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Regulation of modern "grass-sheep-field" agro-pastoral cycle system based on life cycle assessment

Yuan Shen[1,2], Haihou Wang[1,2], Yueyue Tao[1,2], Changying Lu[1,2], Linlin Dong[1,2], Linlin Shi[1,2], Meijuan Jin[1,2], Xinwei Zhou[1,2], Mingxing Shen[3,*]

[1] *Suzhou Academy of Agricultural Sciences (Institute of Agricultural Sciences in Taihu Lake Region), Suzhou 215105, Jiangsu Province, China*

[2] *National Agricultural Experimental Station for Soil Quality, Xiangcheng, Suzhou 215155, Jiangsu Province, China*

[3] *Suzhou Country Cadre Institute (Suzhou Cadre Institute), Suzhou 215011, Jiangsu Province, China*

*** Corresponding author:** Mingxing Shen, smxwwy@163.com

ABSTRACT

Modern circular agriculture is an important way to realize the green development of agriculture and promote the overall revitalization of rural areas. However, the traditional circular agriculture system based on farmers' experience lacks accurate data support and parameter matching, which makes the efficient circular operation of the system face challenges. Therefore, in this study, based on the investigation of the data acquisition and tracking, using the life cycle assessment of the modern "grass-sheep-field" farming cycle system for empirical research, through the analysis of the characteristic, normalized, and weighted assessment categories, potential environmental impacts, and calculating the control system simulation to downgrade the required environment before and after service, The results showed that the potential environmental impacts of feed processing and Huyang breeding subsystems were more than 85% of the total impacts, which were much higher than those of grain planting and organic composting subsystems. The environmental impact of human toxicity and water ecotoxicity in each subsystem is greater, while terrestrial ecotoxicity is the least. The annual environmental services of air, water, and soil required for pollution reduction are 7.42 × 1010 J, 6.03 × 1016 J, and 1.59 × 1012 J, respectively. Through the simulation and regulation of the system through the coordination of coupling parameters and the optimization of key technologies, it is estimated that the annual environmental services required by the system can be reduced by 52%, 44%, and 21%, respectively, compared with the original system. Based on life cycle assessment, this study developed a method system that is suitable for the modern "grass-sheep-field" agro-pastoral cycle system and guides its overall regulation, which has guiding significance for the sustainable development, replication, and promotion of the modern agro-pastoral cycle system and can provide a reference for the optimization and adjustment of other modern agro-pastoral cycle systems.

Keywords: circular agriculture; life cycle assessment; potential environmental impacts; pollution reduction; environmental services

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1. Introduction

Circular agriculture is to realize the industrial cycle of ecological agriculture, which refers to the principle of a compound ecosystem and the theory of circular economy. Industry, upstream and downstream, will be planting, breeding, processing, and other agricultural production organizations built into an approximate closed cycle system to achieve efficient use of resources, reduce waste emissions, and improve the economic benefit of agricultural economic organization form[1]. Different from the spontaneous formation of traditional circular agriculture, large-scale industrialized modern circular agriculture requires precise interfaces and smooth connections of various production links so as to promote the recycling of energy metabolites in the whole agricultural ecosystem and reduce the impact of pollution emissions on the environment[2].

The unique resource endowment and development level of different regions in China give birth to various modern circular agriculture models. However, the construction of these circular agriculture systems mostly relies on the traditional experience of agricultural practitioners and lacks accurate data support and parameter matching. This may lead to an imbalance between demand and supply in certain links, resulting in the dispersion and arrest of substances, poor system circulation, and environmental pollution, thus affecting the sustainable operation of the modern circular agriculture system[3]. In addition, as the actual operators of the system are mostly enterprise entities, driven by the one-sided pursuit of output benefits, they tend to ignore the efficient utilization of local agricultural waste resources and fail to reach the original design intention of the "closed cycle" of the system, making it difficult to replicate and promote the modern circular agriculture model[4].

As an effective tool to evaluate the environmental impact of the whole chain of the product system, life cycle assessment (LCA) has been widely used in industry. With the gradual increase in pressure on agricultural resources and the environment, the application of life cycle assessment in the agricultural field has been gradually expanded[5]. Europe, the United States, and other developed areas are in the leading position for agricultural life cycle assessment methods. Tricase et al.[6] compared the environmental impacts of organic and traditional barley cultivation in Italy. Christensen et al.[7] discussed the life-cycle GHG emissions and improvement measures of community-supported agriculture in the United States. Masuda[8] used the method of combining life cycle assessment and data envelopment analysis to measure the ecological efficiency of wheat production in Japan at the regional scale. Studies on agricultural life cycle assessment in developing countries are increasing. Taki et al.[9] compared the environmental performance of wheat cropping systems under different irrigation methods in Iran. Jimmy et al.[10] evaluated the different impacts of rice production on the environment in Bangladesh. Studies on agricultural life cycle assessment in China focus on the analysis of agriculture-related products and the comparison of industrial chains and models. Yang et al.[11] calculated the energy consumption and emissions in the whole life cycle of biodiesel prepared from soybean oil and gutter oil. Bai[12] studied the environmental impacts and related geographical factors during rice production in different rice regions of Liaoning Province. Chen et al.[13] used agricultural carbon footprint theory and life cycle assessment to quantitatively analyze the carbon footprint composition and influencing factors of rice and wheat rotation patterns in the lower reaches of the Yangtze River. In recent years, some scholars have tried to apply life cycle assessment to the circular agriculture system. Liang et al.[14] improved the life cycle assessment model and studied the circulating duck industry in Hunan Province. Zhang et al.[15] put forward the technical framework of life cycle assessment for the agricultural circular economy. Wang et al.[16] introduced life cycle assessment into emergy analysis to evaluate the sustainability of large-scale pig breeding systems in North China. Fan et al. [17] analyzed the environmental load and benefit of the sub-industrial chain of Fujian's "pig-marsh" circular agriculture model from both environmental and economic aspects. Dorr et al.[18] took recirculating mushroom farms as an example and analyzed the impact of food production systems on the environment through life cycle assessment.

At present, there are few studies on the impact control and pollution abatement of environmental emissions based on the results of life cycle assessment. Bakshi[19] pointed out that from the regional spatial and temporal scale, environmental emissions with relatively high concentrations are usually unusable “harmful outputs”, which need to be “diluted” into environmentally acceptable states or harmless substances with harmless concentrations after entering the environmental system through the services provided by them. Ulgiati et al.[20] proposed to use “indirect environmental services” to calculate the energy input needed to drive the process of atmospheric dilution environmental emissions, which provided a reasonable and feasible method for evaluating the harmful output of the system. The potential impacts of environmental emissions from agroecosystems on different environments, such as air, water, and soil, are very significant and urgently require comprehensive consideration and quantitative assessment. Environmental service energy is the energy consumed by diluting different types of potential pollution to a safe concentration in different environments based on the results of a life cycle assessment. It can comprehensively evaluate the sustainability of the system from the perspective of system output on the basis of system input. This study calculates the environmental service capacity of pollution degradation, which can provide a parameter basis for the overall regulation and control of modern agricultural and animal husbandry cycle systems and has guiding significance for the application, practice, replication, and promotion of modern agricultural and animal husbandry cycle models. At the same time, it can provide a reference for the optimization and adjustment of other modern circular agricultural systems.

2. Research objects and methods

2.1. Research objects

This team created the modern “grass-sheep-field” farming cycle model, which integrated innovation in “mechanical collection wrapping package fermentation and processing technology of straw, mutton sheep full day mixed feed formula technology, mechanical collection and sheep dung compost technology, and sheep dung manure returning moderate mechanical technology” as the core technique[21], has become a technology popularization leading mode in Jiangsu Province. Suzhou Jincanghu Agricultural Technology Co., Ltd., as the main enterprise and production carrier, conducted a case demonstration in Donglin Village, Chengxiang Town, Taicang City, Jiangsu Province. The modern agricultural and animal husbandry cycle system constructed includes four sub-systems: grain planting, feed processing, Huyang breeding, and organic composting (**Figure 1**). Among them, feed processing and organic composting are separated from the intermediate by-products of the agro-pastoral complex ecosystem after industrialization to promote the efficient operation of the system. Their outstanding ecological and economic benefits provide support for the prosperity of the local industry. The system is an agroecological system that connects planting and breeding closely. It is of great significance to realize the integration of planting and breeding, the combination of agriculture and animal husbandry, and the consideration of grain and grass. It is in line with the basic characteristics of modern circular agriculture and is typical.

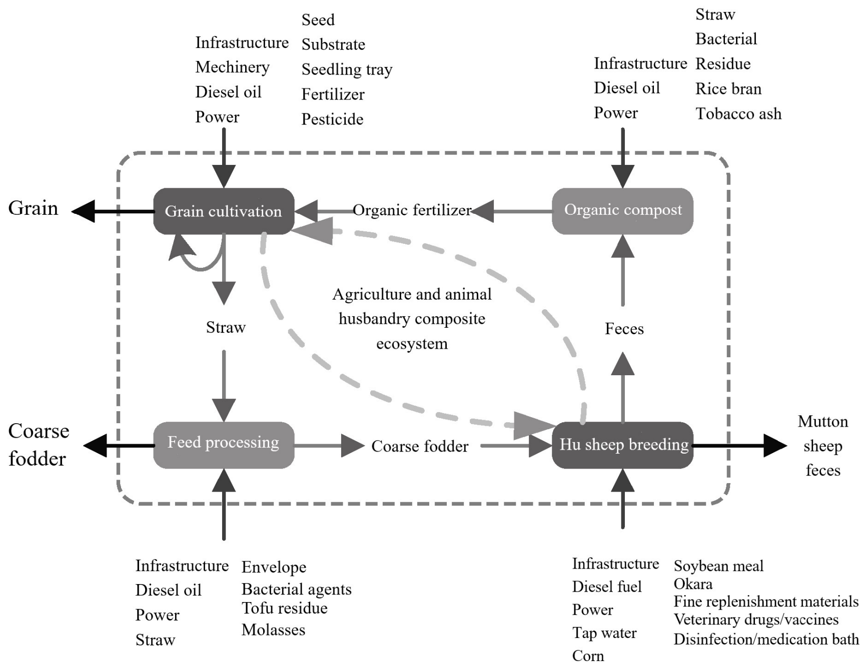

Figure 1. Construction of modern agro-pastoral circular system.

Donglin Village Circular Agriculture Characteristic Demonstration Base has invested 133.33 hm^2 of high-standard farmland, a 1.33 hm^2 feed plant, a 3.33 hm^2 breeding farm, and a 0.5 hm^2 organic fertilizer plant in infrastructure construction and energy support (**Figure 1**). In the wheat season, part of the wheat is fallow. In the rice season, the machine-inserted blanket seedlings raised in the greenhouse are planted in the field after the application of organic manure from sheep manure. In the two seasons of rice and wheat, agricultural machinery such as tillage, seeding, management, and harvesting are equipped for the whole mechanized production, and some straw is directly returned to the field. Feed processing uses crop straw and soybean residue, molasses, and other planting and processing industry wastes through beneficial microbial fermentation to produce forage and livestock. Hu sheep breeding is standardized by feeding a roughage-based, total mixed diet. Organic compost is made of sheep manure as a raw material, supplemented with agricultural wastes such as bacterial residue, rice bran, and crop straw. The application of modern "grass-sheep-field" agricultural and animal husbandry cycles in Donglin Village provides an effective way to alleviate the dual pressure of agricultural resources and the environment in socially and economically developed areas.

As the grey box control method is adopted in the design process of the Donglin Village case and no feedback measurement has been carried out in the implementation process, there is still room for improvement in the overall sustainable cycle operation efficiency. First of all, due to the tight cropping time, wheat straw has not been utilized at a high value due to the implementation of full return to the field, and the collection rate of rice straw is only 80%. As a result, a large amount of straw needs to be purchased from outside for feed processing and organic composting, which fails to make full use of planting waste resources in the system. Secondly, only one-third of sheep manure produced by farming is converted into organic manure by the organic composting sub-system and applied to rice cultivation, which needs to be supplemented by organic manure purchased from other sources, resulting in the waste of farm waste in the system and increasing environmental risks. The input-output mismatch among sub-systems and the neglect of potential environmental impacts result in obstacles to the efficient cycle operation of the system. Therefore, it is necessary to conduct in-depth analysis of the results through evaluation and apply them to case studies to guide the overall regulation of the circular agriculture system so as to promote the popularization and application of modern agricultural and pastoral cycle models.

2.2. Research methods

In this study, life cycle assessment is first applied to interpret and analyze the classification results of the collected data list from the perspective of specific potential environmental impacts, including steps such as characterization, standardization, and weighted assessment[22]. Subsequently, the environmental services of air, water, and soil required by the pollution degradation process with potential environmental impacts are quantitatively calculated[16]. Finally, through sub-system coupling and parameter adjustment, the current system is simulated and regulated, and the required environmental service energy before and after system regulation is compared.

2.2.1. Characteristic

Based on a certain environmental stress factor in an influencing factor, the relative impact potential of the influencing factors was obtained, and then the potential environmental impact characteristics of various influencing factors were calculated (Equation (1)). Six types of potential environmental impacts, namely acid potential, global warming potential, terrestrial ecotoxicity, human toxicity, water ecotoxicity, and eutrophication potential, which are closely related to agricultural production, were selected from the CML-IA baseline evaluation model in the study, according to the life cycle inventory database Ecoinvent 3.7.1[23]. The characteristic value was calculated by Openlca 1.10 software[24].

$$I_{P(x)} = \sum I_{P(x)i} = \sum \left[Q_{(x)i} I_{F(x)i}\right] \tag{1}$$

where $I_{P(x)}$ refers to the eigenvalue of the system's impact on the x environment; $I_{P(x)i}$ refers to the potential impact of the ith stress factor on the x environment; $Q_{(x)i}$ refers to the emission of the ith stress factor in the x environmental impact, kg; $I_{F(x)i}$ refers to the equivalent coefficient of the influence of the ith stress factor on the x environment.

2.2.2. Standardization

The purpose of standardization is to eliminate the differences in dimensions and levels of each single result. The selected benchmark quantity can generally be the total or mean data of resource consumption or environmental emissions in the world, a country or a certain region (Equation (2)). In this study, the characteristics of life cycle assessment results were standardized on the basis of various environmental load benchmarks in the global 100-year time scale of 2000 updated by Van Oers[25] and the total global population in that year[26] calculated by the UN Population Division (**Table 1**).

$$R_x = I_{P(x)}/S_{year(x)} \tag{2}$$

where R_x refers to the standardized result of the characteristic value of the system's influence on the x environment; $S_{year(x)}$ refers to the base value (kg) of the selected year's impact on the x type of environment.

Table 1. Normalization and weight coefficients in this study.

Environmental impact	Normalization/kg	Weight
Acidification potential (AP)	39.06	0.19
Global warming potential (GWP)	6908.81	0.17
Terrestrial ecotoxicity (TE)	178.76	0.13
Human toxicity (HT)	421.78	0.19
Freshwater aquatic ecotoxicity (FAE)	386.74	0.15
Eutrophication potential (EP)	25.90	0.17

Note: Acidification potential, global warming potential, terrestrial ecotoxicity, human toxicity, Freshwater aquatic ecotoxicity and eutrophication potential were indicated by SO_2, CO_2, 1, 4-dcb, 1,4-DCB, 1,4-DCB and PO_4 respectively (the same as below).

2.2.3. Weighted evaluation

Different types of environmental impacts are of different importance to the sustainable development of the same country or region. It is generally necessary to assign specific weights to different types of environmental impacts to calculate the comprehensive pressure of the system on the environment of a specific region (Equation (3)). Based on the existing research progress in China, Wang et al.[27] were referred to in the study to normalize the weight values of different types of environmental impacts determined by expert evaluation, and weighted assessment was carried out on the standardized results of life cycle assessment (**Table 1**).

$$\mathrm{EI} = \sum W_x R_x \tag{3}$$

where EI refers to the weighted assessment value of environmental impact of the system; W_x is the weight of the x- th environmental impact.

The required environmental service energy can be calculated from the energy input to drive the dilution process[16]. The quality of wind, water, and soil required to achieve degradation of potential environmental impacts in air, water, and soil can be calculated from the eigenvalues of environmental impacts and the acceptable concentrations of each pollutant (Equation 4). Then, according to the corresponding energy contributions of wind energy, surface water chemical energy, and surface soil (Equations (5)–(7)), the environmental service energy E required for pollution degradation is calculated.

$$M = I_{P(x)}/c_x \tag{4}$$

where M refers to the mass (kg) of wind (M_A), surface water (M_W) or soil (M_S) used to dilute pollution; c_x refers to the standard limit value of the index pollutant with the x environmental impact in the standards related to ecological and environmental protection.

$$E_A = M_A \cdot DC \cdot v^2 \tag{5}$$

$$E_W = M_W \cdot G \tag{6}$$

$$E_S = M_S \cdot P_{OM} \cdot T \tag{7}$$

where E_A, E_W and E_S refer to the energy contribution of wind, surface water and surface soil, respectively. DC refers to the wind resistance coefficient, 0.001; v is the wind speed, m/s; G is Gibbs free energy, 4940 J/kg; P_{OM} refers to the content of organic matter in soil, g/kg; T refers to the energy conversion coefficient of the corresponding organic matter, 20,900 J/g.

2.2.4. Regulatory pathways

After analyzing the input-output and potential environmental impact of the modern "grass-sheep-field" farming and animal husbandry cycle systems through life cycle assessment, in order to improve the internal material cycle efficiency of the cycle system and reduce the external environmental emission impact, this study believes that the overall regulation of the system can be mainly achieved through two approaches: Firstly, the coupling parameters of each sub-system are coordinated, and the output of the sub-system is matched with the input of its successor sub-system with the objective of waste in situ consumption (Equation (8)). The second is to optimize the technical parameters of the key links, minimize the environmental impact, and implement measures of source reduction, process control, and end treatment to reduce pollution.

$$P_n = D_{n+i} \tag{8}$$

where P_n is *the* waste supply quantity of the *n*th subsystem; D_{n+i} *is* the waste demand *of* the *n*+*i* subsystem. In this study, rice and wheat straw and Hu sheep feces are the main breeding wastes in modern farming and animal husbandry circulation system.

2.3. Data sources

Since May 2019, the research team has conducted a comprehensive data collection and tracking survey on the case of the modern agricultural and animal husbandry circulation system in Donglin Village. On the one hand, semi-structured interviews were used to conduct detailed consultations with the leaders of cooperatives, feed mills, breeding farms, and organic fertilizer factories to grasp the main economic input and output of each link of the system. On the other hand, through the methods of industrial follow-up investigation and ecological monitoring investigation, all inputs entering the system and all output (emission) items leaving the system can be accurately counted. In this process, pay attention to collecting and sorting out the natural environment and socio-economic data in the Suzhou Statistical Yearbook from 2016 to 2020.

Through the statistical collation of the collected data, the annual input-output data of the system is used as the functional unit for analysis. In the research, the boundary of the system is defined by a "four-dimensional space-time scale": "two-dimensional" area is the production place of each subsystem; the upper limit of "height and depth" space is the standard height of 10 m surface wind; and the lower limit is the soil depth of 1 m root system of food crops. The "fourth dimension" of time is one natural year. In this system, 300 lambs, 1300 ewes, and 1200 rams are kept in stock every year, and feed feeding and immunization program adjustment management and input sharing are carried out according to different stages of individuals. The data list of the projects invested by the system throughout the year is shown in **Table 2**.

Table 2. Inventory of input items of modern agro-pastoral circular system annually.

Subsystem	Area/m^2	Input items	Raw data	Source
Cereal cropping	Wheat planting 1,123,333.33	Wheat seed/kg	16,850.00	a
		Formula fertilizer/kg	45,000.00	a
		Urea/kg	37,912.50	a
		Pesticide/kg	610.45	a
		Electricity/(kw·h)	22,008.75	b
		Diesel oil/kg	11,440.97	c
		Mechanical/kg	1297.45	d
	Rice planting 1,333,333.33	Rice seed/kg	8000.00	a
		Matrix/kg	10,7750.00	a
		Seedling tray/kg	2500.00	a
		Greenhouse (damage)/m^2	1000.00	e
		Maintenance/m^2	666.67	f
		Sheep manure organic fertilizer (self-produced)/kg	2,007,500.00	a
		Organic fertilizer (purchased)/kg	992,500.00	a
		Slow release fertilizer/kg	100,000.00	a
		Urea/kg	18,000.00	a
		Pesticide/kg	915.68	a
		Electricity/(kw·h)	138,122.74	b
		Diesel oil/kg	22,279.83	c
		Mechanical/kg	2900.00	d

Table 2. (*Continued*).

Subsystem	Area/m^2	Input items	Raw data	Source
Feed producing	13,266.67	Straw (self-produced)/kg	800,000.00	a
		Straw (purchased)/kg	15,520,000.00	a
		Envelope/kg	113,657.14	a
		Bacterial agent/kg	65.28	a
		Bean curd residue/kg	4,896,000.00	a
		Molasses/kg	326,400.00	a
		Feed mill (damage)/cubic meter	3316.67	e
		Infrastructure maintenance per cubic meter	663.33	f
		Electricity/(kW·h)	1,221,914.77	b
		Diesel/kg	20,216.35	c
Sheep raising	33,333.33	Corn/kg	2,555,000.00	a
		Bean curd/kg	1,277,500.00	a
		Okara/kg	3,193,750.00	a
		Roughage (self-produced)/kg	638,750.00	a
		Intensive supplement/kg	31,500.00	a
		Veterinary drug/vaccine/kg	56.40	a
		Disinfection/medicated bath/kg	12,840.00	a
		Tap water/kg	35,300,250.00	a
		Farm (damage)/head	350.00	e
		Infrastructure maintenance/head	70.00	f
		Electricity/(kW·h)	357,057.28	b
		Diesel/kg	4778.24	c
Organic composting	5000.00	Feces (self-produced)/kg	2,098,750.00	a
		Straw (purchased)/kg	182,500.00	a
		Mushroom residue/kg	365.00	a
		Rice bran/kg	292,000.00	a
		Tobacco ash/kg	182,500.00	a
		Organic fertilizer plant damage)/square meter	250.00	e
		Infrastructure maintenance/square meter	50.00	f
		Electricity/(kW·h)	235,798.48	b
		Diesel/kg	3842.75	c

Note: a was derived from field research; b was converted from electricity fee statistics of agricultural electricity price published by State Grid; c referred to the calculation of transport distance from Liang[28]; d referred to the calculation of mechanical input from Wang[29]; In e, the greenhouse was depreciated by the 10-year service life, while the feed factory, breeding farm and organic fertilizer factory were depreciated by the 20-year service life; f was converted according to the ratio of maintenance cost to investment cost.

2.3.1. Pollution degradation

Pollution degradation and the output of potential environmental impacts generated during system operation. On the other hand, the boundary of the system is defined by industrial tracking investigation and ecological monitoring: the "two-dimensional" area is the production place of each subsystem; the upper limit of "height and depth" space is the standard height of 10 m surface wind; and the lower limit is the soil depth of 1 m root system of food crops. The "fourth dimension" of time is one natural year. In this system, 300 lambs, 1300 ewes, and 1200 rams are kept in stock every year, and feed feeding and immunization program adjustment management and input sharing are carried out according to different stages of individuals. The data list of the projects invested by the system throughout the year is shown in **Table 2**.

The effective products produced by the case system throughout the year are wheat 5.48 × 10^5 kg, rice 1.15 × 10^6 kg, mutton sheep 1.90 × 10^5 kg, roughage 2.46 × 10^7 kg, and the effective products participating in the internal circulation of the system are organic fertilizer 2.01 × 10^6 kg and roughage 6.39 × 10^5 kg, and the by-products involved are 8.00 × 10^5 kg of rice straw and 2.10 × 10^6 kg of sheep manure, and another by-product sheep manure of 3.65 × 10^6 kg is collected and transported out of the system as waste. In addition, the direct emissions of the grain planting and organic composting sub-systems were obtained by analyzing the experimental monitoring data of static black box and gas chromatography, and the comprehensive industrial research data of the direct emissions of the Huyang sub-systems were calculated by referring to the relevant research results of Milan[30] and Li et al.[31].

3. Research results and analysis

3.1. Potential environmental impacts of sub-systems

According to the annual input project data list of the system and referring to the life-cycle inventory database Ecoinvent 3.7.1, the software Openlca 1.10 was used to obtain the characteristics and results of six different types of potential environmental impacts generated by the subsystems and processes of the modern "grass-sheep-field" agro-pastoral cycle, as shown in **Table 3**. The potential environmental impacts of the whole life cycle of each subsystem mainly come from agricultural inputs, agricultural management, transportation processes, and direct emissions.

Table 3. Characterization values for potential environmental impacts of modern agro-pastoral circular system (kg· a^{-1}).

Subsystem	Process	AP	GWP	TE	HT	FAE	EP
Cereal cropping	Wheat - Sowing	256.98	33,349.05	563.45	22,101.00	18,294.29	144.57
	Wheat - Fertilization	833.85	199,637.51	222.55	128,337.29	75,492.56	267.60
	Wheat - Insect and weed control	147.61	22,202.28	54.48	29,429.64	16,148.35	45.09
	Wheat - Harvest	128.21	322,523.82	61.77	13,813.56	11,436.74	36.92
	Wheat - Transportation	129.74	28,641.21	38.77	11,697.84	8925.44	32.51
	Rice - Seedling raising	229.82	187,003.37	101.12	26,566.39	19,904.24	103.93
	Rice transplanting	153.02	24,871.65	73.79	16,844.64	13,890.69	44.20
	Rice farming	183.24	30,511.98	89.09	23,738.28	19,034.35	54.27
	Rice - Irrigation	109.20	26,563.16	24.44	8430.24	6181.76	25.48
	Rice - Fertilization	1291.60	342,622.86	371.34	198,761.55	121,127.08	464.18
	Rice - Insect and weed control	219.95	33,044.87	80.99	43,876.37	24,017.82	67.17
	Rice - Harvest	152.18	740,156.26	73.31	16,395.92	13,574.77	43.82
	Rice - Transportation	407.79	92,407.68	113.18	34,469.23	26,114.34	99.93
	Subtotal	4243.17	2,083,535.70	1868.27	574,461.95	374,142.44	1429.69
Feed producing	Straw treatment	4063.16	647,158.76	367.45	223,605.77	187,081.66	2310.83
	Feed preparation	34,738.75	7,181,260.22	32,147.14	1,859,308.22	1,455,185.86	47,014.66
	Operation and maintenance	5101.43	1,152,684.74	3311.31	2,935,194.79	2,002,685.52	4293.53
	Transport	2774.55	619,990.94	792.07	230,569.35	176,110.03	682.31
	Subtotal	46,677.89	9,601,094.66	36,617.97	5,248,678.14	3,821,063.07	54,301.33
Sheep raising	Hu sheep breeding	34,715.26	9,744,191.27	292,576.22	2,219,385.07	2,776,983.65	40,806.58
	Operation and maintenance	11,074.06	352,847.57	15,333.37	65,783.89	48,604.48	10,323.95
	Transport	824.29	189,710.58	218.12	66,854.34	50,406.85	199.20
	Subtotal	46,613.61	10,286,749.42	308,127.71	2,352,023.31	2,875,994.98	51,329.73
Organic composting	Organic fertilizer composting	2080.53	856,535.02	7784.68	117,735.27	98,561.33	1695.28
	Operation and maintenance	1777.50	358,768.08	418.16	159,058.44	150,533.84	460.34
	Transport	74.78	17,209.95	19.79	6064.81	4572.75	18.07
	Subtotal	3932.81	1,232,513.04	8222.64	282,858.52	253,667.92	2173.69
Total		101,467.48	101,467.48	23,203,892.82	354,836.59	8,458,021.91	7,324,868.40

In the sub-system of grain cultivation, the main sources of different types of potential environmental impacts of the wheat and rice seasons are shown in **Figure 2**. Whether it is wheat or rice cultivation, the fertilization process is an important source that affects the environmental performance of the grain cultivation subsystem. Especially for the four impact categories of acid potential, human toxicity, water ecotoxicity, and eutrophication potential, the environmental impact from the fertilization process accounted for about 50% of the total impact of each category. At the same time, the global warming potential of the wheat and rice harvesting processes was more than 50% of the total impact, mainly because the processes included the environmental impact of the direct emissions of greenhouse gases from growing the crops. The land is produced by the sowing of wheat.

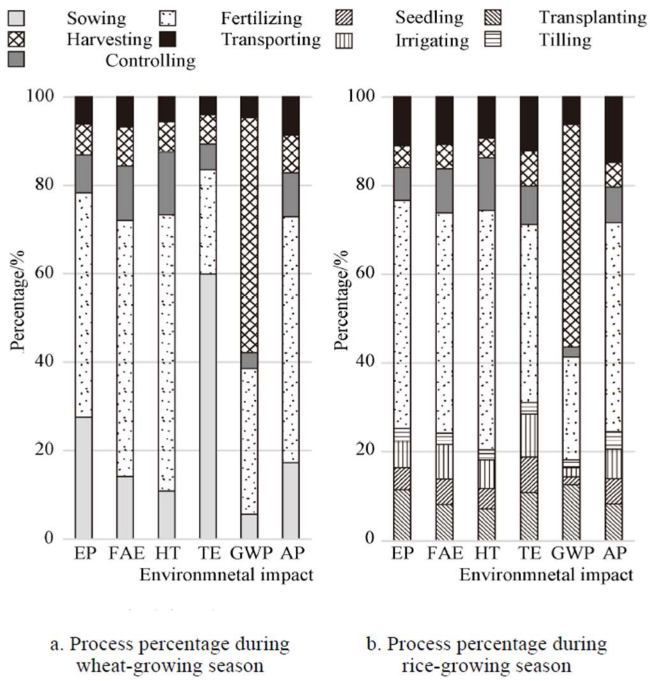

Figure 2. Contribution process of potential environmental impacts of cereal cropping subsystem during wheat-growing and rice-growing seasons respectively.

The effective product of the case system was 5.48 × 10^5 kg of wheat, and the proportion of ecological toxicity was relatively high. This was mainly because of the large amount of wheat seed input needed to ensure seed germination under the condition of mechanical direct seeding, and the land ecological toxicity caused by the whole life cycle of wheat seed production, harvesting, preservation, and transportation was relatively high. In addition, it can be seen from **Table 3** that the wheat season in the grain planting subsystem has fewer agricultural operations than the rice season, so the corresponding input of machinery, energy, and manpower in the former is less, so the sum of all kinds of potential environmental impacts in the wheat season is lower than that in the rice season.

In the feed processing subsystem, the feed preparation process is an important source affecting the environmental performance of the subsystem (**Table 3**). In particular, the environmental impacts from the feed preparation process accounted for more than 74% of the total impacts for the four impact categories of acidic potential, global warming potential, terrestrial ecotoxicity, and eutrophication potential. At the same time, human toxicity and water toxicity caused by the operation and maintenance processes account for more than 52% of the total impact. However, the potential environmental impacts of straw treatment and transportation are relatively small.

In the Hu sheep breeding sub-system, the Hu sheep feeding process is an important source that affects the environmental performance of the sub-system (**Table 3**). For the six impact categories of acidic potential, global warming potential, terrestrial ecotoxicity, human toxicity, water ecotoxicity, and eutrophication potential, the environmental impacts from the Hu sheep feeding process accounted for more than 74% of the total impacts of each category. The potential environmental impacts of operation, maintenance, and transportation are smaller, and the former is higher than the latter.

In the organic composting subsystem, the composting process of organic manure is an important source that affects the environmental performance of the subsystem (**Table 3**). In particular, for the four impact categories of acidic potential, global warming potential, terrestrial ecotoxicity, and eutrophication potential, the environmental impact from the organic manure stacking process accounted for more than 52% of the total impact of each category. At the same time, human toxicity and water ecological toxicity caused by the operation and maintenance processes account for more than 56% of the total impact. However, the potential environmental impacts of the transportation process are relatively small.

3.2. Potential environmental impact of circulatory system

According to the characterization results of the potential environmental impact generated by the case system and its subsystems running throughout the year, the feed processing subsystem is an important source that affects the environmental performance of the whole system (**Figure 3**). Especially for human toxicity and water ecological toxicity, the environmental impact from the feed processing subsystem exceeds 52% of the total impact of each category. At the same time, the land ecological toxicity produced by the Hu sheep breeding subsystem reached 86% of its total impact. Moreover, the acidic potential, global warming potential, and eutrophication potential generated by the above two are relatively high. Comparatively speaking, the potential environmental impacts of different types produced by the grain planting subsystem and organic composting subsystem are small, and the sum of both subsystems does not exceed 15% of the total impacts of various types, which is far lower than the sum of the feed processing subsystem and Hu sheep breeding subsystem (85%).

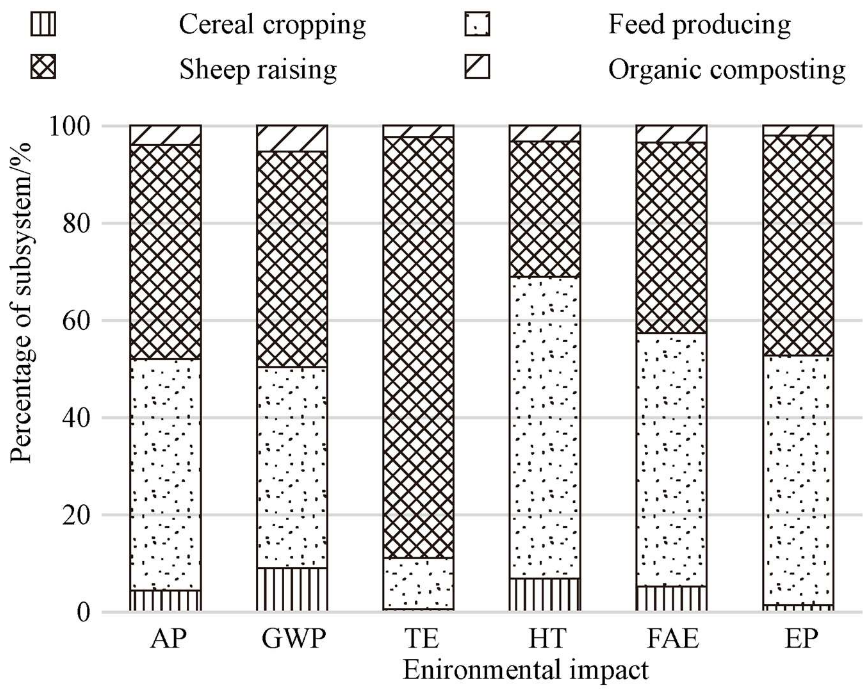

Figure 3. Comparison of potential environmental impacts between subsystems of modern agro-pastoral circular system.

The standardized weighted results are obtained by calculating the characterization results of the potential environmental impacts generated by the case system and its subsystems during the whole year, as shown in **Table 4**. The environmental impact of human toxicity in the subsystems of grain planting, feed processing, and organic composting is the biggest in different categories, followed by the ecological toxicity of water. The environmental impact of ecological toxicity of water bodies in the Hu sheep breeding subsystem is the biggest among different categories, followed by human ecological toxicity. However, the environmental impact of terrestrial ecotoxicity in each subsystem is the smallest. At the same time, the weighted total value analysis shows that the total environmental impact of feed processing and Hu sheep breeding subsystems is much higher than that of grain planting and organic composting subsystems, accounting for more than 90% of the total environmental impact of the whole system. Therefore, for the case system, the environmental impacts of human toxicity and water ecotoxicity are very obvious, and the former (44%) is higher than the latter (33%), while the terrestrial ecotoxicity is only 3% of the total environmental impacts of the whole system.

Table 4. Weighted normalization values for potential environmental impacts of modern agro-pastoral circular system annually.

Subsystem	AP	GWP	TE	HT	FAE	EP	Total
Cereal cropping	21.12	50.26	1.31	264.84	147.80	9.20	494.53
Feed producing	232.37	231.61	25.61	2419.72	1509.46	349.48	4768.25
Sheep raising	215.07	248.16	211.93	1084.32	1136.12	308.63	3204.23
Organic composting	19.58	29.73	5.75	130.40	100.21	13.99	299.66
Circular system	488.15	3244.59	559.77	899.27	2893.59	681.30	8766.67

3.3. Environmental services required for pollution degradation

Based on the life cycle assessment of the characteristic of the result, according to different categories of potential environmental impact indicators of pollutants, the reference for the computation of the corresponding standard limit case system in the process of running throughout the year, in the production of various kinds of effective products at the same time, to realize the potential environmental impact of the production process to safe concentration, The annual environmental service energy of air, water, and soil is 7.42×10^{10} J, 6.03×10^{16} J, and 1.59×10^{12} J, respectively, as shown in **Table 5**. From the above analysis, it can be seen that the environmental impact of water eco-toxicity and human toxicity is relatively large, so the corresponding water and air environmental services required for pollution degradation are also relatively large. Although the environmental impact of terrestrial ecotoxicity is small, the process of pollution dilution using cultivated soil is more complex and consumes more energy, so the soil environmental service energy required for pollution degradation is also large.

Table 5. Environmental service energy to degrade emissions from modern agro-pastoral circular system ($J \cdot a^{-1}$).

Item		AP	GWP	TE	HT	FAE	EP
Environmental service energy	Food crops	7.45×10^{8}	2.44×10^{7}	8.48×10^{9}	5.04×10^{9}	3.08×10^{15}	2.30×10^{12}
	Feed processing	8.19×10^{9}	1.12×10^{8}	1.66×10^{11}	4.61×10^{10}	3.15×10^{16}	8.75×10^{13}
	Hu sheep breeding	7.58×10^{9}	1.20×10^{8}	1.38×10^{12}	2.06×10^{10}	2.37×10^{16}	7.73×10^{13}
	Organic compost	6.90×10^{8}	1.44×10^{7}	3.73×10^{10}	2.48×10^{9}	2.09×10^{15}	3.50×10^{12}
	Whole system	1.72×10^{10}	2.71×10^{8}	1.59×10^{12}	7.42×10^{10}	6.03×10^{16}	1.71×10^{14}
Pollutant	**SO_2**	**CO_2**	**1,4-DCB**	**1,4-DCB**	**1,4-DCB**	**PO_4**	
References standard	HJT 335—2006[32]	HJ 568—2010[33]	HJ 25.3—2014[34]	GB 18468—2001[35]	GB 8976—1996[36]	GB 8976—1996[36]	
Threshold concentration	0.05 mg/m^3	750 mg/m^3	0.07 mg/(kgd)	1.00 mg/m^3	0.60 mg/L	1.00 (P) mg/L	
Environment to degrade emission	Air	Air	Soil	Air	Water body	Water body	

Note: To avoid double counting, environmental service energy for emission degrading in the same environment was only counted as the largest item, the same as below.

3.4. System control scheme and effect

For the sub-system of grain cultivation, the annual rice and wheat cultivation scale will not be adjusted in order to ensure the implementation of policies to steadily increase grain production capacity. In terms of material cycle, in view of the insufficient straw collection, it is suggested to optimize the variety layout, stubble management, and harvest supporting links, which can increase the annual straw harvest by 4.50×10^5 kg. In terms of environmental impact, fertilizer application is an important source of environmental impact. It is recommended to expand the application area of sheep manure on the premise of increasing the yield of organic fertilizer to improve the replacement rate of local organic fertilizer.

For the feed processing sub-system, the main task is to undertake the straw waste of the grain planting sub-system and convert it into the roughage required by the Hu sheep breeding sub-system. At present, the production scale of this sub-system is too large for the whole circulation system, and the environmental impact is also very obvious. Therefore, in the process of promoting and replicating the case system, it is suggested that the production scale of the feed processing sub-system be matched to 3.15×10^3 kg daily output, which can effectively utilize the rice and wheat straw collected by the grain planting sub-system and meet the roughage feeding requirements of the Huyang breeding sub-system.

For the sub-system of Hu sheep breeding, the high potential environmental impact will restrict the sustainable development of the circulatory system. Therefore, it is suggested to optimize the feed formula, improve its utilization efficiency in the feeding process of Hu sheep, and increase the necessary pollution disposal links to reduce the occurrence of potential environmental pollution.

As far as organic composting is concerned, it is the main task to undertake sheep manure waste from the Hu sheep breeding subsystem and transform it into organic fertilizer needed by the grain planting subsystem. However, at present, the production scale of this subsystem can't completely absorb the feces produced by Hu sheep breeding, and the organic fertilizer produced is not enough for food planting. Therefore, it is suggested that the production scale of the organic compost subsystem be matched to the daily output of 1.50×10^4 kg, knowing that its environmental impact is not significant, so as to absorb all the excrement discharge from the Hu sheep breeding subsystem and meet the application requirements of organic fertilizer in the grain planting subsystem.

According to the above regulation suggestions, the circulation system was simulated, and the output of effective products, namely wheat, rice, and mutton sheep, remained unchanged throughout the year, being 5.48×10^5, 1.15×10^6 and 1.90×10^5 kg, respectively. The effective products participating in the internal circulation of the system were organic fertilizer (5.50×10^6 kg) and roughage (1.15×10^6 kg), and the by-product was rice straw (1.25 kg). According to the calculation, the environmental service energy required for the annual pollution degradation of the regulated modern "grass-sheep-field" farming-pastoral circulation system is shown in **Table 6**.

Table 6. Environmental service energy to degrade emissions from regulated modern agro-pastoral circular system ($J \cdot a^{-1}$).

Environmental impact	Cereal cropping	Feed producing	Sheep raising	Organic composting	Total
AP	6.61×10^8	4.32×10^8	7.30×10^9	2.20×10^9	1.06×10^{10}
GWP	2.30×10^7	5.96×10^6	1.08×10^8	4.53×10^7	1.82×10^8
TE	7.91×10^9	8.87×10^9	1.13×10^{12}	1.04×10^{11}	1.25×10^{12}
HT	4.50×10^9	3.64×10^9	1.95×10^{10}	7.89×10^9	3.55×10^{10}
FAE	2.77×10^{15}	2.44×10^{15}	2.20×10^{16}	6.26×10^{15}	3.35×10^{16}
EP	2.06×10^{12}	4.32×10^{12}	7.35×10^{13}	1.01×10^{13}	9.00×10^{13}

After simulating and regulating the modern “grass-sheep-field” agro-pastoral cycle system, the annual environmental services of air, water, and soil are 3.55×10^{10}, 3.35×10^{16} and 1.25×10^{12} J, respectively, in order to reduce the potential environmental impacts generated by the production process to safe concentrations. Compared with the original system, the reduction is 52%, 44%, and 21%, respectively. In the process of this regulation, the various environmental services required by the feed processing sub-system for pollution degradation were significantly reduced; the grain planting and Huyang breeding sub-systems were also reduced to a certain extent; and the organic composting sub-system was increased due to the expansion of scale, but its contribution to the whole system remained within a controllable range. According to the results of environmental service energy estimation and life cycle assessment, it is very beneficial to take targeted regulation measures for the sustainable development of agricultural and animal husbandry cycle systems.

4. Conclusion and prospect

This study's life cycle assessment was applied to the modern “grass-sheep-field” farming circulation system of evaluation. From the input and output of the system, it fully combed the system operation process of the main potential environmental impacts, including acid potential, global warming potential, land ecological toxicity, human toxicity, water ecological toxicity, and the potential of eutrophication. On this basis, according to the life-cycle evaluation results, the parameters of each sub-system were coordinated and the technology optimized, and the environmental service energy needed to dilute the pollution to a safe concentration in different environments was calculated. After the regulation, the environmental services of air, water, and soil required by the modern “grass-sheep-field” agro-pastoral circulation system can be reduced by 21%–52%. Through the exploration of this study, it was found that environmental services based on life cycle assessment can measure the targeted regulation measures proposed, which have practical guiding value for the replication and promotion of modern agricultural and animal husbandry cycle systems and can provide a method reference for the optimization and adjustment of other modern circular agricultural systems.

The life-cycle inventory database referred to in this study is the internationally authoritative Ecoinvent database, of which the newer version contains more than 1900 unit process datasets as well as summary process datasets for corresponding products[25]. Combined with the CML-IA Baseline Model Method developed by the Center for Environmental Sciences of Leiden University in the Netherlands[18], different types of potential environmental impacts can be calculated scientifically and efficiently. It is worth noting that in this study, except for fertilizer, straw, and electricity, the regional data sets of China were selected from the database; the global data sets referred to in other data were generally extrapolated from regional data. Although it can represent the impact level under the current global average productivity conditions, it may mask the differences among small-scale regions in regional comparative analyses. Therefore, when applying life cycle assessment to the analysis of agricultural systems, scholars should also pay attention to the construction of local life cycle inventory databases.

Conflict of interest

The authors declare no conflict of interest.

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