the table, EYR, ELR, and ESI have been widely used to evaluate the environmental sustainability of agricultural systems.

results of water and soil loss as well as ground (underground) runoff variation (Adekalu *et al.* 2007).

Additional insight into the ternary diagram (Giannetti *et al.* 2006) representing the three main energy flows revealed the low proportion of purchased input, which showed that ESI (Environmental Sustainability Index) and ELR are very sensitive to the energy cost of agro-eco-services. The implementation of environment-friendly agricultural production increases additional investment of farmers to the land to a certain extent and increases the positive eco-benefits of agricultural production. According to the calculated data of ESI, the eco-compensation objects are defined as follows. If $\mathrm{ESI} > 5$, the agro-eco-system had high ecological sustainability, and the government was not required to compensate farmers for their inputs. If $1 < \mathrm{ESI} < 5$, the agro-ecosystems required external artificial interference to realize sustainability, and the government was required to compensate farmers for their inputs in environment-friendly production modes. If $\mathrm{ESI} < 1$, the agricultural ecosystem was unsustainable, and farmers and government should share the investment in agricultural environmental measures (Giannetti *et al.* 2012). ESI is based on the relevant relationships among R, N, and F (Figure 2). Figure 2 is the schematic diagram of the relationship between ESI and the implementation of eco-compensation.

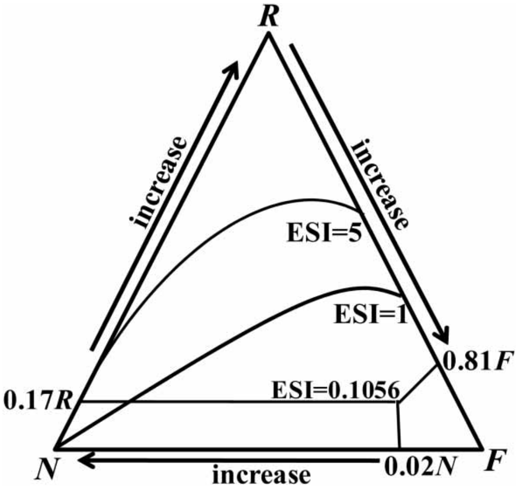

Figure 2 | Schematic diagram of the correlation between ESI and the implementation of eco-compensation. ESI is the environmental load index. The boundaries between different degrees of sustainable development are shown, which indicates that the environment is in an optimal condition and that this condition will maintain for some time if renewable input reaches a given level. The areas of different regions represent the ratio of inputs to resource consumptions at different development level of the study area. The areas have no actual physical meanings. There are an infinite number of combinations of R, N and F, and only some of them correspond to real systems on the planet. The upper part of the diagram shows the region ($\mathrm{ESI} > 5$) where systems are sustainable for a long time; the middle part marks the region ($1 < \mathrm{ESI} < 5$) where systems are sustainable for the medium term; the lower part of the diagram shows a region ($\mathrm{ESI} < 1$) where systems are not sustainable. On the three sides of the diagram, the values of ESI environmental sustainability indices ($\mathrm{ESI} = 0.1056$) can be calculated for a given case.

Basic data

The land use types in the Yongding River watershed were obtained from the remote sensing images of Thematic Mapper (TM) and Enhanced Thematic Mapper plus (ETM+), as well as field survey data in 2013. The data source is from the public website (www.geodata.cn). The land use types were divided into cultivated land (irrigated field and dry field), woodland, grassland, wasteland, water bodies, etc. The area of cultivated land in different calculation units was derived by the statistical analysis function of a geographic information system (GIS), based on the diagram of land use types in the watershed (Table 2). The data of a Digital Elevation Model (DEM), soil properties, land use/cover, climate data such as precipitation, and temperature were comprehensive, and the database of detailed socio-economic data was obtained from the local subareas of 2013. Based on the statistics yearbooks of agriculture in Shanxi and Hebei Provinces (2013), some important crops such as wheat, corn, soybean, peanut, cotton, fruit, and vegetable were selected as the typical crops. Crop growth will lead to nutrient loss from the cultivated land, therefore, we classified and analyzed the amount of nutrient loss in per unit cultivated land based on the multi-year mean values (Table 3).

Table 2 | Area of cultivated land (ha) in the Yongding River Basin

	Administrative region		
Water resource zoning	**Province**	**City**	**Area of cultivated land**
Upper reaches of Cetian Reservoir in the Yongding River watershed	Shanxi	Datong	102,709
		Shuozhou	206,105
		Xinzhou	2,706
	Total		311,520
Between Cetian Reservoir and Sanjiadian in the Yongding River watershed	Hebei	Zhangjiakou	257,069
	Shanxi	Datong	114,881
	Total		371,950
Total sum of the Yongding River Basin			683,470

RESULTS AND DISCUSSION

Calculation result

Because most kinds of available energy are directly or indirectly driven by solar energy, we generally convert each form of energy in a system into its solar energy equivalent, or solar emergy. The calculation of emergy flows per

Table 3 | Condition of nutrient loss in the cultivated land in the study area (kg/ha)

Crop	Phosphorus/P	Potassium/K	Nitrogen/N	Calcium/Ca	Others
Wheat	20.8	20.5	115.8	1.0	9.3
Corn	12.2	16.6	83.4	0.4	9.7
Soybean	8.9	28.6	96.3	9.1	3.9
Cotton	5.7	13.1	30.9	1.2	2.8
Peanut	5.3	45.8	46.3	3.7	5.7
Vegetable	13.3	148.8	92.6	18.5	10.4
Fruit	2.1	30.1	30.9	1.9	2.1
Total	68.3	303.5	496.2	35.8	43.9

unit area in the study area is the basis for determining the values of ecosystem services and input costs. Based on the data of input and output costs in the study area, we calculated the energy flow of the agro-ecosystems in 2013 as follows. The equations are shown in the appendix (available with the online version of this paper).

Input of renewable resources (R)

Sunlight. The irradiation efficiency of sunlight is 5.29 kw/m^2 and ground reflection ratio is 20% (Ulgiati *et al.* 1995). The energy efficiency of the ground is 4.23 kw/m^2 and the energy conversion efficiency of sunlight is 3.6E + 06 J/kw (Brandt-Williams 2002). The irradiated area of sunlight per unit area is 1.0E + 04 m^2/ha (Haden 2003). After energy conversion, the energy of sunlight per unit area is 1.52E + 11 J/ha.

Rainfall. In 2007, the mean precipitation in the Yongding River watershed was 483.5 mm (Fu *et al.* 2012). The energy and density per unit mass of water are 5,000 J/kg and 1,000 kg/m^3, respectively (Wu *et al.* 2013a, 2013b). The quantity of precipitation collected per unit area is 1.0E + 04 m^2/ha. Therefore, the energy input of rainfall is 2.42E + 11 J/ha. The air and water have different energy flows (unit/ha), and energy expression forms. The Wind kinetic energy = (Area) × (Air density) × (Drag coefficient) × (Geostrophic wind)^3. According to the view of Odum & Odum (1996), the intrinsic energy of air is not used as in the water case.

Wind energy. Wind-resisting area per unit ground area is 1.0E + 04 m^2/ha. The air density is 1.3 kg/m^3 (Coppola *et al.* 2009). According to the meteorological data in the recent 50 years in the Haihe River Basin, the annual average wind speed in the study area is 2.5 m/s, and wind speed at the ground layer is 1.5 m/s, which is 60% of the annual average wind speed. The resistance coefficient is 0.001. If the calculation interval is one year, namely, 3.15E + 07 s, the wind energy per unit area is 1.39E + 09 J/ha.

Surface runoff. The quantity of surface runoff was 1.48E + 08 m^3 in 2007 based on the precipitation-runoff conversion coefficient of the area of cultivated land in the study area. The quantity of water for agricultural purposes was 8.58E + 07 m^3, which accounted for 60% of total water consumption in the study area (Hansen & Nielsen 1995). The area of cultivated land in the study area is 683,470 ha. The energy and density per unit mass of water are 5,000 J/kg and 1,000 kg/m^3, respectively. The energy of surface runoff caused by cultivated land is 6.26E + 08 J/ha.

Hydraulic projects. In 2007, the quantity of water acquisition by hydraulic projects was 2.87E + 07 m^3 during the process of agricultural production in the study area (Shao & Chen 2016). Thus, the energy of hydraulic projects per unit area is 2.10E + 08 J/ha.

Nutrient elements. According to the data in Table 3 and corresponding correlation between material and energy (Schjønning 1995; Sibbesen 1995), the energy flow of nitrogen, phosphorus, potassium and calcium in the study area can be as follows.

$$E_N = 496.3\ J/ha;\ E_P = 68.3\ J/ha;\ E_K = 303.5\ J/ha;$$
$$E_{Ca} = 35.8\ J/ha.$$

Biomass. Based on the previous results of Aber & Melillo (2001) and Ponce-Hernandez *et al.* (2004), the biomass in the study area was 4.21E + 09 kg. The arable land area is 683,470 ha. If the valid biomass of one kilogram of biomass is 16,744 J/g, the energy of biomass per unit area in the study area is 1.03E + 11 J/ha.

Inputs of nonrenewable resources (N)

Soil loss in the Yongding River Basin is 4,000 kg/ha (Hu & Wang 2004). According to the results of Huang *et al.* (1994), the soil in the study area is dominated by cinnamon soil, and the content of organic matter in the soil is 0.022 kg/ha. The energy preserved in per unit soil mass is 2.26E + 07 J/kg (Schjønning 1995; Sibbesen 1995). The energy loss caused by soil erosion per unit area is 2.49E + 09 J/ha.

Materials (M)

Material depreciation. Considering the diversification of production tools and their differences in service lives in the agro-ecosystems, the energy of depreciation of agricultural production materials in the study area is ¥925/ha on the basis of Coelho *et al.* (2003).

Fuels. Fuels and other power resources consumed in the study area for agricultural production, crop management and harvesting are 1.15E + 07 L. The density of fuel is 0.75 kg/L. The energy per unit mass of fuel is 4.186E + 06 J/kg (Ghaley & Porter 2013). The energy from fuel combustion per unit area is 5.28E + 07 J/ha.

Electricity. In current agricultural production in the Yongding River Basin, the water for agricultural irrigation is mainly pumped by diesel engine. In some cases, a small quantity of water is pumped by electric engine, but it can be omitted. Thus, the electricity power in the Yongding River Basin, with low agricultural modernization level, can be omitted.

Substances. The energy of substance mainly refers to the cost in cash spent on seeds, mulch membrane, and ground supporting facilities used in agricultural production and management. According to the agricultural statistics yearbook in the watershed, the energy of substance per unit area in the study area is ¥4,300/ha.

Services

Labor force. The current cost of the labor force is very high. Therefore, more labor force and time will be invested to agricultural production when the same amount of value is created. We calculated the energy of the labor force in the study area by scoring the weight of local benefit per yearbook data, comparing the labor force investment of domestic and international labor costs, and considering the opportunity cost of migrant laborers. The energy of the labor force in the study area is ¥3,900/ha. The average investment of eco-forest management in Yongding River basin is ¥3,900/ha. The cost of the labor force is higher than 281.3 $/ha/yr (the cost of labor from land preparation to harvest) (Ghaley & Porter 2013); however, the cost of labor input is related to the low level of agricultural mechanization in Yongding River Basin.

Management and maintenance. During the process of agricultural production, the cost of management and maintenance of agriculture in the Yongding River Basin is low and mainly includes the maintenance of footpaths among farmland and piping networks. This kind of facility has long service life and requires less management and maintenance cost. Thus, according to previous results (Guo *et al.* 2014), the energy of management and maintenance per unit area in the study area is ¥76/ha.

Services. The agricultural landscape for tourism purposes in the Yongding River Basin covers rather less area. Thus, the service energy per unit area in the study area is lower and it is ¥10/ha (Franzese *et al.* 2009).

Result discussion

Emergy flow

Emergy is defined as the available energy of one kind previously used up directly and indirectly to make a service or product, usually quantified in solar energy equivalents and expressed as solar em Joules (Sej). The ratio of emergy required to make a product or service to the present energy of the product or service is defined as the transformity and correspondingly the solar em Joules of a product or service is calculated by multiplying units of energy by the transformity. The units of transformity are solar em Joules/unit, abbreviated as Sej/unit. In addition, other conversion coefficients are also used, such as specific emergy (solar em Joules/ha (Sej/ha), ratio of emergy to currency (solar em Joules/¥(Sej/¥)). And transformity, specific emergy and ratio of emergy to currency can be generally called unit emergy values (Odum & Odum 1996; Brown & Ulgiati 1997; Odum *et al.* 2000). The amount of emergy flow in the agricultural system in the Yongding River Basin was calculated based on the calculated energy inputs and outputs of agro-ecological system, together with the conversion coefficient between emergy and energy, and the available proportion in the calculation list (Table 4).

Based on the results calculated above and the basic data of the study area, the ESI of the environmental and economic input of the agricultural ecosystem was 0.1056, a value far lower than the characteristic value of a sustainable agriculture system, 5 (If ESI < 1, the agricultural ecosystems are unsustainable). In the study area, EYR and ELR were 1.11 and 10.51, respectively. Therefore, unsustainable inputs or outputs account for a large proportion during the process of agricultural production. This is main reason that leads to the inefficient agricultural production and high environment cost in the Yongding River Basin. In order to realize the sustainable development of agriculture in the Yongding River Basin, the governmental department in the study area should increase investments to sustainable agricultural production and strengthen environmental management through the implementation of agro-ecological compensation. We drew an energy triangle to characterize the proportion of various resources and inputs in the total energy of the study area (Figure 2). During the emergy assessment of agro-ecosystems, the energy flow of the Yongding River Basin is shown in Figure 3 (Brown *et al.* 2004). The diagram of emergy flows includes the most important flows of materials and energy at the input and

Table 4 | Evaluation of emergy flow in the agricultural ecosystem in the Yongding River Basin

Items	Description	Renewable ratios	Units	Energy flow (unit/ha)	Emergy transformity (Sej/unit)	Renewable emergy (Sej/ha)	Unavailable emergy (Sej/ha)	Total emergy (Sej/ha)
R	Light	1	J	1.52E + 11	1	1.52E + 11	0	1.52E + 11
	Rainfall	1	J	2.42E + 10	3.10E + 04	1.94E + 15	0	1.94E + 15
	Wind	1	J	1.39E + 09	2.45E + 03	3.41E + 12	0	3.41E + 12
	Surface runoff	1	J	6.26E + 08	4.85E + 04	3.04E + 13	0	3.04E + 13
	Hydraulic projects	1	J	2.10E + 08	2.55E + 05	5.36E + 13	0	5.36E + 13
	Nutrient N	1	kg	496.3	6.38E + 12	2.98E + 15	0	2.98E + 15
	Nutrient P	1	kg	68.3	3.90E + 09	2.66E + 11	0	2.66E + 11
	Nutrient K	1	kg	303.5	1.74E + 12	5.28E + 14	0	5.28E + 14
	Nutrient Ca	1	kg	35.8	1.00E + 12	3.58E + 13	0	3.58E + 13
	Biomass	1	J	1.03E + 11	1.00E + 04	1.03E + 15	0	1.03E + 15
N	Soil erosion	0	J	2.49E + 09	1.24E + 05	0	3.08E + 14	3.08E + 14
M	Material depreciation	0.05	¥	925	3.30E + 12	0.15E + 15	2.90E + 15	3.05E + 15
	Fuel and lubricants	0	J	5.28E + 07	5.50E + 05	0	2.90E + 13	2.90E + 13
	Substances	0.1	¥	4,300	3.30E + 12	0.14E + 16	1.28E + 16	1.42E + 16
S	Labor	0.6	¥	3,900	3.30E + 12	0.77E + 16	0.52E + 16	1.29E + 16
	Management and maintenance	0.1	¥	76	3.30E + 12	0.25E + 14	2.26E + 14	2.51E + 14
	services	0.05	¥	10	3.30E + 12	0.17E + 13	3.14E + 13	3.30E + 13
Total		–	–	–	–	1.59E + 16	1.86E + 16	3.80E + 16

1. All these conversion coefficients were based on the emergy baseline, 15.83E + 24 Sej/year.

2. The reference values for emergy conversion are collected from the results of Odum *et al.* (2000), Brown & Arding (1991), Brown & Bardi (2001), Odum & Odum (1996), Ponce-Hernandez *et al.* (2004), Campbell *et al.* (2005), and Lan *et al.* (1998).

3. The renewable rate indicates the probability of an item belonging to renewable energy.

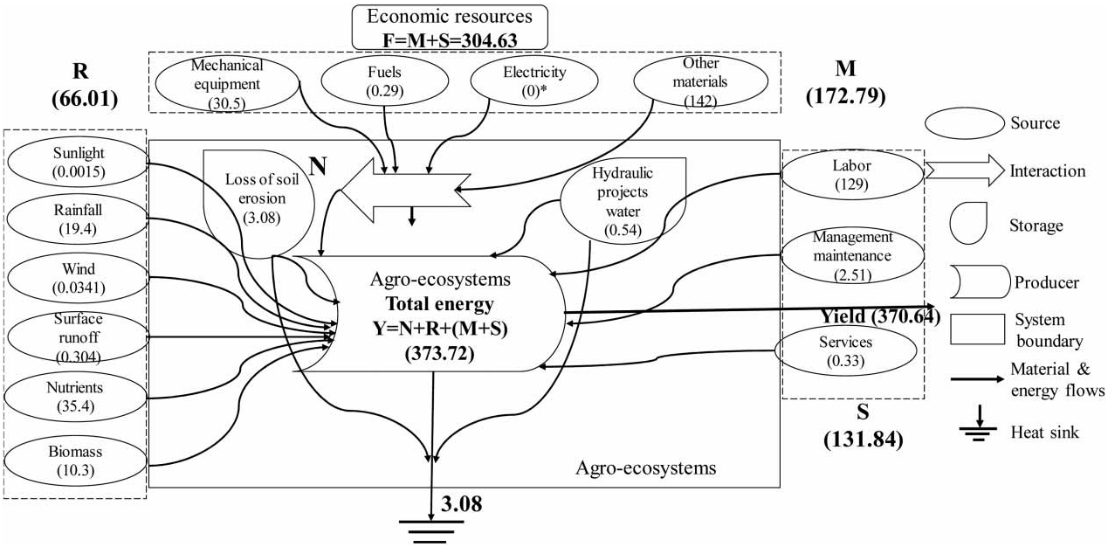

Figure 3 | The emergy flows of the Yongding river basin (unit: E + 14 Sej/ha). Emergy flow can effectively represent the environmental benefits of a system. N, R, and F have been widely used to assess the sustainability of the agricultural production system. The method of emergy analysis is a tool that takes into account the inputs from nature and economic development, an equal base that uses energy as a common basis of measure (Costanza 2000). Energy-based indices account for local renewable emergy inputs (R), local nonrenewable inputs (N) and purchased inputs outside the system (F) (Brown & Ulgiati 1997). In the Yongding River Basin, agricultural irrigation water is mainly pumped with diesel engines and a small quantity of water pumped with electric engines can be omitted. The electricity energy in the Yongding River Basin can be omitted.

output. For the evaluation of emergy units, the most important natural flows considered were energy from the sun, wind kinetic energy, loss of surface soil, food, water, mechanical equipment, electricity, and fuels. The only feature not corresponding to dwelling operational stage considered was the building materials in the structure; this was examined to explore the approximate value they represent of the total emergy used.

Agro-eco-compensation standard

Agricultural production in the Yongding River Basin is in an unsustainable condition. The above-mentioned Figure 3 helps to compare the performance of the considered emergy flows with an emphasis on the environmental support (measured as emergy from the used goods and services) needed for the daily running of agricultural production. Emergy-to-money ratio is calculated as the ratio of the total emergy flow to related monetary evidence. Its expression is derived from a macro-systemic (i.e. a national or a regional) analysis by dividing the total annual emergy by the gross domestic product (GDP). Emergy-to-money ratio depends on the total energy flow, GDP, prices and exchange rates among currencies. Only emergy is directly related to physical entities. The others are determined by market dynamics (Bastianoni *et al.* 2007). In this paper, we calculated the financial compensation value based on the conversion coefficient between energy and economic value of the ecosystems, which is consistent with the energy of environmental investment and ecological services in the study area. Emergy prices of agricultural production inputs and environmental benefits in the Yongding River Basin are listed in Table 5.

From the perspective of material and service inputs during agricultural production, the compensation for agricultural production inputs in the Yongding River Basin is $21.6 G/¥13.4 billion (the sum of the values of materials (M) and services (S)). The maximum ecological service values of the land may be achieved through eco-compensation. However, the value shall not be considered as the agro-ecological compensation standard for the following three reasons. Firstly, the main beneficiaries of agricultural production inputs are the farmers in the upstream. Under the overflow condition of positive ecological benefits (the value of ecosystem services in agricultural production and their agricultural products are shared in the area out of the river basin), the downstream obtains less benefits. According to the rule of 'The beneficiary party makes the compensation', the downstream is unwilling to compensate the upstream for their agricultural production inputs. Secondly, the seriously unsustainable status of agricultural production does not mean that the downstream shall be responsible for the inefficient production in the upstream. Inefficient production and high pollution are caused by

Table 5 | Emergy prices of agricultural production in the Yongding River Basin

Properties	Details	Emergy (Sej/ha)	Emergy price (¥/ha)	Total value ¥E + 08
R	Light	1.52E + 11	0.1	0
	Rainfall	1.94 E + 15	1,246.9	8.52
	Wind energy	3.41 E + 12	2.19	0.01
	Surface runoff	3.04 E + 13	19.54	0.13
	Hydraulic projects	5.36 E + 13	34.45	0.24
	Nutrient element N	2.98 E + 15	1,915.35	13.09
	Nutrient element P	2.66 E + 11	0.17	0
	Nutrient element K	5.28 E + 14	339.36	2.32
	Nutrient element Ca	3.58 E + 13	23.01	0.16
	Biomass	1.03 E + 15	662.02	4.52
N	Soil erosion	3.08 E + 14	594.53	1.35
M	Material depreciation	3.05 E + 15	1,960.34	13.4
	Fuel and lubricants	2.90 E + 13	18.64	0.13
	Substances	1.42 E + 16	9,126.83	62.38
S	Labor	1.29 E + 16	8,291.28	56.67
	Management and maintenance	2.51 E + 14	161.33	1.1
	Services	3.30 E + 13	21.21	0.14

1. Data in the table may be zero due to the requirements of significant digits, but zero does not affect the precision of results.
2. The reference values for emergy conversion are collected from the results of Agostinho & Pereira (2013), Franzese *et al.* (2009), Ghaley & Porter (2013), Odum & Odum (1996), Bastianoni & Marchettini (2000), Brown *et al.* (2004), Brandt-Williams (2002), and Coelho *et al.* (2003).

several factors and the extensive application of fertilizers in the upstream is one of the most important reasons. Thirdly, this value does not reflect the current situation of agro-ecological degradation. It can only reflect the reason for the unsustainable agro-ecological condition. Water and soil loss as well as the farmland ecosystem imbalance leads to an unsustainable agriculture in the study area. Therefore, in the context of agro-ecological environmental degradation, the energy of water and soil loss in the river basin is 3.08×10^{14} Sej/ha, and the resulting economic loss is (soil loss value). Therefore, in order to minimize the environmental damage caused by agricultural production in the Yongding River Basin, local government and the downstream beneficiaries should pay $21.81 M (¥135 million) to the upstream farmers for their inputs in field management.

However, due to the high intensity of renewable energy flow, ESI and EYR in the Yongding River Basin remained relatively low. We therefore concluded that the emergy is the most reasonable estimation of the agro-eco-compensation standard in the Yonding River Basin when taking the ecological services of sustainable development into account. Based on our practice, it is feasible to estimate the emergy of agro-ecological protection cost in another farmland by transformities. In the future, the leading work of compensation standard based on emergy estimation will continue.

CONCLUSIONS

The determination of eco-compensation standard involves complex factors. The current agro-compensation standards were mainly obtained through qualitative decision or survey, whereas quantitative methods were seldom adopted. We firstly calculated the emergy of R, N, M, and S. The ESI of the watershed is 0.1056; the agricultural production in the study area in an unsustainable state. To achieve sustainable agricultural production in the Yongding River Basin, the downstream government and the beneficiary sectors should pay $21.81 M (¥135 million) approximately to the upstream farmers as compensation.

Emergy is a relatively new concept. Researchers have been working to prove the validity of emergy by life cycle assessment, ecological footprint, GIS and strategic environmental assessment (Amaral *et al.* 2016). There are still some shortcomings when performing uncertainty analysis of emergy, clarifying emergy algebra specificities. We should consider emergy as a management tool by taking the methodological improvements of agro-eco-compensation into account, and make it applicable at the operational level in the future.

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