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Leveraging sustainable agronomic practices in smallholder maize production for environmental and economic gains: Evidence from the Erhai Lake Basin, China

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ABSTRACT

Context: Global maize production faces multiple challenges of increasing food security, farmers' profitability, and reducing environmental impacts, especially in smallholder-dominated, environmentally sensitive areas. Leveraging sustainable agronomic practices from high-performing smallholders holds the potential to reconcile crop production and environmental protection.

Objective: This study uses the Erhai Lake Basin, a typical lake basin in China surrounded by intensive crop production, as an example to illustrate how optimized agronomic practices can balance the environmental sustainability and economic benefits in maize production.

Methods: We conducted extensive farmer surveys across the Erhai Lake Basin, collecting 379 valid samples (comprising 226 grain maize and 153 sweet maize). From this dataset, we identified high yield and high N use efficiency (HH) maize farmers, and pinpointed key agronomic practices contributing to superior environmental and economic performance.

Results: Sweet maize had higher environmental impacts (N losses, global warming potential (GWP), eutrophication potential (EP), and acidification potential (AP)), but also higher economic benefits (net profit and net ecosystem economic benefits (NEEB)) than grain maize. Within the grain maize production system, the HH group reduced indicators of environmental impacts by 15.2% - 18.2%, and increased the net profit and NEEB by 35.1% and 52.5%, respectively, compared to the LL group (low yield and low N use efficiency). Similarly, in the sweet maize production system, the HH group reduced the indicators of environmental impacts by 22.7% - 56.2%, and increased the net profit, NEEB by 23.7% and 36.5%, respectively.

Key agronomic practices associated with improved performance in grain maize included adopting long-growth-period varieties (>153 days), reducing the N input (199 kg ha⁻¹), increasing the planting density (8.2 × 10⁴ plants ha⁻¹), and increasing the proportion of straw return, can reduce environmental impacts while enhancing sustainability. For sweet maize, less N input (243 kg ha⁻¹), higher planting density (7.9 × 10⁴ plants ha⁻¹), reducing K fertilizer input, and reducing the irrigation frequency can achieve similar effects.

Conclusion: Optimizing agronomic practices based on HH group can simultaneously reduce environmental impacts and improve economic benefits in maize systems. This approach demonstrates the potential for integrating productivity and sustainability goals in smallholder-dominated agriculture, particularly within intensification and water-sensitive production contexts.

Significance: This study offers practical guidance for improving the sustainability of smallholder maize systems under both environmental and economic pressures. It also provides a transferable framework for other ecologically and hydrologically sensitive agricultural regions worldwide.

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1. Introduction

Maize is China's most extensively cultivated crop, with an annual production of 289 million tons in 2023, contributing 23 % of global maize production, with 21 % of maize cultivated area (FAO, 2024). However, the environmental and economic performance of maize production still faces serious challenges due to growing food demand and the Sustainable Development Goals (SDGs) requirements. Globally, smallholder farming systems, which utilize 24 % of arable land and contribute 30 % of the total food supply, are central to food security (Lowder et al., 2016). However, in smallholder-dominated regions such as China, India, and Sub-Saharan Africa, the lack of management techniques (Holden, 2018), low technology availability (Sanchez, 2015), and small-scale farming (Zhang et al., 2016) result in low farmer incomes (Van Ittersum et al., 2016) and high environmental impacts (Guo et al., 2010; Grassini and Cassman, 2012; Xia et al., 2023). Therefore, understanding the sustainability of smallholder maize production systems' environmental and economic performance is essential to guarantee global food security and environmental friendliness.

Optimizing agronomic practices has been recognized as a cost-effective pathway to simultaneously enhance crop yield, economic returns, and environmental performance (You et al., 2024; Sugianto et al., 2025). For instance, improved nitrogen (N) management can increase maize yield, nutrient use efficiency, and profitability, while reducing reactive N losses, GHG emissions, and environmental footprints (Lyu et al., 2021; Torralbo et al., 2022; Goodkind et al., 2023; Wang et al., 2023; Tamagno et al., 2024; Shen et al., 2025). Optimizing plant density to balance between individual plant growth and population productivity, maintains high photosynthetic capacity and delays leaf senescence, thereby improving biomass accumulation, reducing nutrient losses, and increasing economic returns (Xu et al., 2017; Hou et al., 2020; Shao et al., 2024; Yan et al., 2024). Practices such as straw return and organic-inorganic fertilizer contribute to yield stability, reduce GHG emissions, and increase soil carbon sequestration (Zhang et al., 2022; Pei et al., 2023; Yao et al., 2024). Integrated water and nitrogen management strategies can increase maize productivity and nutrient uptake while minimizing N losses (Lu et al., 2021; Hou et al., 2024). The interaction of nitrogen fertilization and planting density enhances maize yield stability, nutrient efficiency, and net profitability (Wu et al., 2024). Overall, individual or system agronomic practices have great potential to increase yields and resource use efficiency while reducing environmental impacts (Chen et al., 2011; Liu et al., 2018; Yu et al., 2024).

The Erhai Lake Basin, the second-largest freshwater lake in Yunnan Province, is a key ecological conservation zone and agricultural region. However, intensive and poorly managed farming practices have led to substantial nutrient losses, exacerbating agricultural non-point source pollution over the past decades. For example, although garlic cultivation with an input of 700 kg N ha⁻¹ season⁻¹ is economically attractive, it results in large N excess and N losses (Zhang et al., 2017). Similarly, excessive fertilizer application in tobacco systems has increased N and P leaching and runoff (Wang et al., 2024). A recent study indicates that nutrient (N and P) losses in maize, vegetable, and faba bean systems account for more than half of the total inputs in the cropping systems (Zou et al., 2023). These findings highlight the pressing need to identify and implement agronomic practices to balance high productivity with environmental protection in the Erhai Lake Basin.

Environmental and economic benefits are critical indicators for evaluating the sustainability of crop production systems. Environmental benefits (e.g., active nitrogen loss, global warming potential, acidification potential, and eutrophication potential) are used to quantify the ecological impacts of agricultural practices (Nemecek et al., 2008; de Vries et al., 2011; Wang et al., 2018). Economic benefits (e.g., net profit) are the primary drivers influencing smallholder farmers' adoption of improved agronomic practices. To better understand the trade-offs between productivity and environmental impacts, net ecosystem economic

benefits (NEEB) have been proposed, offering a framework that integrates economic gains with ecological costs (Cai et al., 2023). Life Cycle Assessment (LCA) offers a robust method to quantitatively evaluate pollutant emissions across the entire agricultural production chain, from raw material extraction to product output. It enables the identification of key stages contributing to environmental emissions and provides insights for targeted improvement strategies (Rebitzer et al., 2004). In the Erhai Lake Basin, reducing the emissions of carbon (C), nitrogen (N), and phosphorus (P) from farmland and increasing farmers' income remains a major challenge (Hou et al., 2023). Therefore, environmental and economic benefits must be quantitatively assessed to determine the current crop production performance and identify potential improvements for future sustainability.

To address these knowledge gaps, the primary objectives of this study are to: (1) assess the environmental and economic sustainability of current grain maize and sweet maize production in the Erhai Lake Basin; (2) identify the agronomic practices of exceptional farmers who combine high yields with high nutrient use efficiencies (NUE); (3) explore the relationships between key agronomic practices, yield, NUE, and environmental-economic sustainability; and (4) assess the potential of these practices to increase yield performance, NUE, and environmental-economic sustainability.

2. Materials and methods

2.1. Study area

The study was conducted in Erhai Lake Basin, located in Yunnan Province, China (100°05'–100°17' E, 25°36'–25°58' N), with a total area of 2565 km². It is a plateau freshwater lake with a low-latitude plateau subtropical monsoon climate, with the average annual temperature and precipitation of 15.3 °C and 1048 mm, respectively (Zhang et al., 2017). The soils are highly fertile, and fertilizer input is generally intensive (Liu et al., 2025; He et al., 2023). Maize cultivation accounts for 26 % of the total food crop cultivation area, with grain and sweet maize being the primary types. The prevailing cultivation practice involves ridge tillage, flood irrigation, with fertilizers applied by broadcasting on the soil surface (He et al., 2023). Grain maize is typically sown between April and May and harvested from September to October, with one growing season per year. In contrast, sweet maize can be sown from March to July, allowing for two growing seasons annually. The main type of farmers is smallholders (FAO, 2025), with an average of 0.07–0.08 ha of cultivated land per capita and 0.08 ha of cultivated land per unit area. Over 90 % of farmers have not joined cooperatives (Supplementary table 1).

2.2. Farm household survey and dataset establishment

In 2022, we conducted a farmer survey in 16 towns in the Erhai Lake Basin. 4 villages in each town and 12 farmers in each village were randomly selected. Afterwards, we used the same questionnaire to conduct a more intensive survey in 5 villages in Wanqiao (WQ) town, the main sweet maize planting area (70 valid questionnaires were obtained). Professional researchers conducted all surveys to ensure the plausibility of the data obtained, with informed consent obtained from each farmer beforehand. The data was collected exclusively by interviewing farmers. Any questions that came up during the entry and review of the questionnaires were verified by contacting the farmers again by phone. Finally, 226 valid questionnaires for grain maize farmers and 153 for sweet maize farmers were collected. The distribution of surveyed farmers is shown in (Supplementary fig. 2). The main information in the questionnaire includes three parts: (1) input data, including fertilizer, pesticide, seed, plastic mulch, and diesel use; (2) output data, such as harvested yield and market price of maize; and (3) socio-economic characteristics of farmers, including age, education level, and farming experience, etc.

2.3. Calculation of environmental and economic indicators

2.3.1. Environmental indicators

Based on the LCA framework, we evaluated four key environmental indicators (Supplementary methods 1.1):

2.3.1.1. N loss. The main pathways for N loss from upland soils to water and air are N leaching, N runoff, ammonia volatilization (NH_3), and N_2O emissions (Yin et al., 2021). Therefore, the N loss (kg N ha^{-1}) was defined as:

$$N_{\text{loss},i} = \sum_{ij} (\text{Input}_{ij} \times EF_{ij}) + N_{\text{leaching},i} + N_{\text{runoff},i} + N_{\text{NH}_3,i} + N_{\text{N}_2\text{O},i} \quad (1)$$

where i represents the crop types (grain maize or sweet maize), Input represents the amount of agricultural inputs including fertilizers, pesticides, diesel and plastic film, etc. j represents the type of agricultural inputs. EF_j is the emission factor (unitless, 0–1) for N losses from the manufacturing and transportation phase of these agricultural inputs (Supplementary table 2). N_{leaching} , N_{runoff} , N_{NH_3} and $N_{\text{N}_2\text{O}}$ represent the loss paths of leaching, runoff, NH_3 and N_2O , respectively (kg N ha^{-1}). N leaching, N runoff, NH_3 , and N_2O emissions, which were estimated based on empirical formulas and emission factor (Supplementary methods 1.2).

2.3.1.2. Global warming potential (GWP). GWP ($\text{t CO}_2\text{-eq ha}^{-1}$) is an indicator used to assess the effects of greenhouse gas emissions, as defined by Liang et al. (2022):

$$\text{GWP}_i = \sum_{ij} (\text{Input}_{ij} \times EF_{ij}) + \text{N}_2\text{O}_{\text{direct},i} + \text{N}_2\text{O}_{\text{indirect},i} \quad (3)$$

where i represents the crop types (grain maize or sweet maize), Input represents the amount of agricultural inputs including fertilizers, pesticides, diesel and plastic film, etc. j represents the type of agricultural inputs. EF_j is the emission factor (unitless) for GWP from the manufacturing and transportation phase of these agricultural inputs (Supplementary table 2). $\text{N}_2\text{O}_{\text{direct}}$ and $\text{N}_2\text{O}_{\text{indirect}}$ represent the direct and indirect N_2O emissions from the field (Supplementary methods 1.3).

2.3.1.3. Eutrophication potential (EP). Freshwater eutrophication is mainly caused by the accumulation of nitrogen (N) and phosphorus (P) nutrients. In agricultural systems, these nutrients can be transported from farmland to lakes via surface runoff, leading to nutrient over-enrichment and a loss of species diversity in aquatic ecosystems. It has become one of the major environmental impacts of agricultural production (Alexander et al., 2008). The EP ($\text{kg PO}_4\text{-eq ha}^{-1}$) as defined by Wang et al. (2018):

$$\text{EP}_i = \sum_{ij} (\text{Input}_{ij} \times EF_{ij}) + \sum_i \text{FS}_i \quad (4)$$

where i represents the crop types (grain maize or sweet maize), Input represents the amount of agricultural inputs including fertilizers, pesticides, diesel and plastic film, etc. j represents the type of agricultural inputs. EF_j is the emission factor (unitless, 0–1) for PO_4 from the manufacturing and transportation phase of these agricultural inputs (Supplementary table 2). FS represents the total eutrophication potential of the farming system (Supplementary methods 1.4).

2.3.1.4. Acidification potential (AP). Acidification exacerbates the impacts to the sustainability of water and soil ecosystems, leading to increased algal growth in lakes and soil acidification (Schindler et al., 1985). The AP ($\text{kg SO}_2\text{-eq ha}^{-1}$) was defined by Wang et al. (2018):

$$\text{AP}_i = \sum_{ij} (\text{Input}_{ij} \times EF_{ij}) + \sum_i \text{FS}_i \quad (5)$$

where i represents the crop types (grain maize or sweet maize), Input represents the amount of agricultural inputs including fertilizers, pesticides, diesel and plastic film, etc. j represents the type of agricultural inputs. EF_j is the emission factor (unitless, 0–1) for SO_2 from the manufacturing and transportation phase of these agricultural inputs (Supplementary table 2). FS represents the total acidification potential of the farming system (Supplementary methods 1.5).

2.3.2. Economic indicators

2.3.2.1. Net profit. Net profit (CNY ha^{-1}) is calculated with reference to (Goodkind et al., 2023):

$$\text{Net profit}_i = Y_i \times \text{Price}_i - \left(\sum_{ij} \text{Input}_{ij} \times \text{Price}_{ij} \right) \quad (6)$$

where i represents the crop types (grain maize or sweet maize), j represents the agricultural inputs, including fertilizers, pesticides, diesel, and plastic films.

2.3.2.2. Net ecosystem economic benefits (NEEB). The NEEB (CNY ha^{-1}) is used to systematically assess the economic benefits and environmental costs of crop production. The environmental damage cost (EDC) is mainly caused by greenhouse gas emissions, reactive N loss, eutrophication potential and acidification potential on ecosystems, human health and climate warming. Calculation with reference to (Xia et al., 2016):

$$\text{NEEB}_i = \text{Net profit}_i - \text{EDC}_i \quad (9)$$

$$\text{EDC}_i = \sum_{k=1}^n (\text{Nr}_k \times \text{Price}_{\text{Nr},k}) + \text{GWP}_i \times \text{Price}_{\text{GWP},k} + \text{EP}_i \times \text{Price}_{\text{EP},k} + \text{AP}_i \times \text{Price}_{\text{AP},k} \quad (10)$$

where i represents the crop types (grain maize or sweet maize). k indicates reactive N loss with NH_3 , NO_x emissions, leaching and runoff. GWP_i is the total greenhouse gas emission, EP_i and AP_i are the total eutrophication potential and acidification potential, and the damage cost (Price) is shown in (Supplementary table 3).

2.4. Scenarios analyses

Five scenarios were designed separately for grain maize and sweet maize to evaluate the impact of different agronomic practices on yield, NUE and environmental-economic sustainability. All selected indicators were significantly correlated with yield and exhibited distinct optimal values at maximum yield (Section 3.5).

For grain maize, four key agronomic practices were considered: variety growth duration, total nitrogen fertilizer input, planting density and straw return rate. Scenario 1 (S1) extended the variety growth duration (153 days) while maintaining the total nitrogen input, planting density, and straw return rate at farmer practices. Scenario 2 (S2) only optimize total nitrogen input (199 kg ha^{-1}), with other measures unchanged. Scenario 3 (S3) optimized planting density (8.2×10^4 plants ha^{-1}), while keeping the remaining measures at farmer practices. Scenario 4 (S4) assumed 100 % straw return, without altering other measures. Scenario 5 (S5) simultaneously optimized variety growth duration, total nitrogen input, plant density, and straw return rate.

For sweet maize, we focus on four key agronomic measures: planting density, total nitrogen input, total potassium input, and irrigation frequency. Scenario 1 (S1) optimized planting density (7.9×10^4 plants ha^{-1}), while keeping total nitrogen and potassium inputs and irrigation frequency unchanged. Scenario 2 (S2) optimized total nitrogen input (243 kg ha^{-1}), with other measures unchanged. Scenario 3 (S3) eliminated potassium input, maintaining other measures. Scenario 4 (S4) removed flood irrigation without altering other factors. Scenario 5 (S5) simultaneously optimized all four measures: planting density, nitrogen

input, potassium input, and irrigation frequency.

2.5. Data analysis

Before statistical analysis, all data were tested for normality of the residuals and homogeneity of variance. Statistical analyses were conducted using SPSS Statistics 27.0 (SPSS Inc., Chicago, IL, USA). Independent sample t-tests were used to evaluate differences between grain maize and sweet maize in N loss, GWP, EP, AP, net profit, and NEEB at a significance level of $P < 0.05$. One-way analysis of variance (ANOVA) was applied to compare group differences, followed by Duncan's multiple range test for post hoc comparisons ($P < 0.05$).

3. Results

3.1. Inputs, outputs and environmental-economic sustainability performance of grain maize and sweet maize

The farmers' survey showed that there were significant differences in fertilizer input, pesticides, and plastic film between grain maize and sweet maize ($P < 0.05$). The average total N fertilizer input for grain maize was $306.1 \text{ kg N ha}^{-1}$, the pesticide use was 6.5 kg ha^{-1} and the plastic film use was 23.0 kg ha^{-1} . In contrast, sweet maize had higher inputs, with $391.2 \text{ kg N ha}^{-1}$ of total N, 8.4 kg ha^{-1} of pesticide, and 62.8 kg ha^{-1} of plastic film. The average yields of grain maize and sweet maize were 9.1 t ha^{-1} and 21.5 t ha^{-1} , respectively. Dietary energy yield of grain maize is significantly higher than sweet maize (Table 1).

In terms of environmental sustainability, grain maize exhibited significantly lower environmental impacts than sweet maize ($P < 0.001$). The N loss, GWP, EP, and AP of grain maize were $128.7 \text{ kg N ha}^{-1}$, $4.8 \text{ t CO}_2\text{-eq ha}^{-1}$, $46.5 \text{ kg PO}_4\text{-eq ha}^{-1}$, and $68.2 \text{ kg SO}_2\text{-eq ha}^{-1}$, respectively. In comparison, the N loss, GWP, EP, and AP of sweet maize were $165.5 \text{ kg N ha}^{-1}$, $6.7 \text{ t CO}_2\text{-eq ha}^{-1}$, $59.0 \text{ kg PO}_4\text{-eq ha}^{-1}$, and $84.2 \text{ kg SO}_2\text{-eq ha}^{-1}$, respectively. In terms of economic sustainability, the economic benefits of sweet maize were significantly higher than grain maize ($P < 0.001$). The net profit and NEEB of sweet maize were $3.1 \times 10^4 \text{ CNY ha}^{-1}$ and $2.6 \times 10^4 \text{ CNY ha}^{-1}$, respectively, compared to $1.5 \times 10^4 \text{ CNY ha}^{-1}$ and $1.1 \times 10^4 \text{ CNY ha}^{-1}$ (Table 2).

3.2. Yield and PFP_N performance under different groups

Based on the farmers' survey grouping (Supplementary methods 1.6), the average yield of grain maize and sweet maize was estimated at 9.1 t ha^{-1} and 21.5 t ha^{-1} , respectively, with corresponding PFP_N (partial factor productivity of nitrogen) of 32.7 kg kg^{-1} and 64.4 kg kg^{-1} . For grain maize, the yields of the HH, HL, LH, and LL groups were 10.9, 9.8, 7.5, and 7.9 t ha^{-1} , with PFP_N values of 44.1, 26.9, 43.8, and 21.8 kg kg^{-1} , respectively (Fig. 1A). Similarly, for sweet maize, the yields of the HH, HL, LH, and LL groups were 25.2, 23.9, 16.6, and 17.1 t ha^{-1} , with PFP_N values of 89.3, 50.4, 98.8, and 37.5 kg kg^{-1} , respectively (Fig. 1B). Relative to the mean yield and PFP_N across all samples, the yield of grain maize HH group 19.8 % higher and the PFP_N was 11.3 % higher. For the sweet maize HH group the yield was 17.1 % higher and the PFP_N was 24.9 % higher.

3.3. Environmental-economic sustainability performance of different groups

N loss, GWP, AP, and EP were significantly different among the four groups (Fig. 2A–2D). N loss, GWP, AP, and EP were significantly higher ($P < 0.05$) in HL and LL groups than in HH and LH groups in grain maize. In the HH group, N loss was 32.0 % and 32.3 % lower than in the HL and LL groups, respectively. Similarly, GWP was reduced by 31.6 % and 32.2 %, EP by 31.1 % and 31.4 %, and AP by 28.1 % and 28.3 %, compared to the HL and LL groups, respectively. The HH group had the highest net profit and NEEB, significantly higher than HL, LH, and LL

Table 1

The inputs and outputs inventory of grain maize and sweet maize in Erhai Lake Basin.

Inputs/ Outputs	Grain maize (n = 226)			Sweet maize (n = 153)			P-value
	Mean	SD	CV	Mean	SD	CV	
Inputs							
Total N fertilizer (kg N ha ⁻¹)	306.1	88.6	0.29	391.2	156.6	0.40	P < 0.001
Total P fertilizer (kg P ha ⁻¹)	60.9	21.8	0.36	90.0	54.0	0.57	P < 0.001
Total K fertilizer (kg K ha ⁻¹)	127.6	44.2	0.35	184.4	108.0	0.56	P < 0.001
N in organic fertilizers (kg N ha ⁻¹)	26.3	42.7	1.63	41.2	76.2	1.85	P = 0.028
P in organic fertilizer (kg P ha ⁻¹)	9.3	16.0	1.73	18.4	33.9	1.84	P = 0.002
K in organic fertilizer (kg K ha ⁻¹)	16.6	27.2	1.64	43.2	78.7	1.82	P < 0.001
Synthetic N fertilizers (kg N ha ⁻¹)	279.8	96.7	0.35	347.8	179.8	0.52	P < 0.001
Mineral P fertilizers (kg P ha ⁻¹)	51.6	22.2	0.43	76.1	49.5	0.65	P < 0.001
Mineral K fertilizers (kg K ha ⁻¹)	110.9	45.6	0.41	149.3	92.0	0.62	P < 0.001
Diesel (kg ha ⁻¹)	93.6	14.1	0.15	92.6	14.9	0.16	P = 0.518
Pesticide (kg ha ⁻¹)	6.5	3.2	0.48	8.4	2.8	0.33	P < 0.001
Plastic film (kg ha ⁻¹)	23.0	32.9	1.43	62.8	16.8	0.27	P < 0.001
Outputs							
Yield (t ha ⁻¹)	9.1	1.8	0.20	21.5	4.5	0.21	P < 0.001
Dietary energy yield (Gcal ha ⁻¹)	31.7	6.3	0.20	11.1	2.34	0.21	P < 0.001

Note: SD means standard deviation, CV means coefficient of variation. Dietary energy yield (Gcal ha⁻¹) represents the energy output of grain and sweet maize, and was estimated as: dietary energy yield = yield × dietary energy content (Gcal ha⁻¹). The dietary energy contents of grain and sweet maize were estimated to be $3.48 \text{ Gcal ha}^{-1}$ and $1.12 \text{ Gcal ha}^{-1}$, respectively. The edible portion of sweet maize accounts for 46 % of the yield (Yang et al., 2018).

($P < 0.05$). The net profit was $0.39 \times 10^4 \text{ CNY ha}^{-1}$, $0.78 \times 10^4 \text{ CNY ha}^{-1}$ and $0.91 \times 10^4 \text{ CNY ha}^{-1}$ higher, and the NEEB was $0.53 \times 10^4 \text{ CNY ha}^{-1}$, $0.70 \times 10^4 \text{ CNY ha}^{-1}$ and $1.05 \times 10^4 \text{ CNY ha}^{-1}$ higher, respectively (Fig. 2E, F). N leaching accounted for 64.2 % of N losses (Supplementary fig. 3A). Fertilizer production and transportation during the agricultural material stage contributed 56.4 % of the GWP (Supplementary fig. 3B). Fertilizer application during the farming stage accounted for 95.4 % of the EP and 79.0 % of the AP (Supplementary fig. 3 C, D). N losses contributed 62.8 % of NEEB (Supplementary fig. 3E).

Similarly, for sweet maize, the HH group showed lower environmental impacts (Fig. 2A–2D). N loss was lower in the HH group than in the HL and LL groups by 66.1 % and 68.5 %, GWP by 48.0 % and 48.9 %, EP by 68.4 % and 71.1 %, and AP by 37.0 % and 36.0 %, respectively. The net profit of HH group was higher by $0.14 \times 10^4 \text{ CNY ha}^{-1}$, $1.70 \times 10^4 \text{ CNY ha}^{-1}$, and $1.74 \times 10^4 \text{ CNY ha}^{-1}$, respectively, and the NEEB was higher by $0.51 \times 10^4 \text{ CNY ha}^{-1}$, $1.59 \times 10^4 \text{ CNY ha}^{-1}$, and $2.14 \times 10^4 \text{ CNY ha}^{-1}$ compared with the HL, LH, and LL combinations, respectively (Fig. 2E, F). N leaching accounted for 71.3 % of N losses (Supplementary fig. 4A). Fertilizer production and transportation during the agricultural material stage accounted for 50.7 % of the GWP (Supplementary fig. 4B). Fertilizer application during the farming stage

Table 2
The environmental-economic sustainability performance of grain maize and sweet maize in Erhai Lake Basin.

Dimensions	Indicators	Grain maize (n = 226)			Sweet maize (n = 153)			P-value
		Mean	SD	CV	Mean	SD	CV	
Environmental	N loss (kg N ha ⁻¹)	128.7	36.8	0.29	165.5	67.1	0.41	P < 0.001
	GWP (t CO ₂ -eq ha ⁻¹)	4.8	1.3	0.28	6.7	3.5	0.52	P < 0.001
	EP (kg PO ₄ -eq ha ⁻¹)	46.5	12.9	0.28	59.0	22.7	0.38	P < 0.001
	AP (kg SO ₂ -eq ha ⁻¹)	68.2	16.7	0.25	84.2	29.2	0.35	P < 0.001
Economic	Net profit (×10 ⁴ CNY ha ⁻¹)	1.5	0.6	0.43	3.1	1.6	0.52	P < 0.001
	NEEB (×10 ⁴ CNY ha ⁻¹)	1.1	0.7	0.60	2.6	1.6	0.62	P < 0.001

Note: GWP represents global warming potential, EP represents eutrophication potential, AP represents the acidification potential, NEEB represents net ecosystem economic benefit. SD means standard deviation, CV means coefficient of variation.

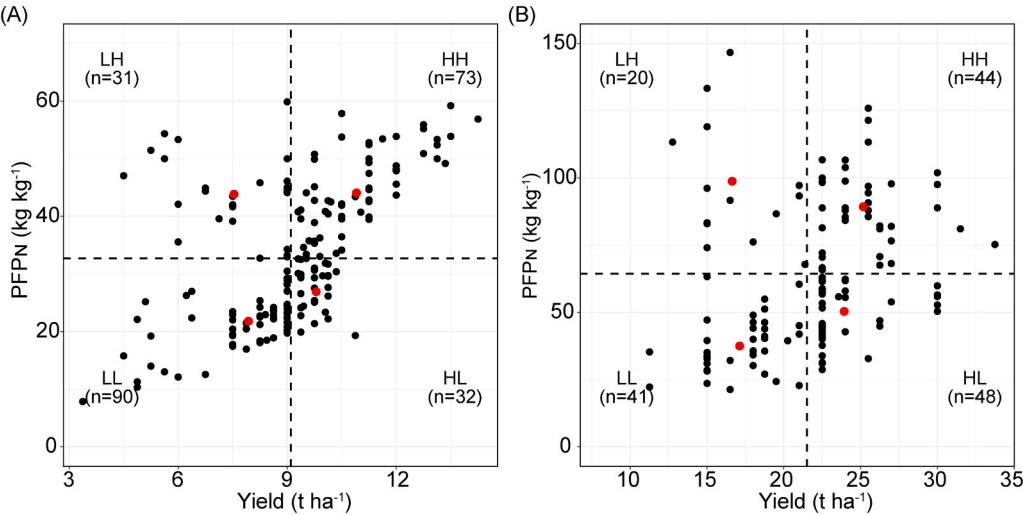


Fig. 1. Relationship between yield and PFP_N for grain maize (A) and sweet maize (B). The gray dashed line represents the average yield (kernel dry weight for grain maize and fresh weight including kernels, cobs, and husks for sweet maize) and PFP_N across all samples. Black dots represent each independent survey sample (226 for grain maize and 153 for sweet maize), and the red dots represent the mean for each group, “n” represents the number of samples for each group.

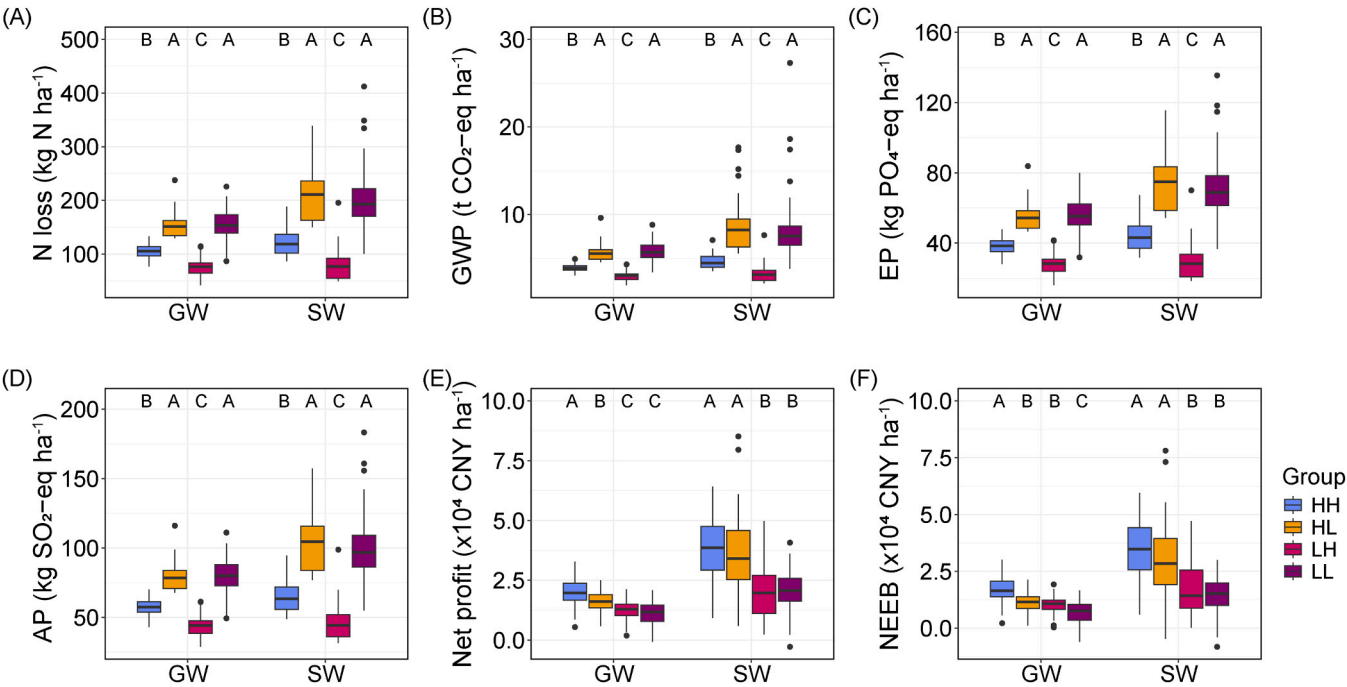


Fig. 2. Comparisons of environmental (A-D) and economic (E-F) performance of different groups. GW denotes grain maize, SW denotes sweet maize, GWP represents global warming potential, EP represents eutrophication potential, AP represents the acidification potential, NEEB represents net ecosystem economic benefit. Up-percase letters denote significant differences among groups ($P < 0.05$).

accounted for 97.0 % of the EP and 80.7 % of the total AP (Supplementary fig. 4C, D). N losses contributed 63.6 % of NEEB (Supplementary fig. 4E).

These results suggest that the HH group has dual advantages in enhancing the environmental sustainability and economic profitability of maize production systems (Supplementary fig. 5).

3.4. Agronomic practices of different groups

We compared agronomic practices across the different groups. For grain maize, total N input, planting density, variety growth period, and the proportion of straw returned showed significant differences among the four groups ($P < 0.05$). No significant differences were found in total P input, total K input, pesticide frequency and herbicides frequency ($P > 0.05$). The HH group had a total N input of 250.8 kg ha^{-1} , a planting density of $6.8 \times 10^4 \text{ plants ha}^{-1}$, a growth period of 153 days, and a proportion of straw returned of 73.5 % (Fig. 3).

For sweet maize, significant differences were observed in total N input, planting density, irrigation frequency, pesticide frequency, and the proportion of straw returned among the four groups ($P < 0.05$). The HH group had a total N input of 289.4 kg ha^{-1} , a planting density of $7.4 \times 10^4 \text{ plants ha}^{-1}$, irrigation frequency of 1.7 times, and a proportion of straw returned of 78.4 %. No significant differences were found in growth period or herbicide use frequency ($P > 0.05$) (Fig. 4).

3.5. Agronomic practices effect on maize yield and environmental-economic sustainability

In grain maize, yield was significantly influenced by the growth

period, total N input, planting density, and the proportion of straw returned ($P < 0.05$) (Fig. 5A). The highest yield was observed when the growth period was 153 days, total N input was 199 kg ha^{-1} , and planting density was $8.2 \times 10^4 \text{ plants ha}^{-1}$. Additionally, a higher proportion of straw returned was associated with a greater yield increase (Fig. 5B–5E). Total N fertilizer input was significantly and positively correlated with environmental sustainability (e.g., N loss, GWP, AP, and EP), and growth period was significantly and positively correlated with economic sustainability (net profit and NEEB). NUE was significantly and negatively correlated with environmental sustainability, and was significantly and positively correlated with economic sustainability ($P < 0.05$) (Fig. 6A).

While sweet maize yield was significantly associated with planting density, total N input, total K fertilizer input, and irrigation frequency ($P < 0.05$) (Fig. 5F). The highest yield was achieved at a planting density of $7.9 \times 10^4 \text{ plants ha}^{-1}$ and a total N input of 243 kg ha^{-1} . However, when the total K fertilizer input exceeded 250 kg ha^{-1} , yield decreased. Additionally, an increase in irrigation frequency also led to lower yields. (Fig. 5G–5J). Total N fertilizer input was significantly and positively correlated with environmental sustainability, and NUE was significantly and negatively correlated with environmental sustainability ($P < 0.05$) (Fig. 6B).

3.6. Scenarios analyses

Across scenarios 1–5, grain maize exhibited an estimated total yield ranging from 6.0 to $6.9 \times 10^4 \text{ t}$ and the partial factor productivity of nitrogen (NUE) of 32.9 – 52.8 kg kg^{-1} , respectively. Environmental performance, the N loss, GWP, EP, and AP, varied from 555.5 to 846.8 t ,

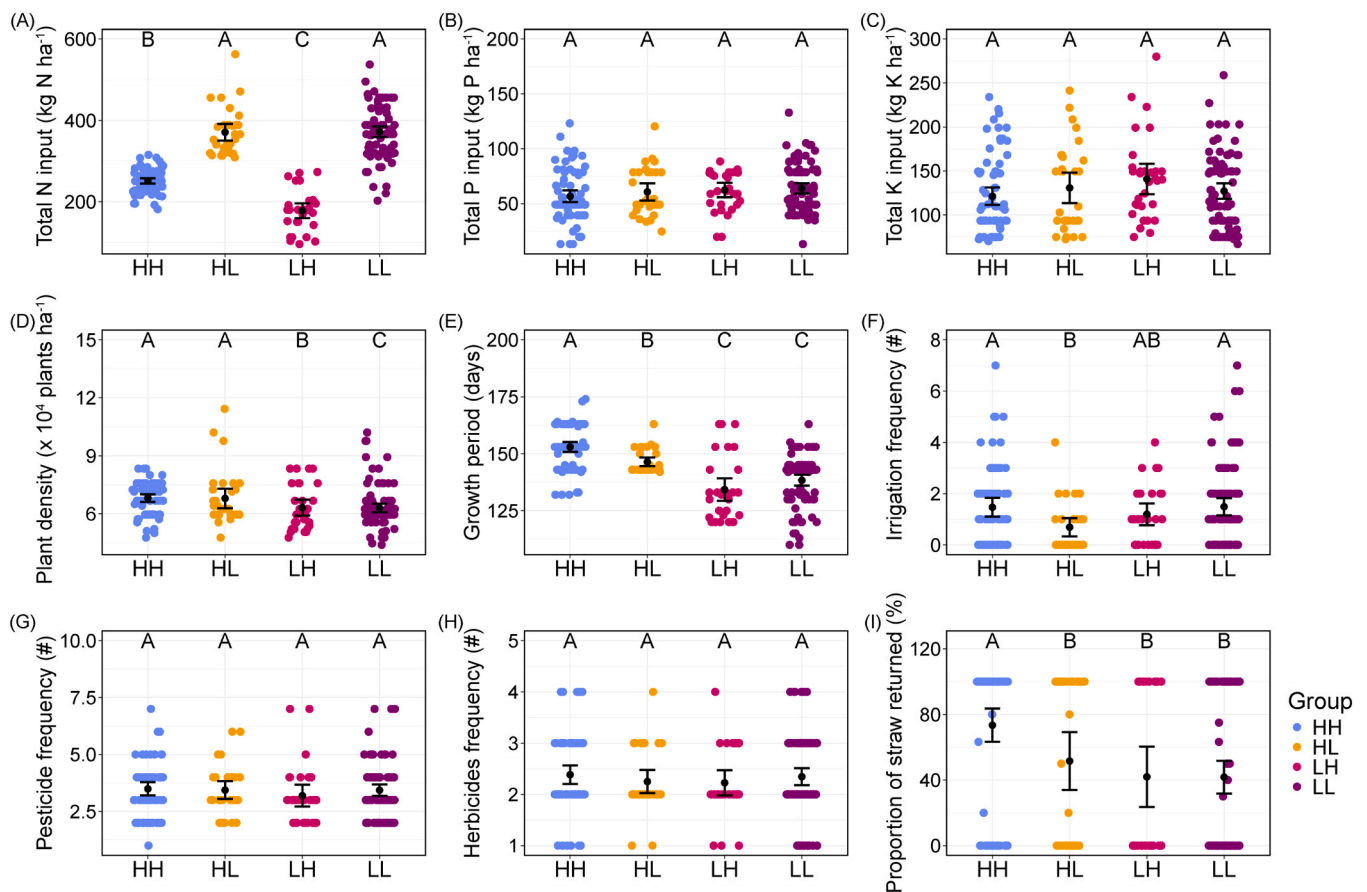


Fig. 3. Comparison of agronomic measures for grain maize of different groups. Uppercase letters denote significant differences among groups ($P < 0.05$). Points of different colors represent individual samples for each group: HH ($n = 73$), HL ($n = 32$), LH ($n = 31$), and LL ($n = 90$). Error bars indicate means $\pm$ 95 % confidence intervals.

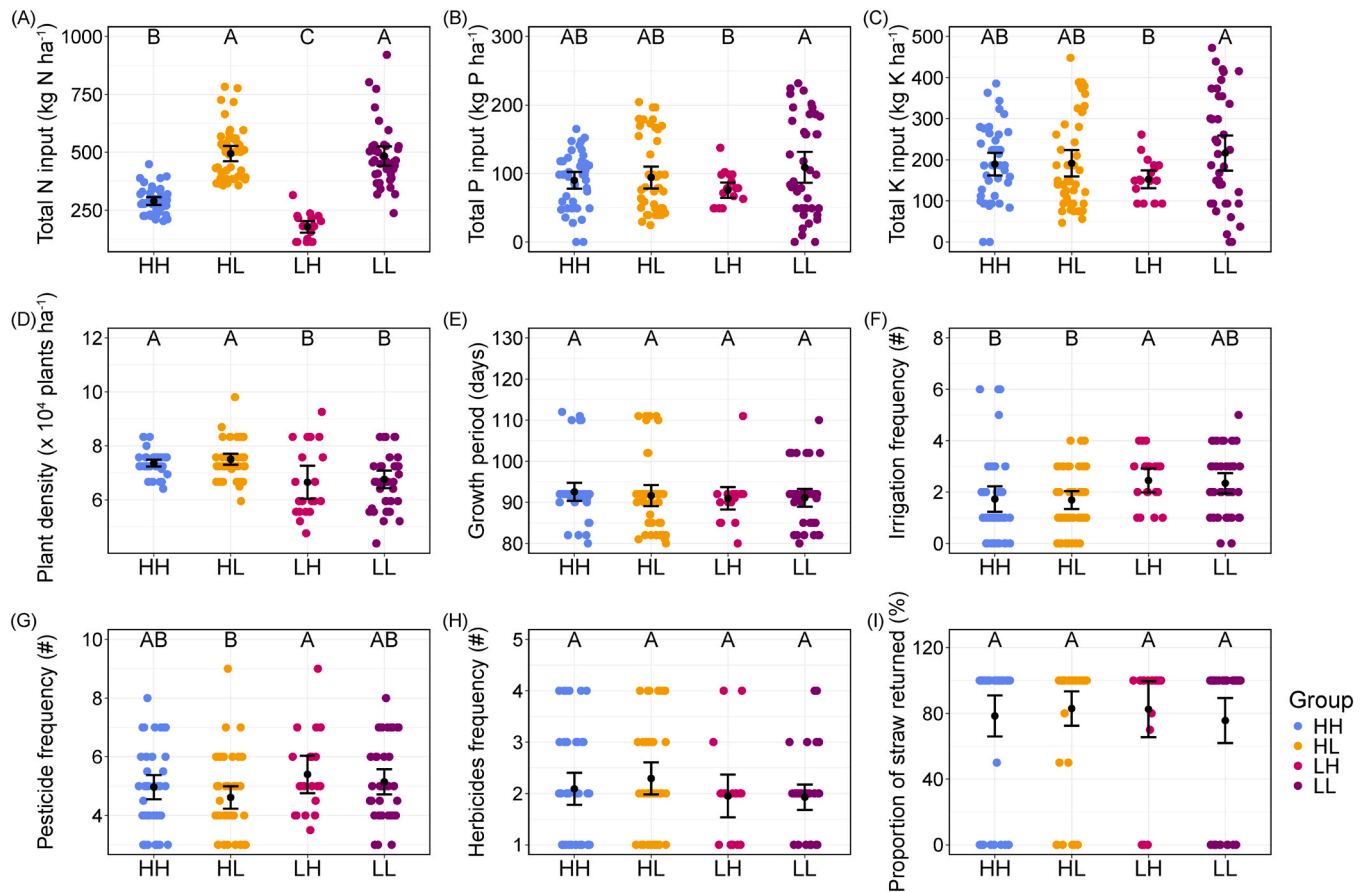


Fig. 4. Comparison of agronomic measures for sweet maize of different groups. Uppercase letters denote significant differences among groups ($P < 0.05$). Points of different colors represent individual samples for each group: HH ($n = 44$), HL ($n = 48$), LH ($n = 20$), and LL ($n = 41$). Error bars indicate means $\pm$ 95% confidence intervals.

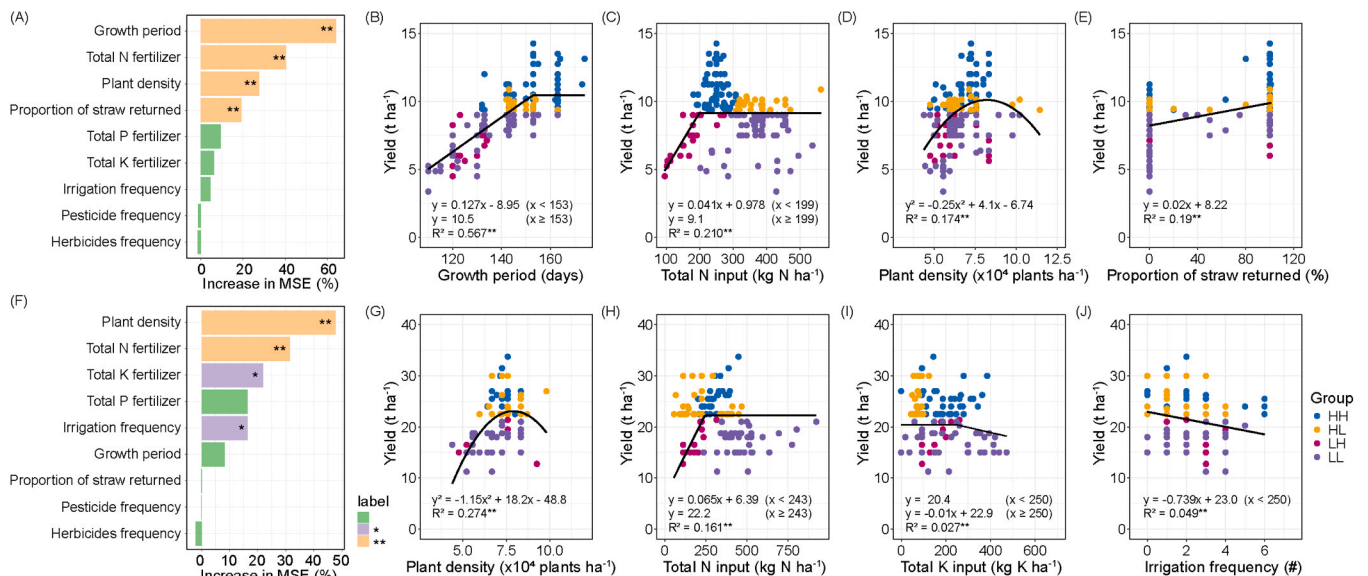


Fig. 5. Relative importance and regression relationships of key agronomic practices affecting maize yield. The left figure indicates the relative importance of each agronomic variable of grain maize (A) and sweet maize (F) based on the farmers' survey, with * and ** denoting significance at the 0.05 and 0.01 levels, respectively. Fig. B-E show the regression relationships between grain maize yield and significant agronomic practices: growth period (B), total N input (C), planting density (D), and proportion of straw (E). Fig. G-J show the regression relationships between sweet maize yield and significant agronomic practices: planting density (G), total N input (H), total K input (I), and irrigation frequency (J).

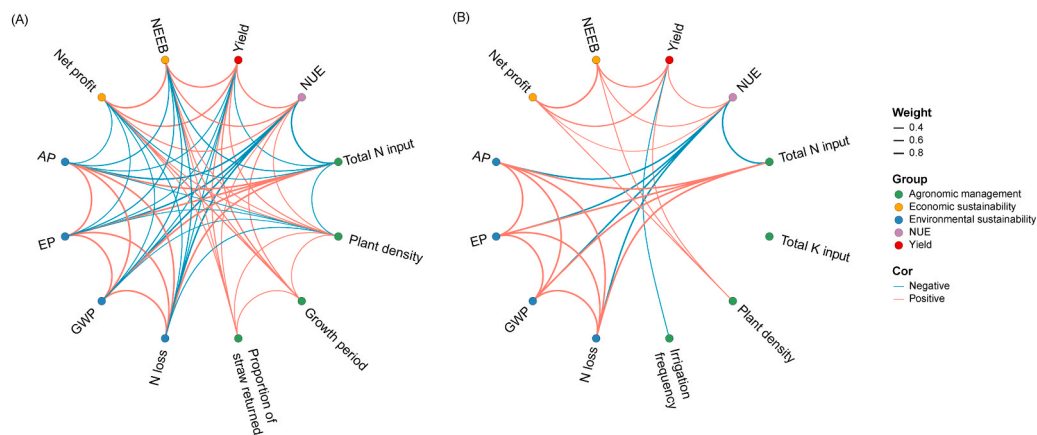


Fig. 6. Correlation between agronomic practices, environmental-economic sustainability indicators, NUE, and yield for (A) grain maize and (B) sweet maize. AP represents acidification potential, EP represents eutrophication potential, GWP represents global warming potential, NEEB denotes net ecosystem economic benefits, and NUE refers to the partial factor productivity of nitrogen.

$2.1\text{--}3.2 \times 10^4$ t CO₂-eq, 204.3–306.4 t SO₂-eq, 316.7–448.7 t PO₄-eq, respectively. The economic performance (net profit, and NEEB) is 103.6–127.1 million CNY and 87.2–110.7 million CNY, respectively. Notably, scenario 5 outperformed the Baseline, the yield and NUE increased by 15.3 % and 19.5 %, respectively, while simultaneously reducing N loss, GWP, EP, and AP by 34.4 %, 32.1 %, 33.3 %, and 29.4 %. Net profit and NEEB also increased by 28.7 % and 52.9 %, respectively (Table 3).

For sweet maize, the estimated total yield and NUE across scenarios 1–5 ranged from 2.7 to 3.1×10^4 t, 63.0–95.5 kg kg^{−1}, respectively. Environmental impacts were relatively moderate, with N loss ranging from 95.9 to 263.2 t, GWP from 0.51 to 0.90×10^4 t CO₂-eq, EP from 32.7 to 96.7 t SO₂-eq, and AP from 74.6 to 111.6 t PO₄-eq. Economic performance was also favorable, with net profit and NEEB ranging from 39.9 to 48.7 million CNY and 33.0–45.2 million CNY, respectively. Compared to the Baseline, the total yield and NUE of S5 increased by 7.9 % and 31.0 %, respectively, while the N loss, GWP, EP, and AP decreased by 63.6 %, 45.2 %, 66.1 % and 33.1 %, respectively. These reductions were accompanied by economic improvements, with net profit and NEEB rising by 18.7 % and 32.7 % (Table 4).

4. Discussion

4.1. Smallholder-dominated maize systems in the Erhai Lake Basin are characterized by high inputs and excessive environmental burdens

Our study reveals that smallholder maize production systems in the Erhai Lake Basin suffer from low N use efficiency and high environmental costs, primarily due to excessive fertilizer inputs and inefficient agronomic practices. The average yields of grain maize and sweet maize

were 9.1 t ha^{−1} and 21.5 t ha^{−1}, and the values for PFP_N were only 32.7 kg kg^{−1} and 64.4 kg kg^{−1} (Table 1; Fig. 1). More than 40 % of the farmers have both yield and PFP_N below the average, indicating that excessive N fertilizer input has not translated into productivity gains, but rather contributed to reduced N use efficiency and greater losses (Fig. 2).

Environmental emissions further underscore this imbalance. In this study, the estimated N losses of grain maize and sweet maize were 128.7 kg N ha^{−1} and 165.5 kg N ha^{−1}, respectively (Table 2), which were more than twice the average in China (Cui et al., 2018), and near equivalent to the total N loss of wheat-maize crop rotation system in the North China Plain (135 kg N ha^{−1} year^{−1}) (Liang et al., 2022). The GWP of grain and sweet maize were 4.8 t CO₂-eq ha^{−1} and 6.7 t CO₂-eq ha^{−1}, respectively (Table 2), far exceeding the average of 3.52 t CO₂-eq ha^{−1} in China (Cui et al., 2018), and similarly far exceeding the maize production systems in the United States (3.3 t CO₂-eq ha^{−1}) (Pelton, 2019). Additionally, the eutrophication and acidification potentials were significantly higher than those evaluated in vegetable systems in China (Wang et al., 2021) and even intensive systems in Iran (Khoshnevisan et al., 2014). Therefore, the smallholder-dominated maize production systems in the Erhai Lake Basin are a hotspot of high N loss, high GWP, and high eutrophication and acidification.

These results stem not only from technical inefficiencies but also from socio-structural constraints. Lack of advanced knowledge and better agronomic practices (George, 2014; Cairns and Prasanna, 2018; Pasley et al., 2020) have resulted in low productivity of smallholder maize production systems. In this study, we found that smallholder farmers in the Erhai Lake Basin possess extensive farming experience; however, their limited participation in cooperative organizations and the absence of large-scale production structures hinder their ability to

Table 3
Effects of optimized growth period (S1), total N input (S2), plant density (S3), the proportion of straw returned (S4), and integrated agronomic practices (S5) on yield, NUE, and environmental-economic sustainability for grain maize under different scenarios in the Erhai Lake Basin.

Scenarios	Total yield ($\times 10^4$ t)	NUE (%)	Environmental sustainability				Economic sustainability	
			Total N loss (t)	Total GWP ($\times 10^4$ t CO ₂ -eq)	Total EP (t SO ₂ -eq)	Total AP (t PO ₄ -eq)	Total net profit (million CNY)	Total NEEB (million CNY)
Baseline	6.0	33.3	847.1	3.2	306.1	448.9	98.7	72.4
S1	6.9	34.3	846.8	3.2	306.4	448.7	124.0	99.6
S2	6.0	45.7	555.5	2.1	204.3	316.7	103.6	87.2
S3	6.6	32.9	846.8	3.2	306.4	448.7	113.8	89.4
S4	6.7	33.4	846.8	3.2	306.4	448.7	118.8	94.4
S5	6.9	52.8	555.5	2.1	204.3	316.7	127.1	110.7

Note: Baseline represents the current situation based on the farmer survey, the detailed descriptions of each scenario were shown in the Materials and methods 2.6. NUE refers to the partial factor productivity of nitrogen, GWP represents global warming potential, EP represents eutrophication potential, AP represents acidification potential, and NEEB denotes net ecosystem economic benefits.

Table 4

Effects of optimized plant density (S1), total N input (S2), total K input (S3), and irrigation times (S4), and integrated agronomic practices (S5) on yield, NUE and environmental-economic sustainability for sweet maize under different scenarios in the Erhai Lake Basin.

Scenarios	Total yield ($\times 10^4$ t)	NUE (%)	Environmental sustainability				Economic sustainability	
			Total N loss (t)	Total GWP ($\times 10^4$ t CO ₂ -eq)	Total EP (t SO ₂ -eq)	Total AP (t PO ₄ -eq)	Total net profit (million CNY)	Total NEEB (million CNY)
Baseline	2.8	64.4	263.2	0.90	96.7	111.6	41.0	34.1
S1	3.1	71.7	263.2	0.90	96.7	111.6	45.2	38.3
S2	2.9	91.4	95.9	0.51	32.7	74.8	44.2	40.7
S3	2.7	63.0	263.2	0.89	96.6	111.4	39.9	33.0
S4	3.0	71.0	263.2	0.90	96.7	111.6	45.1	38.2
S5	3.1	95.5	95.9	0.49	32.7	74.6	48.7	45.2

Note: Baseline represents the current situation based on the farmer survey, the detailed descriptions of each scenario were shown in the Materials and methods 2.6. NUE refers to the partial factor productivity of nitrogen, GWP represents global warming potential, EP represents eutrophication potential, AP represents acidification potential, and NEEB denotes net ecosystem economic benefits.

adopt more efficient and sustainable practices (Supplementary table 1). These constraints highlight the urgent need to implement targeted measures to optimize maize production systems in the Erhai Lake Basin.

4.2. Identifying high-performing farmers provides a pathway for sustainable intensification

To explore sustainable intensification pathways in smallholder-dominated systems, we identified a group of high-performing farmers (HH group) with superior N use efficiency and yield advantages. We aimed to understand their agronomic practices and use them as models for other smallholders. The results showed that the HH group and the grain maize yield were 10.9 t ha^{-1} and the PFP_N was 44.1 kg kg^{-1} (Fig. 1A), which exceeded the high yield level in southwest China (Hou et al., 2020; Luo et al., 2023). The sweet maize yield was 25.2 t ha^{-1} and 89.3 kg kg^{-1} (Fig. 1B), which is also consistent with the results of field trials (Gao et al., 2020; Pei et al., 2023).

Moreover, these advantages were accompanied by significant reductions in N losses, GWP, acidification and eutrophication potential (Fig. 2), suggesting that sustainable intensification is achievable through optimized agronomic strategies. For example, grain maize systems achieved NUE and yield gains through optimized nitrogen inputs, planting density and variety, etc., while sweet maize improvements resulted from reduced nitrogen application, planting density, and irrigation frequency (Figs. 3, 4).

These cause-effect relationships between agronomic practices and performance outcomes demonstrate that targeted interventions can synergistically improve productivity, environmental and economic performance. Group-based approaches that identify and promote exemplary practices among peer farmers represent a scalable model for sustainable intensification in smallholder systems.

4.3. Optimizing agronomic practices to improve maize environmental-economic sustainability

Optimizing agronomic practices is a critical way to improve the sustainability of cropping systems. Optimizing N management (Kanter et al., 2019; Elrys et al., 2023), planting density (Duvick, 2005; Assefa et al., 2016), varieties (Ying et al., 2019), and straw return (Yao et al., 2024) can reduce the environmental impacts, improve yields, and profits of maize. In this study, we found that the optimized N fertilizer for grain maize and sweet maize is 199 kg ha^{-1} and 243 kg ha^{-1} , respectively (Fig. 5C, H), which is consistent with the nitrogen fertilizer rate recommended by previous field experiments (180 kg ha^{-1} - 256 kg ha^{-1}) (Chen et al., 2014a; Yao et al., 2021) and 240 – 300 kg ha^{-1} (Gao et al., 2020; Pei et al., 2023). A significant positive correlation was observed between N input and environmental impact indicators, including N loss, GWP, EP, and AP ($P < 0.05$), while fertilizer input showed a negative correlation with net profit and NEEB (Fig. 6). This indicates that excessive fertilizer use not only exacerbates

environmental impacts but also undermines economic profits. One potential cause is the mismatch between fertilizer nutrient supply and crop uptake. Excessive nitrogen fertilizer input cannot be effectively absorbed by crops and is lost through volatilization and leaching. Moreover, it suppresses the translocation of dry matter and nutrients, thereby hindering yield formation (Chen et al., 2014b; Du et al., 2024). In contrast, appropriately N management can delay leaf senescence, enhance nitrogen uptake and remobilization efficiency, and improve source-sink dynamics, thereby supporting higher yield.

The optimal planting density for grain maize and sweet maize is 8.2×10^4 plants ha^{-1} and 7.9×10^4 plants ha^{-1} (Fig. 5D, G), respectively, which is similar with the results of previous studies (Hou et al., 2020; Luo et al., 2023; Ye et al., 2023). Moreover, planting density was positively correlated with economic benefits (Fig. 6), primarily due to its strong association with increased yield (Fig. 5), which directly contributes to higher net profit. This is because appropriate planting density improves canopy structure and population-level photosynthetic efficiency, enhances light interception and nutrient uptake, and reduces inter-plant competition (Yan et al., 2024).

We also found that for grain maize, with a longer growth period variety (>153 days) and a higher straw return can achieve high maize yields (Grassini et al., 2011; Liu et al., 2023; Guo et al., 2024) (Fig. 6B, E). A longer growth period extends the duration of photosynthesis, thereby enhancing dry matter accumulation in the grain. Meanwhile, increased straw return contributes to the accumulation of soil organic matter and improves nutrient retention, which enhances soil fertility and yield stability (Zhao et al., 2019; Yao et al., 2024). Our results also show that traditional flooding and over-irrigation are detrimental to yield formation (Fig. 6J), possibly due to inhibited root development and impaired nutrient uptake (Chilundo et al., 2017; Zhang et al., 2021). In contrast, rational irrigation scheduling enhances water-nutrient coupling and reduces nutrient leaching and runoff (Hassanli et al., 2009).

Importantly, improvements based on individual agronomic practices (S1 to S4) exhibited limited potential to enhance yield, reduce environmental impact, and increase economic profits. In contrast, integrated agronomic practices (S5) optimized both environmental and economic sustainability (Tables 3, 4), underscoring the value of holistic management approaches (Wang et al., 2021). Such strategies are particularly crucial in ecologically sensitive regions like the Erhai Lake Basin, where agricultural systems must reconcile agricultural productivity with ecological conservation goals.

4.4. Limitation and outlook

Although our study demonstrates the potential to balance environmental and economic benefits through improved agronomic practices, several uncertainties remain. First, we evaluated sustainability indicators (e.g., N loss, GWP, EP, AP, and NEEB) using empirical models, emission factors, and other parameters based on the life cycle concept;

however, the lack of field experiments may increase the uncertainty of the results. Secondly, although the agronomic measures recommended in this study (N application rate, planting density, etc.) are similar with previous research reports, the heterogeneity of climate and soil in different regions necessitates site-specific adjustments and field-level validation to propose more precise agronomic practices (Sugianto et al., 2025). Thirdly, our study utilizes yield and PFP_N as classification indicators to screen out the HH group. Although synergy is achieved in both environmental and economic indicators, trade-offs may occur if this method is used for other sustainability indicators (such as biodiversity and dietary nutrition). Therefore, multidimensional evaluation methods, such as the Pareto optimal method (Liang et al., 2022), can be further explored to balance the sustainability of other dimensions in the context of sustainable development.

5. Conclusions and implications

This study reveals that smallholder maize systems in the Erhai Lake Basin are characterized by excessive nutrient inputs, low use efficiency, and high environmental burdens, without corresponding gains in yield and economic benefits. By identifying the high-performing farmers (HH group), we demonstrate that it can reconcile environmental and economic performance through the adoption of optimized agronomic practices. For grain maize, strategies such as optimizing the variety growth period, reducing N fertilizer input, adopting optimal planting density, and increasing straw return significantly improved environmental and economic performance. For sweet maize, reduced N and K fertilizer use, higher planting densities, and lower irrigation frequencies were associated with improved performance. These results establish clear cause-and-effect relationships between specific practices and sustainability outcomes, indicating that targeted management can reconcile productivity, environmental and economic performance. To support broader adoption, policies should focus on strengthening technical support services and improving smallholder access to locally adapted, knowledge-based recommendations. Overall, our research provides a scalable pathway for promoting sustainable intensification in smallholder systems, particularly in ecologically and hydrologically sensitive regions.

CRedit authorship contribution statement

Zhengyuan Liang: Methodology, Conceptualization. **Yuewen Huo:** Writing – review & editing, Investigation, Formal analysis, Conceptualization. **Torsten Müller:** Writing – review & editing, Methodology, Conceptualization. **Cong Wenfeng:** Writing – review & editing, Methodology, Funding acquisition, Formal analysis, Conceptualization. **Feiyu Ying:** Writing – review & editing, Writing – original draft, Visualization, Investigation, Formal analysis, Conceptualization. **Hao Ying:** Writing – review & editing, Methodology, Investigation, Conceptualization. **Jagdish K. Ladha:** Methodology, Conceptualization. **Fusuo Zhang:** Resources, Methodology, Funding acquisition, Conceptualization. **Zhengxiong Zhao:** Resources, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at [doi:10.1016/j.fcr.2025.110124](https://doi.org/10.1016/j.fcr.2025.110124).

Data Availability

Data will be made available on request.

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