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Research on the ecological–economic effects of combined planting–breeding modes: a case study of *Zizania latifolia*–shelduck in China

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In the context of global climate change, it is crucial to adopt ecologically sound production practices to promote sustainable agricultural development. Combined rice–fish, rice–crab, and *Zizania latifolia* (ZL)–shelduck modes are increasingly advocated by scholars because of the complex farmland landscapes and environmentally friendly nutrient cycles associated with these modes. In this study, a comprehensive evaluation of the ecological–economic benefits of a combined planting–breeding system in Jinyun, Zhejiang, China, was conducted via life cycle assessment (LCA) and cost–benefit analysis on the basis of literature review and field research data. The following results were obtained. (1) The single-season total carbon footprint for the combined ZL–shelduck planting–breeding mode was 4062.19 kg CO_2 eq/ha, whereas it was 4553.32 kg CO_2 eq/ha for the ZL monoculture mode. Compared with those of the ZL monoculture mode, the carbon emissions of the combined ZL–shelduck mode decreased by 10.79%, with agricultural inputs identified as the primary source of carbon emissions for both modes. (2) The net ecological and economic benefits of the combined planting–breeding mode and the monoculture mode were 102,482.26 yuan/ha and 70,423.60 yuan/ha, respectively. Compared with those of the ZL monoculture mode, the net benefits significantly increased by 45.52% in the combined planting–breeding mode. Notably, the sale of shelduck products and reductions in agricultural inputs and labor costs were important factors leading to the income gap between the two types of modes. This study not only provides a quantitative evaluation of the comprehensive ecological–economic benefits of different agricultural production modes but also serves as an important reference for the introduction of relevant ecological compensation policies and the promotion of production and ecological win–win in the future.

KEYWORDS

ecological agriculture, combined planting–breeding modes, agricultural carbon footprint, agricultural heritage, ecological compensation

1 Introduction

Agricultural production modes not only determine food supply levels but also have an impact on the environment (Tilman et al., 2002). Due to the increasing world population, global food demand is expected to double by 2050 (Janni et al., 2024), posing a considerable challenge to agricultural sustainability both in terms of meeting the growing demand for food and for reducing the adverse environmental impacts of adaptations to climate change (Cui et al., 2018). Combined rice–fish, rice–crab, rice–duck and *Zizania latifolia* (ZL)–shelduck modes play important roles in improving crop yield and reducing greenhouse gas emissions from agriculture (Zhang et al., 2023; Chen et al., 2024). Compared with monoculture modes for agricultural production, combined planting–breeding modes closely integrate the planting–breeding industries, which not only improves the utilization efficiency of agricultural resources but also reduces environmental pollution and ecological damage (Huang et al., 2021). For example, in a combined farming mode, organic matter and nutrients from animal manure are introduced into cultivated land to maintain or even improve soil fertility and ultimately improve food production efficiency (Franzluebbers et al., 2014). Crop residues is used as feed for livestock and poultry breeding, which reduces feed costs (De Faccio Carvalho et al., 2021). Combined farming modes have certain ecological and economic benefits and realize the efficient utilization of resources (Chen et al., 2024). Therefore, it has been widely used in modern agricultural production.

In combined planting–breeding modes, the synergistic relationships among different food animals and plants are exploited to increase the yield of agricultural products, which is an important pathway for promoting green and sustainable development in agriculture (Feng et al., 2023). Mahapatra (1994) defined a combined planting–breeding system as a system in which production factors such as land, labor, and capital are optimally allocated and complex interactions among each subsystem are optimized through production processes. Intensive agricultural production has led to a series of ecological and economic issues, including the overuse of chemical fertilizer, excessive energy consumption, and a reduction in biodiversity (Bai et al., 2018; Xing et al., 2022). The coupling of planting–breeding is an important way to improve agricultural sustainability (Jin et al., 2021; Tan et al., 2023). On this basis, scholars have conducted much research on the ecological and economic benefits of combined planting–breeding mode (Tang and Jin, 2021; Rufino et al., 2021; Wang et al., 2023; Kang et al., 2024), covering a variety of systems such as rice–fish systems (Ahmed and Garnett, 2011), rice–shrimp systems (Feng et al., 2023), rice–duck systems (Du et al., 2023) and other combinations of agriculture and animal husbandry (Brewer and Gaudin, 2020; Franzluebbers et al., 2021).

To assess ecological benefits, scholars have employed the life cycle assessment (LCA) method (Xing et al., 2022), the emergy method (Tan et al., 2023), and the equivalence factor method (Jia et al., 2021) to analyze the impact of combined planting–breeding modes on soil microbial communities (Bashir et al., 2020), soil biodiversity and functions (Feng et al., 2023), ecological footprint (Xian et al., 2023), and ecosystem services (Liu et al., 2023), and concluded that combined planting–breeding modes can effectively reduce the use of chemical fertilizers and pesticides (Kang et al., 2024), improve soil quality (Li et al., 2025), and reduce greenhouse gas emissions (Fang et al., 2023). For instance, Ye et al. (2024) compared the ecosystem service values (ESVs) of rice–fish–water spinach system, rice–fish system, rice monoculture through a field experiment. They discovered that the net ESVs of the rice–fish–water spinach system and the rice–fish system increased by 31.4% and 14.1%, respectively, compared with the rice monoculture. According to a study by Berg et al. (2024), they compared rice–fish system and rice monoculture in the Mekong Delta and found that the rice–fish system can significantly improve ecosystem services. However, some studies have suggested that combined planting–breeding modes can have certain negative environmental impacts, such as causing water quality deterioration; therefore, it is necessary to establish locally adapted combined planting–breeding modes on the basis of regional differences in agriculture (Li et al., 2023).

To determine economic benefits, scholars have explored the impact of combined planting–breeding modes on agricultural economics from the aspects of the net income of farmer households (Cui et al., 2023), agricultural resource utilization efficiency (Wang et al., 2024), crop quality and yield (Li et al., 2022), and agricultural input (Greenfeld et al., 2021). For example, Ma et al. (2022) compared combined crop–livestock systems with decoupled specialized livestock systems and reported that the net profit per kilogram of animal products in combined systems was greater than that in decoupled systems. Minviel and Veysset (2021) compared combined farms and specialized farms in France and reported that combined farms were not necessarily more economical than specialized farms in terms of production factors; under the combined mode, farms might need to be reorganized to achieve better scale economy, and more targeted policies might be needed to promote an optimal allocation of farm resources. Yang et al. (2024) compared the economic benefits of rice–fish, rice–shrimp, and rice–duck systems with those of rice monoculture, and found that the economic benefits of the three integrated systems were significantly higher than those of rice monoculture, with an increase of 153.06–431.40%.

In conclusion, combined planting–breeding modes are sustainable agricultural production modes (Rufino et al., 2021) that can prevent biodiversity loss (Goswami et al., 2024), are better adapted to climate change (Delandmeter et al., 2024) and can increase employment (Li et al., 2011). Many studies have explored the ecological effects (Fang et al., 2023; Chen et al., 2023), and economic effects (Cao et al., 2017; Ma et al., 2022) of combined planting–breeding modes. However, these studies have often been focused on singular perspectives, and comprehensive ecological and economic benefits have rarely been considered (Ling et al., 2021). In addition, most studies on combined planting–breeding modes have been focused on rice paddies (Ahmed and Garnett, 2011; Du et al., 2023; Feng et al., 2023), and research on other crops and animal breeding modes is lacking. Liu et al. (2024) compared the fruit tree–crayfish system with rice–crayfish system and crayfish monoculture, and found that the fruit tree-crayfish system emitted almost no CO_2 and N_2O. Although combined economic crops and animal planting–breeding modes have attracted more and more attention, there are still obvious deficiencies in the quantitative evaluation of their ecological and economic benefits, which need to be further improved. ZL and shelduck are economically valuable agricultural products (Xiao et al., 2023). In addition, the combined farming mode involving ZL and shelduck enhances the efficiency of water and soil resource utilization, reduces the use of chemical fertilizers and pesticides, and advances the development of ecologically sound agriculture. Therefore, in this study, a symbiotic system consisting of ZL and shelduck was taken as an example, the carbon footprint of the system was used to calculate carbon emissions, and cost–benefit analysis was conducted to determine the comprehensive ecological and economic benefits of this mode.

2 Materials and methods

2.1 Study area and system introduction

In this study, the ZL–shelduck symbiotic system in Jinyun County, Zhejiang Province, China (28°24′39″ to 28°57′12″N, 119°51′57″ to 120°25′20″E) (Figure 1), is used as an example to explore the ecological and economic effects of combined planting–breeding modes. The terrain in the study area is complex and diverse, with large elevation fluctuation and obvious slope undulation. The successful practice of the ZL–shelduck symbiotic system can provide references for the development of sustainable agriculture in mountainous areas.

This research case was selected on the basis of three reasons. First, the ZL–shelduck symbiotic mode is a typical example of a combined planting–breeding mode. This mode combines the cultivation of crops grown in water with the breeding of waterfowl, making full use of the water surface space of ZL fields to raise shelducks. Second, both ZL and shelduck occupy significant positions in the current dietary structure of China as common vegetables and meat. The promotion of the combined planting–breeding of these species is highly important for safeguarding food security. Third, the Jinyun ZL and shelduck industry is widely renowned. Jinyun County is the largest production base for ZL, with a planting area of 66,000 mu (approximately 4,400 hectares), accounting for 8% of the national total in China. The area has been called the “Hometown of Zhejiang *Zizania latifolia*” and “Hometown of China *Zizania latifolia*” and received the title of “Hometown of Chinese Shelduck” in 1997. In 2010, Jinyun shelduck became the first livestock and poultry species in Zhejiang Province to receive protection as an “Agro–product Geographical Indications” from the Ministry of Agriculture and Rural Affairs of the People’s Republic of China. In 2021, the ZL–shelduck symbiotic system was recognized by the Ministry of Agriculture and Rural Affairs of the People’s Republic of China in the sixth edition of China Nationally Important Agricultural Heritage. The development and preservation of the local ZL–shelduck symbiotic system have received much attention from relevant governmental departments.

In the ZL–shelduck symbiotic system, on the one hand, ZL fields can provide habitat for shelducks; on the other hand, shelducks feed on weeds and snails in ZL fields, and their excrement can provide organic fertilizer for ZL. The combined planting–breeding mode involving ZL and shelduck not only reduces reliance on chemical fertilizers and pesticides for ZL cultivation but also offers a more natural environment for shelducks (Figure 2).

2.2 LCA method and calculation procedures

In this study, the LCA framework was used to estimate the carbon footprint of the ZL–shelduck symbiotic system. LCA is a methodological tool for calculating the carbon emissions of products or services (including crops). In accordance with the International Organization for Standardization (ISO) process for documenting and

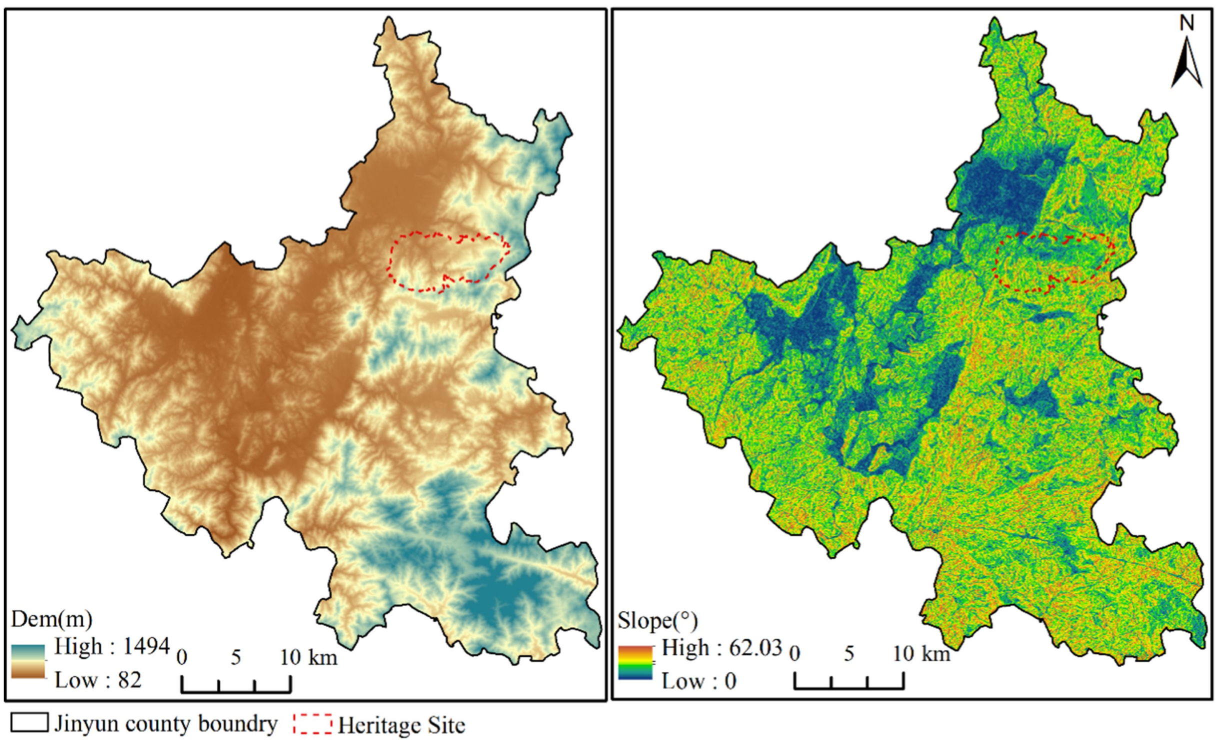

FIGURE 1
Location and topography of the Zhejiang Jinyun ZL–shelduck symbiotic system.

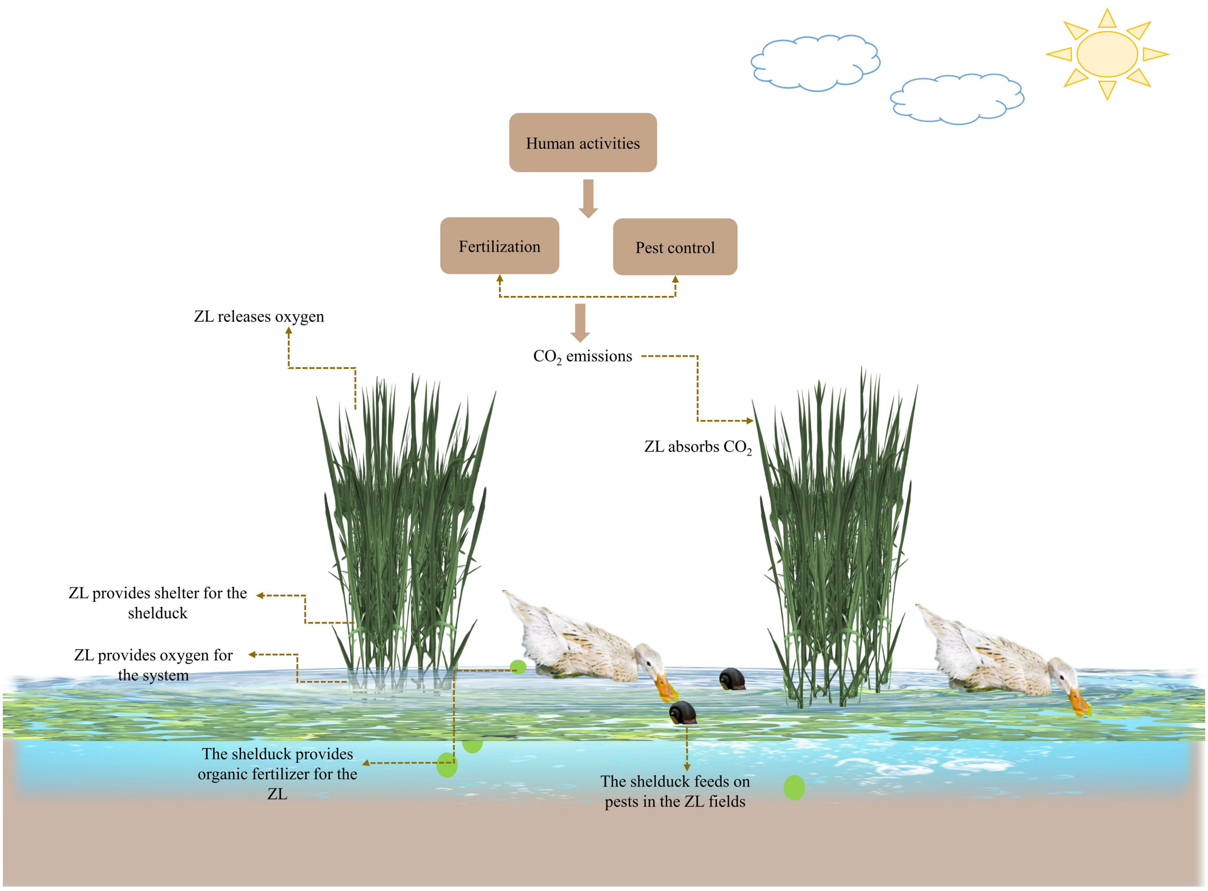

FIGURE 2
The symbiotic landscape of ZL and shelducks.

evaluating LCAs, this study includes a complete objective and scope definition, inventory analysis, impact assessment and results analysis procedure (ISO, 2006).

2.2.1 Definition of objectives and scope

In this study, the carbon footprint of the ZL–shelduck symbiotic system was measured by taking the unit area as a functional unit, and the carbon footprint was expressed as CO_2 equivalents (CO_2 eq) (ISO, 2018). In a complete agricultural LCA, resource utilization and potential environmental impacts from all raw material extraction, crop production, processing and use, and waste disposal processes should be considered (Liang et al., 2009). The scope of the assessment was determined on the basis of the production and growth activities of ZL and shelduck, ranging from the raw material acquisition and production of agricultural inputs such as fertilizers to the harvest of ZL and shelduck products, and the transportation of them (Figure 3).

In this study, only single-season ZL was considered. Field survey results show that farmers start applying base fertilizer in March each year; after the ZL seedlings are planted, fertilizers and pesticides are applied for crop management, and shelducks are placed in the ZL fields from April to June. Before the shelducks are placed in the fields, they are vaccinated and regularly fed with maize. The harvest period for single-season ZL is from July to September, during which shelducks can be slaughtered in a timely manner. Due to the unique growth habit of ZL, farmers use artificial means to harvest them. Since it is difficult to quantify resource utilization and the environmental impacts of packaging, consumption, and waste disposal in this symbiotic system, only transportation was considered. The carbon footprint accounting process included both direct and indirect carbon emissions, with direct emissions consisting of greenhouse gas emissions from fields (Huang et al., 2016). Owing to limitations in data precision and experimental conditions, only indirect carbon emissions, such as those from chemical fertilizers, pesticides, and irrigation, were considered. Therefore, this study includes three processes in carbon footprint accounting: the first is the agricultural input process (including raw materials production and agricultural inputs production), which includes fertilizers, pesticides, and maize feed, the second is the agricultural process, which involves mainly agricultural machinery irrigation, and the third is the transportation process, which involves the sale of ZL and shelduck products.

2.2.2 Inventory analysis

In this study, the amounts of compound fertilizer, urea, bactericides and insecticides for ZL monoculture were obtained from the 'Regulation for the cultural practice of *Zizania latifolia* Turcz', which was introduced by Quality and Technology Supervision of Zhejiang Province (2014). The amounts of compound fertilizer, urea, and maize used were obtained from the 'Technical Regulations for the Production

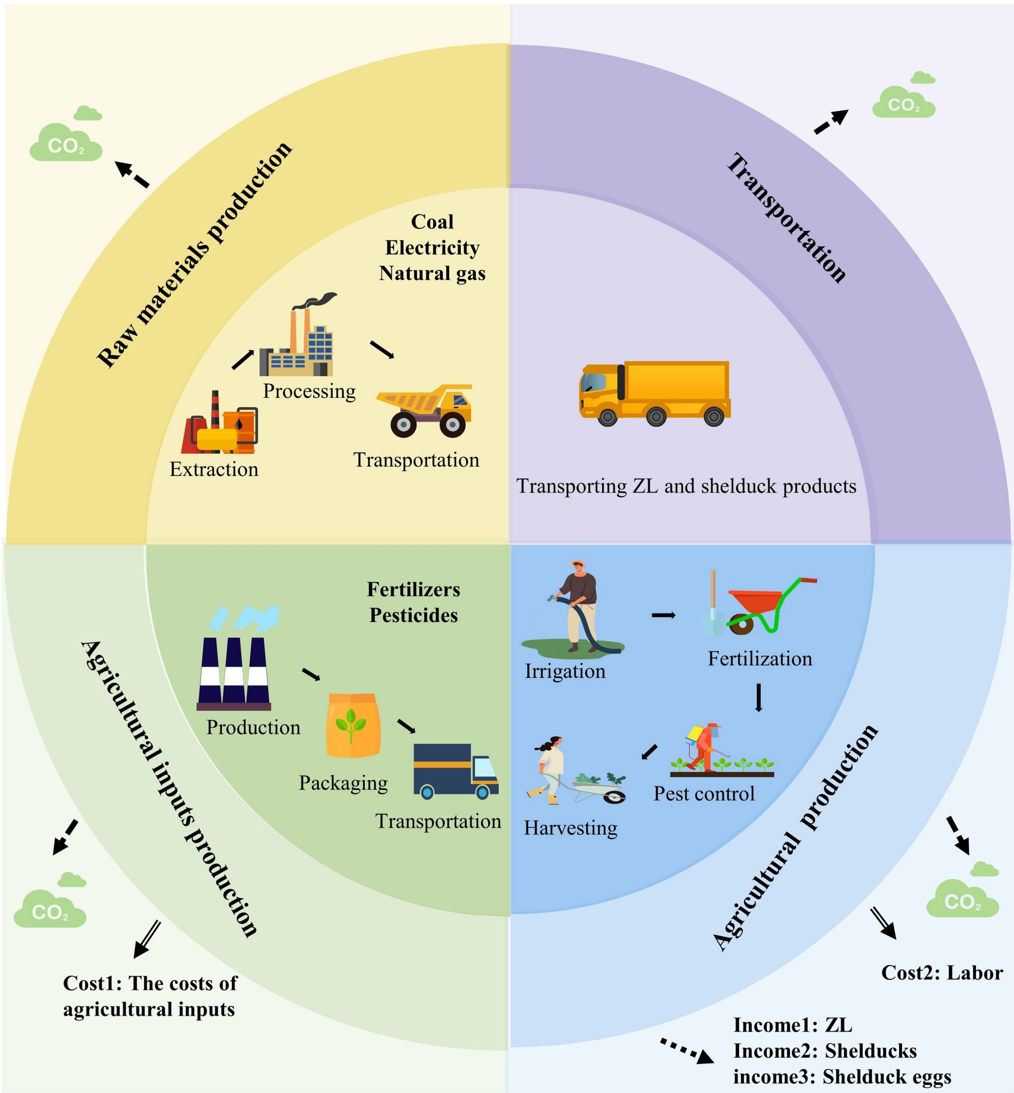

FIGURE 3
Life cycle CO_2 emissions of the ZL–shelduck symbiotic system.

of *Zizania latifolia* and Shelduck Nesting', which was introduced by Lishui Market Supervision Administration (2020) (Table 1). Compared with the ZL–shelduck system, when a ZL monoculture mode is adopted, it is necessary to spray a 1,500 times greater amount of 20% WP myclobutanil (0.12 kg/ha) to prevent Uromyces coronatus, a 600 times greater amount of 20% WP tricyclazole (0.30 kg/ha) to prevent Helminthosporium leaf spot, an 800 times greater amount of 5% WP validamycin (0.05625 kg/ha) to prevent sheath blight, a 2000 times greater amount of 25% WP buprofezin (0.1125 kg/ha) to prevent the green slender planthopper, and a 4,000 times greater amount of 20% SC chlorantraniliprole (0.045 kg/ha) to prevent stem borer, each of which is applied once. According to previous studies, shelducks prey on insect pests such as planthoppers and borers in a symbiotic mode involving ZL and shelduck. Therefore, the use of buprofezin and chlorantraniliprole can be ignored when the combined mode of ZL and shelduck is used. The prices of ZL and shelduck were taken from related research conducted by Xiao et al. (2023). The fertilizer price and maize feed price were obtained from relevant research by Zhang et al. (2015). The labor cost was obtained from relevant research by Wu et al. (2014). The prices of pesticides and shelduck eggs were based on general market prices. The shelduck density was taken to be 45-75/ha according to the 'Technical Regulations for the Production of *Zizania latifolia* and Shelduck Nesting'(Lishui Market Supervision Administration 2020), with an average of 60/ha. The data for electricity consumption for irrigation was based on relevant research by Cao et al. (2014), ZL production (Lishui Daily, 2024) (according to the information provided by local technicians, the yield difference of ZL under the two modes is small, so it is ignored in this study and calculated according to the unified standard), shelduck egg production (Lishui Network, 2023), and the price of electricity (Xiangshan County People's Government, 2024) obtained from official local government information.

2.2.3 Carbon footprint analysis

In this study, the carbon footprint estimation procedure for the ZL–shelduck symbiotic system mainly included (1) the carbon dioxide produced by agricultural inputs, (2) the carbon dioxide emitted during farming processes, and (3) the carbon dioxide produced during transportation. To facilitate the summation of emissions, carbon dioxide emissions from different processes were measured in units of carbon dioxide equivalent (CO_2 eq).

According to field research, compound fertilizer and urea are the main fertilizers used for ZL, and maize is the main feed for shelducks. Therefore, in the process of calculating the carbon footprint of agricultural inputs, the carbon dioxide produced by the inputs of compound fertilizer, urea, bactericides, insecticides, and maize feed were considered.

The estimation method for carbon dioxide produced by agricultural inputs (CF_{inputs}) is shown in Equation 1:

$$CF_{inputs} = \sum_{i=1}^{n} \theta_i \cdot \xi_i \tag{1}$$

where CF_{inputs} represents the carbon footprint of agricultural production inputs, with units of kg CO_2 eq/ha. n represents the type of agricultural input. θ_i represents the quantity of the i type of agricultural input, with units of kg/ha. ξ_i represents the carbon emission factor of the i type of agricultural input, with units of kg CO_2 eq/kg (Table 2).

In the energy consumption estimation process for farming, only electricity consumption for irrigation was considered.

The estimation method for carbon dioxide produced during farming processes ($CF_{farming}$) is shown in Equation 2:

$$CF_{farming} = ELE_{input} \times \varepsilon \tag{2}$$

where $CF_{farming}$ represents the carbon dioxide emissions arising from electricity consumption for irrigation, with units of kg CO_2 eq/ha. ELE_{input} represents the input of irrigation electricity, with units of kWh/ha. ε represents the greenhouse gas emission factor of electricity, with units of kg CO_2 eq/kWh.

The estimation method for carbon dioxide produced during transportation (CF_{trans}) is shown in Equation 3:

$$CF_{trans} = W_j \times L \times \lambda \tag{3}$$

where CF_{trans} represents the carbon dioxide emissions derived from transportation, with units of kg CO_2 eq/ha. W_j represents the weight of the ZL and shelduck eggs transported, with units of kg/ha. L represents the transport distance, which is estimated according to the distance from the Qianlu Township People's Government to Hangzhou. According to the Gaode map, this distance is 206 kilometers. λ represents the carbon emission coefficient of road transportation, with units of kg CO_2 eq/t·km.

The calculation method for the carbon footprint of the ZL–shelduck symbiotic system is shown in Equation 4:

TABLE 1 Life cycle inventory analysis of the ZL–shelduck symbiotic system.

Characteristics		Unit	ZL monoculture	ZL–shelduck symbiotic system
Agricultural inputs	Compound fertilizer	kg/ha	2100.00	1912.50
	Urea	kg/ha	412.50	127.50
	Bactericide	kg/ha	0.48	0.48
	Insecticide	kg/ha	0.16	–
	Maize	kg/ha	–	135.00
Farming	Electricity for irrigation	kWh/ha	222.75	222.75
Outputs	Yield of ZL	t/ha	28.86	28.86
	Quantity of shelduck	shelduck/ha	–	60.00
	Quality of shelduck egg	kg/ha	–	730.26

Data were rounded to two decimal places according to standard rounding rules.

TABLE 2 Greenhouse gas emission factors for various agricultural activities.

Items		Emission factors	Data sources
Agricultural inputs	Compound fertilizer	1.77 kg CO_2 eq/kg	Huang et al. (2016)
	Urea	0.956 kg CO_2 eq/kg	Chinese Academy of Environmental Planning, Beijing Normal University, Sun Yat-Sen University, and China City Greenhouse Gas Working Group (2022)
	Bactericide	10.60 kg CO_2 eq/kg	Huang et al. (2016)
	Insecticide	16.60 kg CO_2 eq/kg	Huang et al. (2016)
	Maize	0.80 kg CO_2 eq/kg	Chinese Academy of Environmental Planning, Beijing Normal University, Sun Yat-Sen University, and China City Greenhouse Gas Working Group (2022)
Farming	Electricity consumption for irrigation	0.5617 kg CO_2 eq/kWh	Ministry of Ecology and Environment of the People's Republic of China (2024)
Transportation	Transportation	0.052 kg CO_2 eq/t·km	Peng et al. (2016)

$$CF_{total} = CF_{inputs} + CF_{farming} + CF_{trans} \quad (4)$$

2.3 Analysis of economic benefits

The economic benefits of the system were calculated on the basis of the cost and output of ZL and shelduck per hectare and the economic cost of the carbon footprint (Table 3). The calculation method is shown in Equation 5:

$$NI = TI - TC \quad (5)$$

In this formula, NI represents net income, TI represents total income, and TC represents total cost, which includes not only labor and agricultural costs but also carbon emission costs. According to the research of Xia et al. (2016), the economic cost per ton of CO_2 is 174.3 yuan.

3 Results

3.1 Carbon footprints of different farming modes

The carbon footprints of the ZL monoculture and combined ZL–shelduck planting–breeding mode were 4553.32 kg CO_2 eq/ha and 4062.19 kg CO_2 eq/ha, respectively (Figure 4). Compared with those of ZL monoculture, the carbon emissions of the combined ZL–shelduck planting–breeding mode were 10.79% lower, indicating that the combined farming mode has significant effects on reducing carbon emissions.

From the perspective of different emission sources, the carbon emissions from chemical fertilizers use under the two modes were the highest. The carbon emissions from chemical fertilizers in the ZL monoculture was 4111.35 kg CO_2 eq/ha, whereas the carbon emissions from chemical fertilizers in the ZL–shelduck combined planting–breeding mode was 3507.02 kg CO_2 eq/ha. Compared with those in ZL monoculture, the carbon emissions of chemical fertilizers in the combined mode decreased by 14.70%. Carbon emissions from transportation were second only to those from fertilizers, with 309.19 kg CO_2 eq/ha in the ZL monoculture mode, accounting for 6.79% of the total carbon emissions in this mode. The carbon emissions from the transportation process in the combined ZL–shelduck planting–breeding mode were 317.01 kg CO_2 eq/ha, representing 7.80% of the total carbon emissions for this mode. Maize feed was also a source of carbon emissions, compared to ZL monoculture, the carbon emissions from maize feed in the combined ZL–shelduck planting–breeding mode were 108 kg CO_2 eq/ha, which accounted for 2.66% of the total carbon emissions in the combined mode. In general, the combined planting–breeding mode could significantly reduce the carbon emissions caused by agricultural production activities. Chemical fertilizers were the main source of carbon emissions, followed by transportation, and maize feed was also an important source of carbon emissions.

In the two modes, the carbon emissions of agricultural input process were the largest, followed by those from the transportation process, and finally that from the farming process (Figure 5). Compared to ZL monoculture, the carbon emissions of farming processes in the combined ZL–shelduck planting–breeding mode did not change, while the carbon emissions from agricultural inputs and transportation decreased by 12.11 and 2.53%.

TABLE 3 The unit price of agricultural inputs and outputs.

Characteristics	Unit	ZL monoculture	ZL–shelduck symbiotic system
Compound fertilizer	yuan/kg	2.80	2.80
Urea	yuan/kg	2.40	2.40
Maize	yuan/kg	–	3.60
Bactericide	yuan/kg	45.67	45.67
Insecticide	yuan/kg	171.50	–
ZL	yuan/kg	3.76	3.76
Shelduck	yuan/shelduck	–	90.78
Shelduck egg	yuan/kg	–	24.00
Electricity	yuan/kWh	0.48	0.48
Labor	yuan/ha	30375.00	22125.00
CO_2	yuan/t	174.30	174.30

Data were rounded to two decimal places according to standard rounding rules.

3.2 Economic benefits of different farming modes

In general, the total income from the combined ZL–shelduck planting–breeding mode was 131,590.30 yuan/ha, and it was 108,617.25 yuan/ha for ZL monoculture (Table 4). Compared with that from ZL monoculture, the total income of the combined planting–breeding mode was 21.15% greater. The net income of the monoculture mode and the combined planting–breeding mode was 70,423.60 yuan/ha and 102,482.26 yuan/ha, respectively. Compared with that of the monoculture mode, the net income of the combined planting–breeding mode increased by 45.52%.

From the perspective of income channels, the combined ZL–shelduck planting–breeding mode generated income from the cultivation of ZL and from the sale of shelducks and shelduck eggs, which account for 4.14 and 13.32% of the total income, respectively. These findings indicate that revenue from shelduck eggs plays a significant role in the combined planting–breeding mode.

For input costs, labor is the primary source of cost (Figure 6). In the ZL monoculture mode, the cost of labor was 30,375 yuan/ha, accounting for 79.53% of the total cost of this mode. In the combined ZL–shelduck planting–breeding mode, the cost of labor was 22,125 yuan/ha, representing 76.01% of the total cost of this mode. Compound fertilizer is an important source of cost. In the monoculture mode and the combined planting–breeding mode, the cost of compound fertilizer accounted for 15.40 and 18.40%, respectively, of the total cost. Compared with that in the monoculture mode, the cost of compound fertilizer in the combined ZL–shelduck planting–breeding mode decreased by 8.93%. Notably, in this study, carbon emissions were translated into economic costs and incorporated into the economic benefit analysis

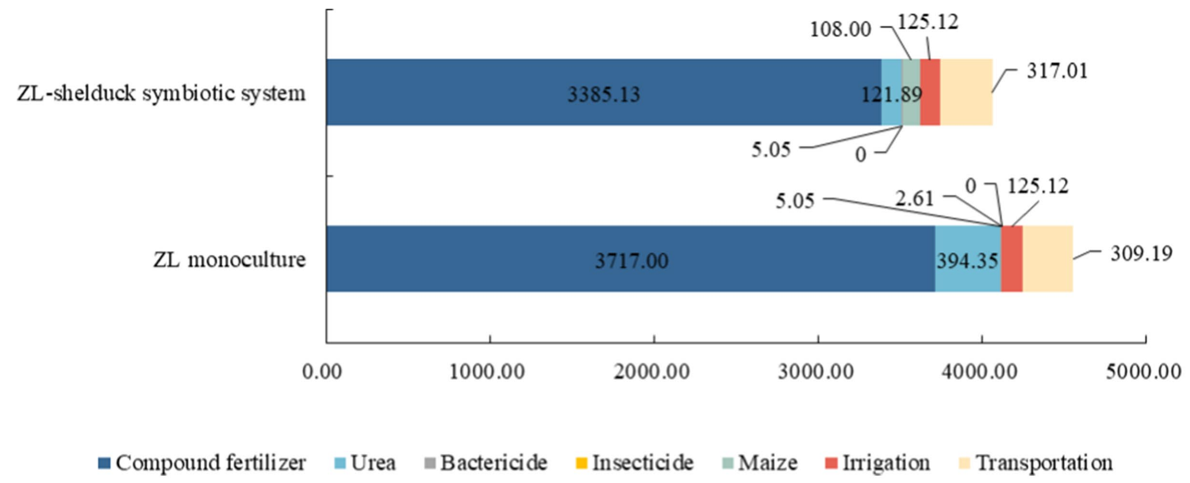

FIGURE 4
Composition of the carbon footprints of the ZL–shelduck symbiotic system and ZL monoculture (unit: kg CO_2 eq/ha). Data were rounded to two decimal places according to standard rounding rules.

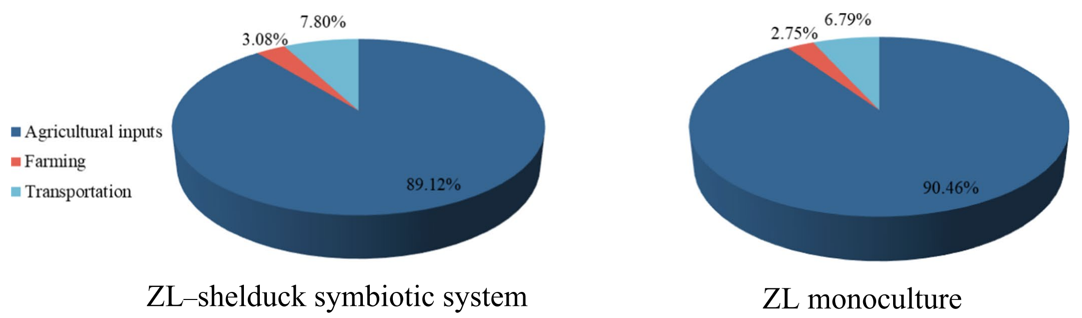

FIGURE 5
Composition of carbon footprints of the three emission processes in the ZL–shelduck symbiotic system and in ZL monoculture.

TABLE 4 The income and cost of outputs and inputs (unit: yuan/ha).

Indicators			ZL monoculture	ZL–shelduck symbiotic system
Income	Crop income	ZL	108617.25	108617.25
	Shelduck products income	Shelduck	–	5446.80
		Shelduck egg	–	17526.25
Cost	Agricultural inputs cost	Compound fertilizer	5880.00	5355.00
		Urea	990.00	306.00
		Bactericide	21.75	21.75
		Insecticide	27.01	–
		Maize	0.00	486.00
		Electricity	106.25	106.25
	Labor cost	Labor	30375.00	22125.00
	Environmental cost	CO_2	793.64	708.04

Data were rounded to two decimal places according to standard rounding rules.

framework. The carbon emission costs in the monoculture mode and the combined planting–breeding mode accounted for 2.08 and 2.43% of their respective total costs.

The labor cost was highest under the two modes, followed by agricultural input cost, and the environmental cost was the lowest (Figure 7). Compared with those in the monoculture mode, the labor

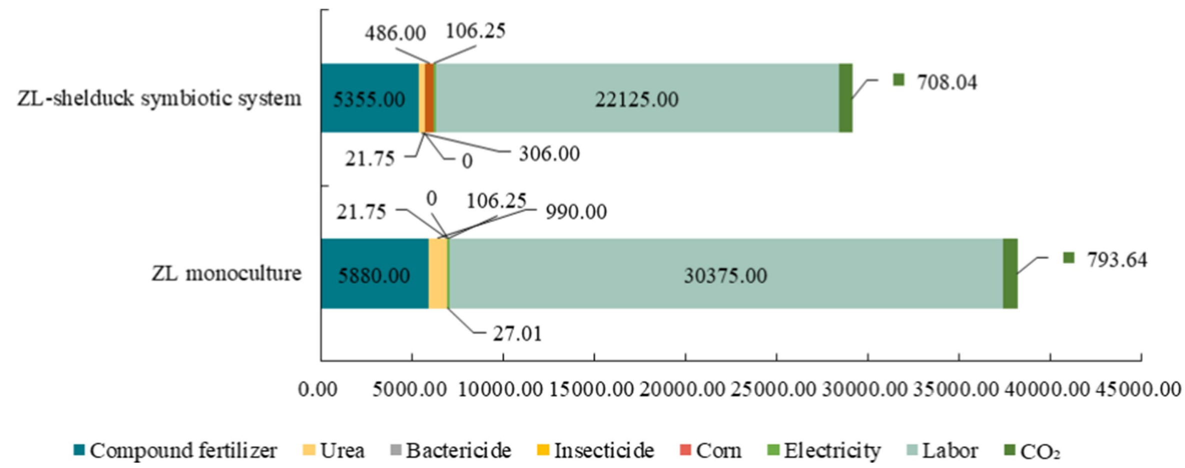

FIGURE 6
Composition of costs in the ZL–shelduck symbiotic system and in ZL monoculture (unit: yuan/ha). Data were rounded to two decimal places according to standard rounding rules.

costs, agricultural input costs, and environmental costs in the combined ZL–shelduck planting–breeding mode decreased by 27.16, 10.68, and 10.79%, respectively. The results suggest that the combined planting–breeding mode has the potential to reduce costs and emissions relative to monoculture methods.

The net income of the monoculture mode and the combined ZL–shelduck planting–breeding mode account for 64.84 and 77.88%, respectively, of the total income. This finding also indicates that, compared with the monoculture mode, the combined ZL–shelduck planting–breeding mode has advantages in terms of resource utilization and cost control.

4 Discussion

The combined ZL–shelduck planting–breeding mode can reduce the use of chemical fertilizers and pesticides, thereby decreasing carbon emissions. Compared with those of ZL monoculture, the carbon emissions of the combined planting–breeding mode decreased by 10.79%. This is because shelducks feed on weeds, duckweed, and pests in ZL fields, which reduces the use of pesticides. The organic excrement of shelducks can also serve as natural fertilizers for the growth of ZL, which reduces the use of chemical fertilizers, results in a beneficial ecological cycle, reduces environmental impact, and has significant ecological benefits. This finding is consistent with the findings of Du et al. (2023), who compared ratoon rice monoculture with a combined rice–duck planting–breeding mode and reported that, compared with ratoon rice monoculture, the combined mode reduced the input of chemical fertilizers by 15%, and significantly lowered carbon emissions. In this study, chemical fertilizers were the main source of carbon emissions, which is consistent with the conclusions of Fan et al. (2022) and Xu et al. (2023), who studied different agricultural modes and reported that chemical fertilizer was the main factor leading to greenhouse gas emissions. Fang et al. (2023) compared the rice–shrimp symbiotic mode with rice monoculture and reported that the combined planting–breeding mode effectively reduced greenhouse gas emissions. Compared with the monoculture mode, the combined mode increased feed input and carbon emissions to a certain extent but did not affect the overall emission-reducing effect of the combined mode. However, Jiao et al. (2023) demonstrated in their study of the Qingtian rice–fish culture system that the rice–fish mode contributed to a reduction in carbon emissions. However, after comparing data from different years, they authors concluded that environmental risks associated with increased feed input exist for this mode.

The combined ZL–shelduck planting–breeding mode can significantly improve economic benefits. On the one hand, compared with the monoculture mode, the combined planting–breeding mode can not only produce ZL, but also harvest products such as shelducks and shelduck eggs, thus increasing the overall income. On the other hand, this mode effectively reduced the input cost of agricultural resources and labor. In this study, compared with the monoculture mode, the net income of the combined planting–breeding mode increased by 45.52%, and the proportion of net income in the total income was greater, accounting for 77.88% of the total income. This finding is consistent with the conclusions of Franzluebbers et al. (2021) and Yang et al. (2024)on different combined modes for planting–breeding. From the perspective of input economy and input diseconomy, Minviel and Veysset (2021) studied combined farming in France and reported that most farms presented an input diseconomy because the economic benefits of combined farming were affected by the farm scale, public subsidies and other factors. It can be seen that the combined planting–breeding mode has the potential to achieve production and ecological win–win.

The first goal of this study was to integrate ecology and economy into the same framework, calculate the economic cost of carbon emissions, and comprehensively consider the net benefits of the two modes. In analyzing input costs, most researchers measure only ecological or economic benefits (Yu et al., 2023; Ling et al., 2021). The second objective was to quantify the carbon emissions over the life cycle of agricultural products and clarify the carbon emissions at each stage, which can provide systematic support for the formulation of emission reduction policies for agricultural production.

However, there are several shortcomings in this study. Owing to the limited availability of data, our carbon footprint accounting process did not involve the consumption of agricultural products or material exchange processes within soil systems. In subsequent studies, researchers could extend the life cycle chain and supplement

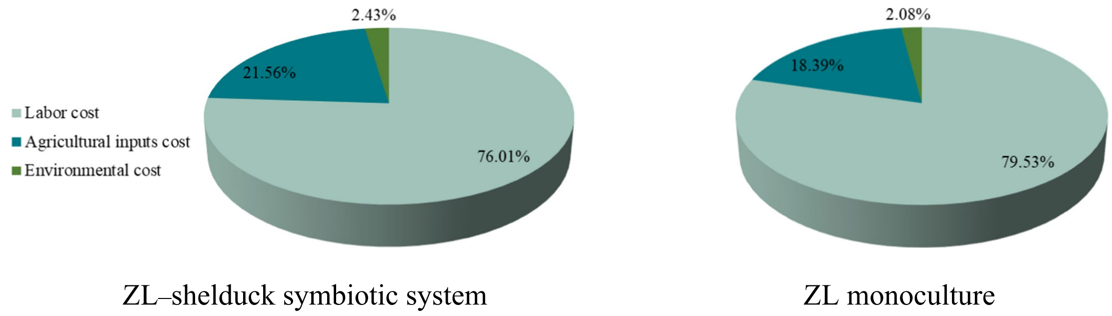

FIGURE 7
Composition of three types of costs for the ZL–shelduck symbiotic system and for ZL monoculture.

experimental measurements to quantify ecological effects more precisely. At the institutional level, ecological protection compensation mechanisms should be explored for farming practices to promote combined planting–breeding modes and sustainable development in modern agriculture. For example, by improving the ecological subsidy policy of combined planting–breeding modes, farmers were guided to continue to adopt combined planting–breeding modes rather than turning to crop monoculture, thus promoting the synchronous development of the local environment and economy (Jiao et al., 2023). At the same time, the accounting system of ecological compensation standards should be improved to establish appropriate compensation benchmarks for different agricultural ecosystems (Qiao et al., 2025).

5 Conclusion

In this study, the LCA method was employed for the ZL–shelduck symbiotic system as an example to calculate the carbon footprint of ZL monoculture and the combined planting–breeding mode to explore the ecological benefits of both modes. On this basis, the carbon footprint cost was transformed into economic cost, and the comprehensive ecological–economic benefits of the combined mode were obtained by combining the economic benefit results in the cost–benefit calculations. The results showed that (1) the combined ZL–shelduck planting–breeding mode could effectively reduce the use of chemical fertilizers and pesticides relative to the monoculture mode. Compared with those of ZL monoculture, the carbon emissions of the combined mode were 10.79% lower. (2) In addition to income from ZL, shelduck products provided additional income to farmer households in the combined planting–breeding mode. Compared with that of ZL monoculture, the net income of the combined mode was 45.52% higher. The results suggested that the combined planting–breeding mode is an efficient and ecologically sustainable agriculture mode that achieves mutual benefits in terms of ecology and the economy by integrating resources, optimizing resource allocation, and managing biodiversity.

This study demonstrates the potential of combined planting–breeding modes to achieve mutual benefits in terms of both ecology and economy. In future studies, researchers could quantify ecological effects more precisely by improving the analysis of the life cycle chain. At the institutional level, ecological compensation mechanisms could be explored and combined planting–breeding modes could be promoted in agricultural practices, thereby advancing sustainable development in modern agriculture.

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

WT: Formal analysis, Investigation, Visualization, Writing – original draft. LX: Project administration, Supervision, Writing – review & editing. ZL: Conceptualization, Funding acquisition, Project administration, Supervision, Writing – review & editing. ML: Funding acquisition, Investigation, Writing – review & editing. DR: Investigation, Visualization, Writing – review & editing. QW: Investigation, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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