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RESEARCH ARTICLE

# Farmer survey-based agricultural non-point source pollution assessment in the typical regions of the Erhai Lake Basin, China

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## KEYWORDS

Agricultural activity, agricultural non-point source pollution, water quality, Erhai Lake Basin

## HIGHLIGHTS

- Agricultural non-point source pollution was quantified in Erhai Lake Basin.
- $NH_3$-N, TN, TP, and COD discharged reached 72.9, 264.1, 29.2, and 1453.3 t·yr$^{-1}$, respectively.
- Maize, vegetables, and beans dominated crop-related pollutant contributions.
- Dairy cattle and pigs were primary contributors to livestock pollutant discharges.
- Shangguan Town was identified as the key control area for pollutant mitigation.

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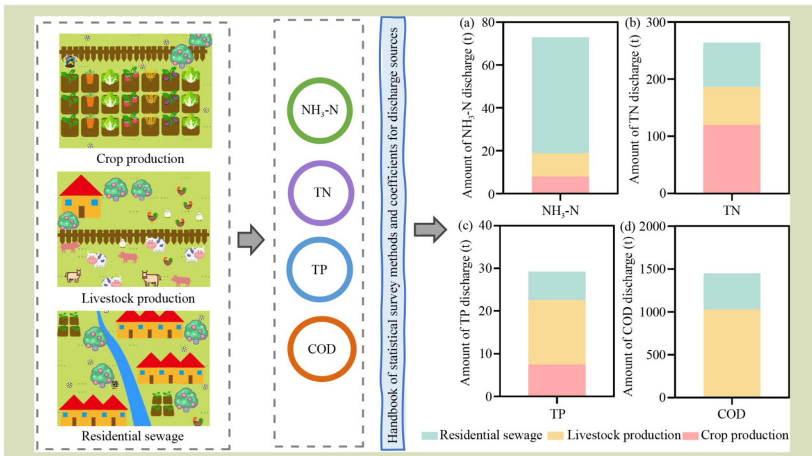
## GRAPHICAL ABSTRACT




## ABSTRACT

Human activities are the main contributors to non-point source pollution. Understanding the relative contributions of various sources to pollutant discharge is essential for effective water quality management. This study aimed to quantify ammonia nitrogen ($NH_3$-N), total nitrogen (TN), total phosphorus (TP) and chemical oxygen demand (COD) to the environment from crop and livestock production, and residential sewage in the Haixi Region of the Erhai Lake Basin, south-west China, using integrated data from farmer surveys, literature reviews and statistical data. The results revealed that the $NH_3$-N, TN, TP and COD discharges were 72.9, 264.1, 29.2, and 1453.3 t·yr$^{-1}$, respectively, in 2022 in Haixi Region. Shangguan township, as a high-intensity discharge area, accounted for 21%–44% of the total discharges of four pollutants. Maize, vegetables and beans crops were the largest contributors to water pollution in Haixi Region, which are responsible for 6.3, 94.1, and 5.5 t·yr$^{-1}$ of $NH_3$-N, TN, and TP, respectively. Dairy cattle and pig rearing were the main contributors in the livestock production. Compared to crop and livestock production, $NH_3$-N discharged from residential sewage were 186%

higher, while the other three pollutants were 59%–71% lower. These findings support the refined management of agricultural activities in accordance with water quality protection policies of Erhai Lake Basin.



## 1 Introduction

Agricultural non-point source pollution control is an important task in global water pollution control[1]. Also, ensuring food safety and improving water quality are important challenges for water pollution control[2]. Agricultural non-point source pollution is primarily attributable to agricultural activities and residential sewage (which means the proportion of sewage from administrative villages is untreated). According to the *First National Pollution Source Census Bulletin*[3], 40% of the major water pollutants in China originates from agricultural sources in 2007. In particular, the discharges of chemical oxygen demand (COD), total nitrogen (TN) and total phosphorus (TP) have reached 1.2, 2.7 and 0.3 Mt·yr$^{-1}$, respectively[4]. The *Second National Pollution Source Census Bulletin* noted that agricultural (22%–67%) and residential activities (30%–73%) are major contributors of these pollutants (TN, TP, $NH_3$-N, and COD)[5,6]. From 1998 to 2017, the pollution loads of COD, TN and TP increased by 91%, 196% and 244%, respectively[7,8]. These pollutants (TN, TP, $NH_3$-N, and COD) enter water bodies through various pathways[9,10], disrupting aquatic environments and lake ecosystems[11], posing risks to the safety of drinking water and human health[12].

The water pollutant emission from agricultural source has an increasing trend in China. Notably, in 2007, the TN and TP discharges into water bodies from crop production reached 1.6 and 0.11 Mt·yr$^{-1}$, respectively[13,14]. In addition, from 2008 to 2020, the discharges of TN, TP and COD to water from agricultural non-point sources gradually increased in China, with annual growth rates of 5.6, 10.3 and 3.9%, respectively. Livestock production constituted over 40% of the total national discharges for these three key pollutants[4].

The Erhai Lake, as the primary surface water resource in the western region of Yunnan Province[15–17], faces the issue of pollutant discharge water from agricultural activities[18]. Before 2010, the primary source of pollutants in the Erhai Lake Basin was agricultural activities[19]. Additionally, the dam area of the lake has a high population density, reaching 256 people km$^{-2}$, serving as an important discharge source of local non-point source pollution[20]. However, the contributions of residential and agricultural activities remain unclear. Also, relevant research is lacking in pollutant discharge from agricultural activities and residential sewage in recent years. About 10 kt·yr$^{-1}$ of TN and TP are estimated to enter Erhai Lake each year, with point source pollution accounting for only 2.9% and 7.5%, respectively[21]. The Haixi Region is a large intensive agricultural area within the Erhai Lake Basin[15]. The Haixi Region also is directly connected to Erhai Lake, which is the confluence of the 18 streams of Cangshan Mountain. Due to geographic location characterized by higher terrain in the east and lower terrain in the west, the pollutants discharged in this region directly flow into the Erhai Lake[16]. Therefore, identifying the contributions of different pollution sources in the Haixi Region of the Erhai Lake Basin is essential for pollution control efforts.

Many modeling approaches have been adopted to estimate non-point source pollution in China's lakes[4,22,23]. For example, MARINA has been used to distinguish diffuse sources (mineral fertilizer application) of nitrogen in water from point sources (direct discharge of animal manure) in the Erhai Lake Basin[22]. The NUFER model has been used to estimate the relative contributions of N and P emissions from the crop and livestock system in the Erhai Lake Basin[23]. However, these models do not consider the discharge of $NH_3$-N and COD. The Chinese government published the *Manual of the Second Pollution Census Correlation Coefficients: Handbook of Methods and Coefficients for Statistical Surveys of Emission Sources*, which can help in quantifying the contributions of agricultural activities and residential sewage to the discharge of four types of pollutants ($NH_3$-N, TN, TP and COD) to the environment. However, researchers have not applied this approach to the Erhai Lake Basin or accounted for the local characteristics of agricultural management. As a result, the contributions of crop production, livestock production, and residential sewage to the discharge of the four types of pollutants to the environment in watersheds like the Haixi Region remain unclear. An approach to quantify these contributions of agricultural activities and residential sewage to the discharge of these pollutants is needed for effective water quality management.

In this study, we applied the approach of the *Manual of the Second Pollution Census Correlation Coefficients: Handbook of*

*Methods and Coefficients for Statistical Surveys of Emission Sources* to quantify the contributions of crop production, livestock production, and residential sewage to the discharge of these four types of pollutants to the environment. The approach was updated based on local data from farmer surveys, literature reviews, and statistical data in the Haixi Region of the Erhai Lake Basin. The findings are expected to support precise management of agricultural non-point source pollution in the Erhai Lake Basin.

## 2 Materials and methods

### 2.1 Study area

The Haixi Region of the Erhai Lake Basin is in Yunnan Province in Southwest China[23]. The Haixi Region is located on the west side of the Erhai Lake and the east side of Cangshan Mountain[23,24]. It covers an area of 670 km$^2$ and has a population of 450,000 people. The administrative area and population represent 26% and 63% of the entire Erhai Lake Basin (Fig. S1 and Table S1). The Haixi Region encompasses the main agricultural production areas in the Erhai Lake Basin. The crop sown area and livestock number account for about 28% and 16% of the Erhai Lake Basin, respectively (Table S1). The area of crops is 14.1 kha, and the area of all economic crops is 815 ha. The major crops include vegetables, maize and rice, with a total area of 9.80 kha (Fig. S2). Livestock production includes laying hens, dairy cattle and pigs. Also, the N losses from crop and livestock to air and water were 1.9 and 0.13 kt, respectively. There are 19 townships in the Erhai Lake Basin, of which seven are in the Haixi Region. The area includes Shangguan, Xizhou, Wanqiao, Yinqiao, Dali, Taihe, and Xiaguan towns[23,24].

### 2.2 Calculation of pollutant discharge

In this study, we quantified the discharges of $NH_3$-N, TN, TP and COD from crop production, livestock production and rural residential sewage in the Haixi Region in 2022, respectively. The approach was adopted from the *Manual of the Second Pollution Census Correlation Coefficients: Handbook of Methods and Coefficients for Statistical Surveys of Discharge Sources* published in June 2021. We applied the approach to the Haixi Region by integrating data from farmer surveys, literature review, and statistical data. Specifically, over 300 farmer surveys were conducted, in which more than 30 government agencies and wastewater treatment plants were visited and the status of sewer systems pipe connection in 21 type administrative villages was investigated. Choosing three or more administrative villages in each town as the object of research to get sewer systems pipe connection rate. It is noteworthy that three administrative villages were randomly selected in each township to conduct a survey on the damage rate of the sewage pipeline network. Locations are chosen to ensure coverage of all aspects of the village. Agricultural production data (such as fertilizer applications) and the sewer systems pipe connection rate of each township were obtained from the farmer surveys (Figs. S2 and S3). The farmer survey data were used are divided into 2021 and 2022, with 2021 fertilizer application data used as background data for the calculations. Data for rural population, types of local crops and production areas, and livestock production were obtained from the *Dali City Statistical Yearbook* in 2022. Relevant coefficients were derived from field investigation and the *Handbook of Methods and Coefficients for Statistical Surveys of Discharge Sources*. Some of the coefficients are given in Table S2. The details of the calculation are described below.

#### 2.2.1 Crop production

We quantified the contribution of crop production to the discharge of the four pollutants ($NH_3$-N, TN, TP and COD) to water in the Haixi Region of the Erhai Lake Basin. For crop production, eight crop types were considered, namely maize, vegetables, beans, rice, tobacco, potato, cereals and fruit trees. The discharge of pollutants from crop production was calculated as:

$$Q_j = (A_g \times e_{gj} + A_y \times e_{yj}) \times \frac{q_j}{q_0} \times 10^{-3} \quad (1)$$

where, $Q_j$ is the discharge of pollutant $j$ from crop production to water (t·yr$^{-1}$), $A_g$ is the total planting area of crops except fruit trees (ha), $e_{gj}$ is the loss coefficient of pollution $j$ during crop production (kg·ha$^{-1}$), $A_y$ is the area of fruit trees (ha), $e_{yj}$ is the loss coefficient of water pollution $j$ in fruit trees (kg·ha$^{-1}$), $q_j$ is the amount of nitrogen or phosphate fertilizer per unit area used for crop production in the survey year (kg·ha$^{-1}$), and $q_0$ is the amount of nitrogen or phosphate fertilizer per unit area used for crop production in the year 2021 (kg·ha$^{-1}$). The amount of nitrogen and phosphate fertilizers used in crop production was determined based on data from farmer surveys (Fig. S3).

#### 2.2.2 Livestock production

In this study, five categories of livestock animals (dairy cattle, pig, laying hens, broilers and beef cattle) were considered for estimating the contribution of livestock production to the discharge of the four pollutants to the environment. The equation for calculating the discharge of pollutants from livestock production was:

$$Q_{ijLivestockdischarge} = (q_{iIntensiveLivestock} \times e_{ijIntensiveLivestock} + q_{ifree-rangelivestock} \times e_{ijfree-rangelivestock}) \times 10^{-3} \quad (2)$$

$$Q_{jLivestockdischarge} = \sum_{j}^{n} Q_{ijLivestockdischarge} \quad (3)$$

where, $Q_{ijLivestockdischarge}$ is the discharge of pollutant $j$ from category $i$ livestock production (t·yr$^{-1}$), $q_{iIntensiveLivestock}$ is the stocking/turnover amount of category $i$ livestock production in intensive livestock farms (head), $e_{ijIntensiveLivestock}$ is the discharge coefficient of pollutant $j$ from intensive livestock of category $i$ livestock (kg per head), $q_{ifree-rangelivestock}$ is the stocking (turnover) amount of category $i$ livestock production in free-range livestock (head), $e_{ijfree-rangelivestock}$ is the discharge coefficient of pollutant $j$ from free-range livestock of category $i$livestock and poultry (head), and $Q_{jLivestockdischarge}$ is the discharge of pollutant $j$ from livestock production (head).

### 2.2.3 Residential sewage

The residential sewage to the discharge of the four pollutants to the environment was quantified as:

$$G_n = N \times F_n \quad (4)$$

where, $G_n$ is the amount of rural residential sewage discharge (kt·yr$^{-1}$); $N$ is the population (thousand people), and $F_n$ is the rural residential sewage discharge coefficient, which was 30.34 (L per person per day) (Table S2).

The amount of pollutant discharge from rural residential sewage $G_{pn}$ was calculated as:

$$G_{pn} = G_{cn} \times (1 - \theta \times \eta_n) \quad (5)$$

where, $G_{pn}$ is the pollutant discharge (t·yr$^{-1}$), $G_{cn}$ is the pollutant production (t·yr$^{-1}$), $\theta$ is the proportion of administrative villages where sewage is treated, and $\eta_n$ is the comprehensive pollutant removal rate.

Site visits to the wastewater treatment plants revealed that treated wastewater is discharged directly downstream of Erhai Lake Basin, bypassing the lake entirely. Therefore, the sewage treatment rate considered to be 100%. However, untreated sewage is discharged directly into Erhai Lake due to damaged pipelines (Fig. S4).

# 3 Results

## 3.1 Situation of pollutants discharging in the Haixi Region

The total $NH_3$-N, TN, TP and COD from all sources (crop production, livestock production and residential sewage) were 72.9, 264.1, 29.2, and 1,453.3 t·yr$^{-1}$, respectively, in the Haixi Region in 2022 (Fig. 1). For $NH_3$-N pollution, residential sewage is the largest contributor, accounting for 74% of the three sources(crop production, livestock production and residential sewage)of discharge. The second-largest contributor is livestock production, accounting for 15% of the total $NH_3$-N discharge (Fig. 1(a)). For TN pollutant, crop production accounted for 45% of total TN discharges at 120.1 t·yr$^{-1}$ and livestock production accounted for 25% at 66.5 t·yr$^{-1}$ (Fig. 1(b)). For TP pollutants, livestock production is the main source of TP discharge accounting for 52% of the total TP discharge at 15.1 t·yr$^{-1}$ (Fig. 1(c)). For COD discharge, the largest contributor was livestock production, which accounted for 71% of the total COD discharge at 1.03 kt·yr$^{-1}$, followed by residential sewage at 423 t·yr$^{-1}$ (Fig. 1(d)).

## 3.2 Spatial distribution characteristics of different types of pollutants in the Haixi Region

Pollutant discharges differed between towns in the Haixi Region in 2022 (Table 1). For $NH_3$-N pollutants, the township with the highest discharge was Dali, with 16.2 t·yr$^{-1}$, followed

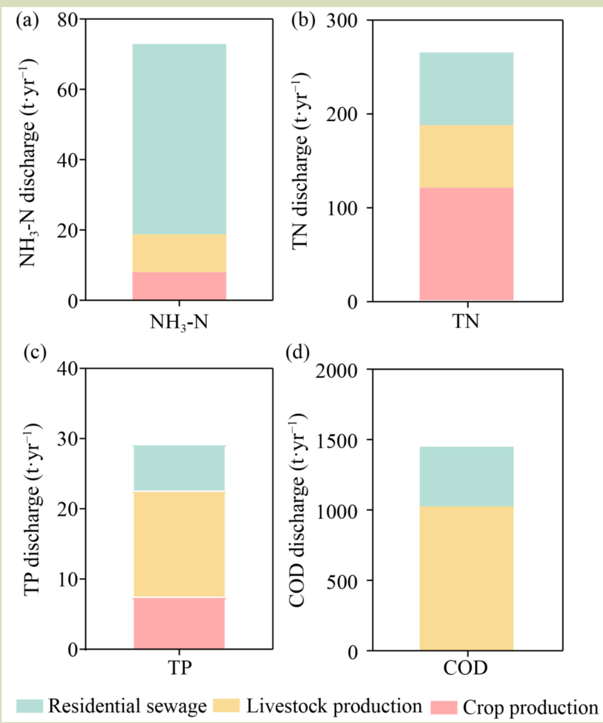



**Fig. 1** Amounts of $NH_3$-N (a), TN (b), TP (c), and COD (d) discharges from residential sewage, crop production and livestock production.

Table 1 Pollutant discharge by towns and proportions of different discharge sources (unit: $t \cdot yr^{-1}$)

| Discharge source | Pollution | Xiaguan | Taihe | Dali | Xizhou | Wanqiao | Yinqiao | Shangguan | Total |
|---|---|---|---|---|---|---|---|---|---|
| Crop production | $NH_3$-N | 0.2 | 0.5 | 1.6 | 1.4 | 1.7 | 1.1 | 1.6 | 8.1 |
| | TN | 2.7 | 8 | 23.7 | 21.4 | 25.3 | 15.7 | 23.3 | 120.1 |
| | TP | 0.2 | 0.5 | 1.5 | 1.4 | 1.7 | 1 | 1.3 | 7.5 |
| Livestock production | COD | 58.9 | 87.5 | 29 | 155.1 | 66.8 | 42.2 | 591 | 1030 |
| | $NH_3$-N | 0.6 | 0.7 | 0.2 | 1.4 | 0.5 | 0.2 | 7 | 10.8 |
| | TN | 4 | 4.8 | 1.7 | 9.7 | 3.8 | 1.9 | 40.6 | 66.5 |
| | TP | 0.8 | 1.1 | 0.3 | 2.1 | 0.7 | 0.4 | 9.7 | 15.1 |
| Residential sewage | COD | 33.8 | 102 | 112.8 | 75.5 | 30.4 | 17.4 | 51.2 | 423.1 |
| | $NH_3$-N | 4.3 | 13 | 14.4 | 9.6 | 3.9 | 2.2 | 6.5 | 54 |
| | TN | 6.2 | 18.7 | 20.6 | 13.8 | 5.6 | 3.2 | 9.4 | 77.5 |
| | TP | 0.5 | 1.6 | 1.8 | 1.2 | 0.5 | 0.3 | 0.8 | 6.6 |

by Shangguan and Taihe, with 15.1 and 14.3 $t \cdot yr^{-1}$, respectively. The lowest discharge was observed in Yinqiao, with 3.5 $t \cdot yr^{-1}$. For TN discharge, the second-largest discharge area was Dali, with 46.1 $t \cdot yr^{-1}$. The secondary source of TP and COD discharge was Xizhou, with 4.6 and 231 $t \cdot yr^{-1}$, respectively. The town with the lowest TN and TP discharges was Xiaguan, with 12.9 and 1.5 $t \cdot yr^{-1}$, respectively. The town with the smallest COD discharge was Yinqiao, with 59.7 $t \cdot yr^{-1}$. For the four pollutant discharges, the greatest discharge was from Shangguan, which is likely related to its developed livestock industry (Fig. S2).

The discharge of the four pollutants differed between various sources in the towns (Table 1). For $NH_3$-N pollutants, residential sewage was the largest contributor in all towns except Shangguan in 2022. Although Taihe and Xiaguan have higher levels of residential activity, the low rate of sewer systems pipe damage results in low discharges from residential sewage (Fig. S4). The primary source of discharges for the remaining three pollutants (TN, TP and COD) was Shangguan. For TN pollutant, crop production was the main source in Xizhou, Wanqiao, Yinqiao and Dali. The main sources of TP and TN were similar in Wanqiao and Yinqiao. In Taihe and Xiaguan, the predominant discharge sources of TN and TP were residential sewage in 2022. In Xizhou and Dali, the main TP discharge sources were livestock production and residential sewage, respectively. For COD pollutants, the main source was livestock production in all towns, except Dali and Taihe.

## 3.3 Pollutant discharges from different crop and livestock types

Pollutant discharge differed between crop types (Fig. 2). The $NH_3$-N, TN and TP from crop production were 8.1, 120, and 7.5 $t \cdot yr^{-1}$ in the Haixi Region in 2022 (Fig. 1). In particular, maize, vegetables and beans production accounted for over 75% of the TN discharge from crop production. Maize and vegetables production led to $NH_3$-N discharges of 2.7 and 2.6 $t \cdot yr^{-1}$, respectively. This may be due to the high amount of nitrogen fertilizer applied in maize and vegetables production, with 619 and 448 $kg \cdot ha^{-1}$, respectively (Fig. S3). Vegetables, maize, beans and rice accounted for over three-quarters of the TP discharge in 2022 (Fig. 2(c)). The application of phosphorus fertilizer to these four crops decreases in sequence (Fig. S3). Additionally, the significant areas of maize, vegetables and beans production in the Haixi Region contribute to these three crop types having the highest discharges (Fig. S2)

Pollutant discharge also differed between animal types (Fig. 2). $NH_3$-N, TN, TP and COD from livestock production were 10.8, 66.5, 15.1 and 1030 $t \cdot yr^{-1}$, respectively, in the Haixi Region in 2022 (Fig. 1). Dairy cattle farming was the largest contributor among livestock production, with $NH_3$-N, TN, TP and COD discharges of 7.6, 42.1, 11.1, and 641 $t \cdot yr^{-1}$, respectively. Additionally, pig farming contributed a significant portion, accounting for 13%–21%, while the contributions of laying hens, broilers and beef were smaller. Pollutant discharge from the farming of these three animals accounted for 10%–25%.

Differences in pollutant discharge from different crops were investigated between towns (Fig. 3). The largest $NH_3$-N discharge from crop production was observed in Wanqiao, with 1.7 $t \cdot yr^{-1}$ (Fig. 3(a)). The largest TN discharge from crop production was observed in Wanqiao, with 25.3 $t \cdot yr^{-1}$ (Fig. 3(b)). The highest pollutant discharge from crop production occurred in Wanqiao due to the high level of crop

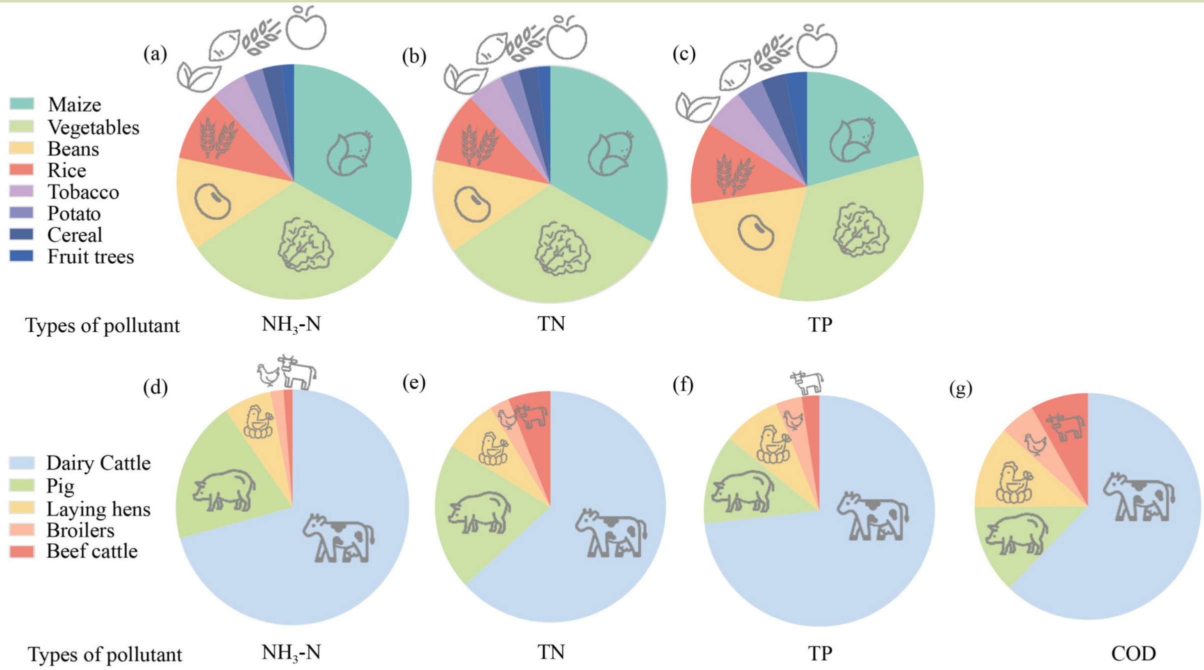



**Fig. 2** Proportion of pollutant discharge by different crops and animal types.

production. It is possible that the sown area of Wanqiao reached 3.42 kha, which was the largest percentage of the sown area of all the towns in the Haixi Region. Wanqiao had the highest TP discharge, with 1.7 $t \cdot yr^{-1}$, with beans and vegetables production accounting for about 50%. Maize planting was the primary contributor to pollutant discharge in the north of the Haixi Region, and vegetables planting was the primary contributor in the south. The main crop in Xiaguan Town was fruit trees. Although the amount of fertilizer applied was the highest, the area of the fruit tree production is small (Fig. S3).

Differences in pollutant discharge from different animals were investigated between towns (Fig. 4). The largest pollutant discharge from livestock production was observed in Shangguan (Fig. 4), which is closely related to the level of livestock production. $NH_3$-N, TN, TP and COD discharge from livestock production in this town amounted to 7.0, 40.6, 9.7, and 591 $t \cdot yr^{-1}$, respectively. The main source of $NH_3$-N discharge in Shangguan, Xizhou and Taihe was dairy cattle. The main source of $NH_3$-N discharge in Xiaguan, Dali and Wanqiao was pig production, accounting for 41%–45% in each town. The main source of $NH_3$-N discharge in Yinqiao was broiler production, accounting for over 32%. The main source of TN discharge from livestock production was similar to that of $NH_3$-N. The primary source of TP discharge in Dali and Wanqiao was laying hens, accounting for 31% and 44%, respectively. The primary source of TP discharge in Yinqiao was broilers, accounting for 48%. In other towns, the main source was dairy cattle. The COD discharge pattern was similar to that of TP, except for Taihe, where the primary source was layer hens.

## 4 Discussion

### 4.1 Comparison with other studies

We calculated the discharge of the four pollutants following the approach prescribed by the *Handbook of Methods and Coefficients for Statistical Surveys of Discharge Sources*. This approach provided critical insights into the discharge amount of different pollutants and their spatial distribution, focusing on main crop and animal types to propose strategies for reducing pollutant discharge. Meanwhile, the results of this study are reliable for the following reasons:

First, by focusing on the spatial characteristics of pollutant discharge, we compared the spatial distribution of pollutant discharge in the Haixi Region with existing research findings. In terms of the spatial patterns of pollutant discharge, Shangguan was identified as most problematic area for pollutant discharge. These findings are consistent with results reported in previous studies[25]. The northern part of the area

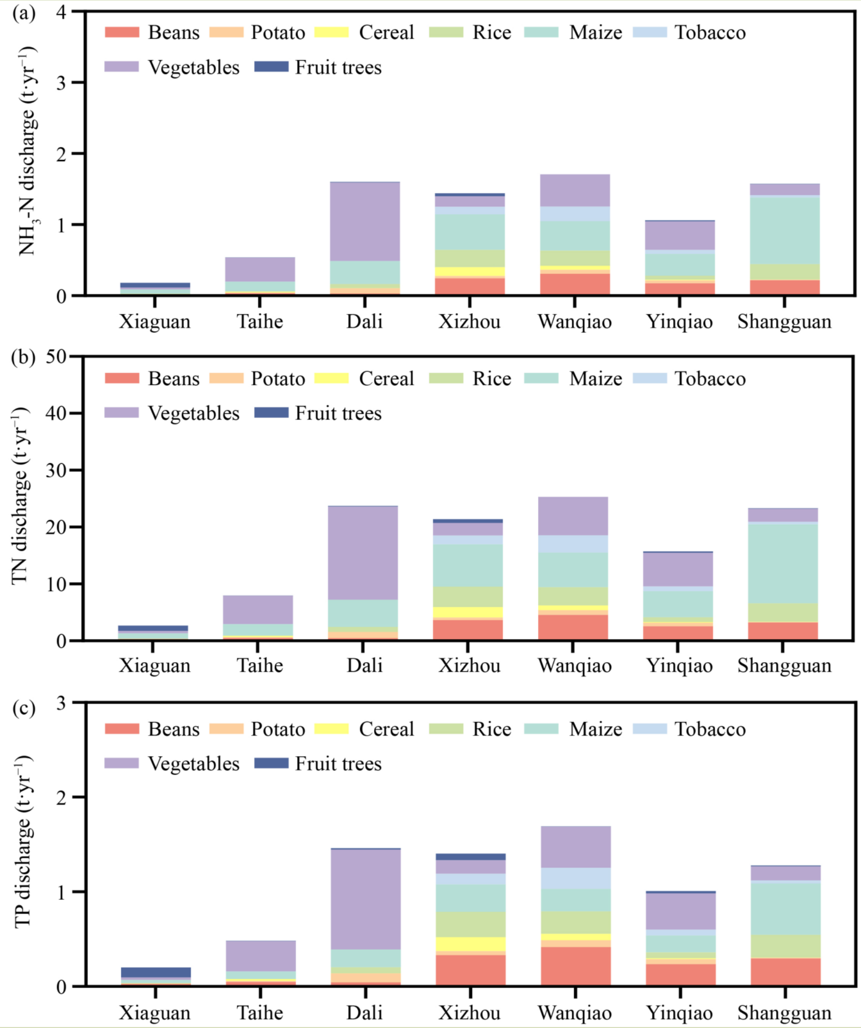



**Fig. 3** Distribution of $NH_3$-N (a), TN (b), and TP (c) discharges from cultivated land in towns and proportion of pollutant discharge by different crop types.

has higher pollutant loads compared to the south, which is similar to the findings of Xu et al.[26] and Gong et al.[27]. The Dali Water Environment Monitoring Center also indicates that northern rivers discharge more pollutants than southern rivers. This may be related to the higher prevalence of livestock production in northern towns, such as Shangguan. This is primarily because, in the northern part of the basin, pollutant discharge from crop and livestock production are the main factors affecting water quality, whereas in the southern part, economic development and rapid urbanization are the primary factors (Fig. 4).

Second, we compared pollutant discharge data obtained using different methods over the last two years. The results of this study indicate that vegetables, maize and beans were the main contributors to pollutant discharge from crop production, whereas dairy cattle and pigs were the primary contributors to pollutant discharge from livestock production. These findings are consistent with the results of studies by Peng et al.[28] and Wang et al.[29]. Also, damaged sewage treatment facilities were identified in residential areas through our farmer surveys, potentially leading to increased pollution discharge. The change of $NH_3$-N may also be related to this.

Third, our study is generally consistent with that of Zou et al.[23], but there are some subtle differences. For example, using a substance flow model output results it was shown that TN output is the highest in Dali within the crop and livestock system. This may be attributed to their consideration of meteorological factors, soil types, geological conditions and other factors influencing the quantification of pollutant processes.

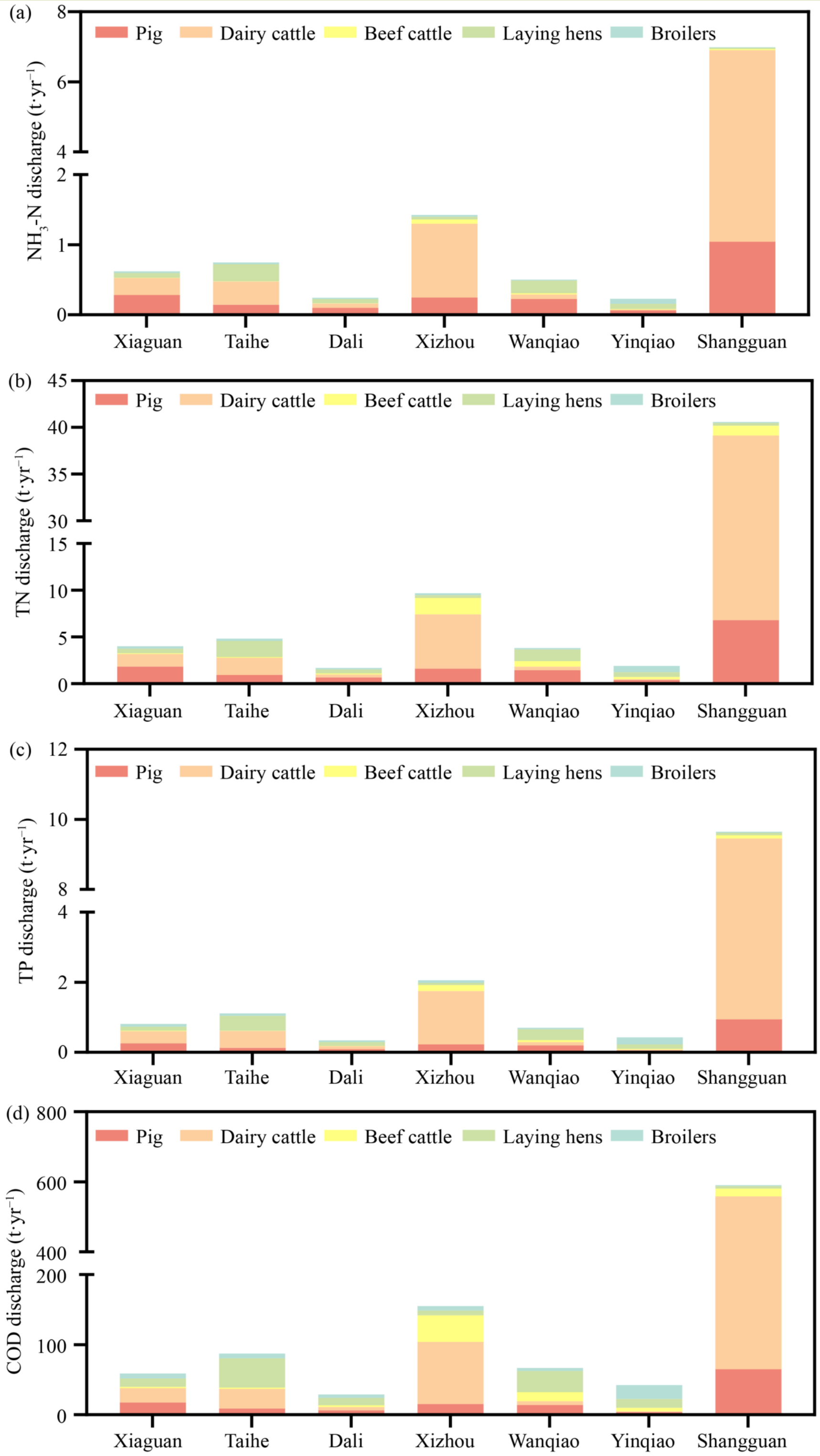



**Fig. 4** Distribution of $NH_3$-N (a), TN (b), TP (c), and COD (d) discharges from livestock production in towns and proportion of pollutant discharge by different animals.

It should be noted that our study involves some uncertainties. For example, the discharge coefficients for pollutant discharge from crop and livestock production are still based on empirical data from Yunnan Province. Additionally, the government notice, "Regarding Further Strengthening of Erhai Lake Protection Measures" of 2017, explicitly prohibits aquaculture in Erhai Lake and its surrounding lakes. Therefore, this study did not consider discharge from aquaculture. Nonetheless, this should not result in significant deviations, as the primary factors, such as crop types, fertilizer application rates, livestock numbers and rural resident population were collected from field data specific to the Haixi Region of the Erhai Lake Basin.

## 4.2 Outlook on pollutant discharge control

The water quality of Erhai Lake is closely related to human activities and water quality policy[15]. Taking Haixi Region of Erhai Lake Basin as an example, this study calculated the environmental discharge of pollutants from production activities related to different crops and livestock types. Based on the analysis of relevant policies in the Erhai Lake Basin and the calculation of pollutant discharge from different sources, management measures are proposed to reduce non-point source pollution. These suggestions would provide support for the three-year action plan to combat agricultural non-point source pollution in the Erhai Lake Basin.

First, based on the spatial distribution, the northern part of the Haixi Region is significantly affected by livestock production, especially Shangguan, where the level of livestock production is relatively high. In addition, the nutrient flow into the aquatic ecosystem is directly related to the density of animal stocking[30]. Various types of pollutants discharged from dairy cattle, as the main source of discharge from livestock production, account for more than half of the total discharge. Therefore, farming management should be a key focus. Measures such as comprehensive ammonia treatment[31,32] and improved dairy cattle feed[33,34] should be implemented to reduce pollutant discharge. Crop production is more prominent in the northern and central parts of the Haixi Region. According to the results of pollutant discharge from different crops (Fig. 4) and fertilizer application practices (Fig. S3), management measures should be prioritized for maize, vegetables and beans. Previous studies have shown that the rice-wheat rotation systems reduce N and P runoff losses in Taihu Lake Basin[35]. Similarly, pollutant entry into water bodies can be reduced by optimizing planting structures in the Erhai Lake Basin. Husain et al.[36] found that yields of rice-fava beans rotations can be increased and environmental nutrient losses can be decreased by reducing urea inputs and using refined organic fertilizers in combination. Therefore, appropriate fertilizer application practices can reduce environmental nutrient losses[37]. Similarly, rational improvement of fertilizer application practices for vegetables, maize and beans and use of suitable planting practices in the Erhai Lake Basin can help reduce pollutant discharge from crop production. In the southern part of the Haixi Region, pollutant discharge is significantly affected by residential sewage. In the Erhai Lake Basin, the direct discharge of sewage into the lake is prohibited. However, $NH_3$-N discharge from residential sources remains the highest. The water quality of the lake is closely related to the population density in the surrounding areas[38] and residential discharge sources are the primary contributors to non-point source pollution in the Erhai Lake Basin. Therefore, the prevention and control of non-point source pollution remains a priority[39]. During our farmer surveys, we found that although all towns have implemented separate sewage systems and interceptors, some pipeline networks are still damaged (Fig. S4). Therefore, regular strengthening of municipal pipeline inspections and repairs are necessary to reduce sewage discharge into the lake. Although the causes of resident sewage discharge are complex, strengthening the process of urbanization and improving education levels can help reduce sewage discharge from rural residents[40].

Second, our study approach is helpful for comprehensively analyze emissions of various pollutants for more precise control. A comparison of different literature sources reveals that while hydrological models such as HEC-HMS can be used to estimate the hydrological responses of lake basins, they do not directly simulate pollutant loads. Conversely, specialized models for non-point source pollution calculation (e.g., SWAT) can accurately quantify pollutant discharges but require numerous parameter updates[41]. Additionally, many studies focus on the calculation of nitrogen and phosphorus pollution[42], neglecting the estimation of $NH_3$-N and COD. The method prescribed by the *Handbook of Statistical Survey Methods and Coefficients for Discharge Sources* is a parameter calculation method. Through surveys on local agricultural activity levels and the implementation of relevant policies, the parameters were updated to simultaneously quantify multiple pollutants. This study identified key areas for management by analyzing the discharge of various pollutants together, allowing for more precise control.

Third, this methodology can be used as an assessment tool for pollutant abatement measures related to crop production, livestock production and residential activities in the Erhai Lake Basin. By simultaneously quantifying multiple pollutants, pollutant emissions can be effectively reduced through regional management and control of different pollution sources. These strategies deserve attention and policy support from the local government. This will significantly improve the water environment of Erhai Lake and provide the local government with effective strategies for the prevention and control of non-point source pollution. For crop production, the Haixi Region and the Erhai Lake Basin continue to develop the rice-faba beans rotation model, and slow-release bulk mixed fertilizers designed specifically for target crops and soils[43–45]. These methods can effectively reduce nitrogen and phosphorus runoff losses, with studies showing a reduction in nitrogen runoff by up to 30% and phosphorus by 25% under optimized crop rotation and fertilizer application practices[43]. For livestock production, except the need to give attention to nitrogen and phosphorus emissions from livestock and poultry manure, there is also a need to give attention to antibiotic pollution. Research indicates that antibiotic resistance genes in livestock waste can increase by up to 50% without proper management, highlighting the importance of integrated waste management strategies[46]. Therefore, it is possible to reduce the impact of various types of pollution on the environment by adjusting livestock feed. In addition, it is a method to reduce pollutants discharge to water that realized the scientific return of livestock and poultry manure to the field. Finally, the implementation of tail drain water treatment can effectively reduce the discharge of pollutants, but attention needs to be paid to improve the utilization rate of wastewater treatment facilities, regular inspection of pipeline network equipment and other operating conditions[47].

## 5 Conclusions

This study focused on agricultural problem areas and critical locations for pollutant entry into the lake in the analysis of three major discharge sources, while comprehensively quantifying the discharge of various pollutants, and proposes relevant pollution control strategies based on the accounting results. In different pollutant discharge contexts, $NH_3$-N load was found to range from 3.5 to 15.1 t·yr$^{-1}$ in various towns. The largest contributor was found to be residential sewage. The TN load in the Haixi Region ranges from 12.9 to 73.3 t·yr$^{-1}$ in various towns, with crop production as the largest contributor. The TP load ranged from 1.5 to 11.7 t·yr$^{-1}$ in various towns. Livestock production was the main contributor to TP discharge in the Haixi Region. The main contributor to COD discharge was also livestock production. Spatially, Shangguan is a key area for the control of all pollutants, primarily considering its developed livestock industry. In addition, analyzing pollutant discharge by different crop and animal types, vegetables, maize and beans were identified as the main contributors to discharge by crop production and dairy cattle and pigs were the main contributors to discharge by livestock production. Therefore, sustainable production practices should be examined and optimized for these crop and livestock types.

In the future, the following issues require further exploration: strengthening the supervision of fertilizer application, prioritizing the improvement of the production of maize, vegetables and beans; and developing suitable planting models. Pollutant discharge can be reduced by optimizing the free-range farming system. Additionally, special attention should be given to improving dairy cattle farming. The inspection and repair of wastewater treatment facilities should be strengthened. Discharge can be reduced by increasing the education and knowledge of residents, thereby raising awareness and achieving emission reduction.

### Supplementary materials

The online version of this article at https://doi.org/10.15302/J-FASE-2025622 contains supplementary materials (Figs. S1–S4; Tables S1–S2).

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### Compliance with ethics guidelines

Chenxi Yao, Sijie Feng, Fanlei Meng, Shuyu Fu, Jingwen Cheng, Jiajie Liu, Xuejun Liu, and Wen Xu declare that they have no conflicts of interest or financial conflicts to disclose. All applicable institutional and national guidelines for the care and use of animals were followed.

## REFERENCES


1. Zou L L, Liu Y S, Wang Y S, Hu X D. Assessment and analysis of agricultural non-point source pollution loads in China: 1978–2017. *Journal of Environmental Management*, 2020, **263**: 110400
2. Cui Z L, Zhang H Y, Chen X P, Zhang C C, Ma W Q, Huang C D, Zhang W F, Mi G H, Miao Y X, Li X L, Gao Q, Yang J C, Wang Z H, Ye Y L, Guo S W, Lu J, Huang J L, Lv S H, Sun Y X, Liu Y Y, Peng X L, Ren J, Li S Q, Deng X P, Shi X J, Zhang Q, Yang Z P, Tang L, Wei C Z, Jia L L, Zhang J W, He M R, Tong Y A, Tang Q Y, Zhong X H, Liu Z H, Cao N, Kou C L, Ying H, Yin Y L, Jiao X Q, Zhang Q S, Fan M S, Jiang R F, Zhang F S, Dou Z X. Pursuing sustainable productivity with millions of smallholder farmers. *Nature*, 2018, **555**(7696): 363–366
3. The Ministry of Environmental Protection of the People's Republic of China (MEE). The First National Pollution Source Census Bulletin, 2010. Available at MEE website on April 17, 2025
4. Xu L Y, Jiang J, Lu M Y, Du J G. Spatial-temporal evolution characteristics of agricultural intensive management and its influence on agricultural non-point source pollution in China. *Sustainability*, 2023, **15**(1): 371
5. The Ministry of Environmental Protection of the People's Republic of China (MEE). The Second National Pollution Source Census Bulletin, 2020. Available at MEE website on April 17, 2025.
6. Wang X, Hao F H, Cheng H G, Yang S T, Zhang X, Bu Q S. Estimating non-point source pollutant loads for the large-scale basin of the Yangtze River in China. *Environmental Earth Sciences*, 2011, **63**(5): 1079–1092
7. Sun B, Zhang L X, Yang L Z, Zhang F S, Norse D, Zhu Z L. Agricultural non-point source pollution in China: causes and mitigation measures. *Ambio*, 2012, **41**(4): 370–379
8. Harrault L, Milek K, Jardé E, Jeanneau L, Derrien M, Anderson D G. Faecal biomarkers can distinguish specific mammalian species in modern and past environments. *PLoS One*, 2019, **14**(2): e0211119
9. Hu W X, Wu Z B, Mu Y, Liu Z J, Chen W H. Evaluation of the upper lakes of the Erhai watershed in China based on water quality, land cover, and macrobenthic invertebrates. *Environmental Science and Pollution Research International*, 2023, **30**(47): 104169–104180
10. Liu Y, Li H Y, Cui G, Cao Y Q. Water quality attribution and simulation of non-point source pollution load flux in the Hulan River Basin. *Scientific Reports*, 2020, **10**(1): 3012
11. Conley D J, Paerl H W, Howarth R W, Boesch D F, Seitzinger S P, Havens K E, Lancelot C, Likens G E. Controlling eutrophication: nitrogen and phosphorus. *Science*, 2009, **323**(5917): 1014–1015
12. Wang P, Keller A A. AgInput: an agricultural nutrient and pesticide source model. *Environmental Modeling and Assessment*, 2009, **14**(3): 391–403
13. Nsenga Kumwimba M, Zhu B, Stefanakis A I, Ajibade F O, Dzakpasu M, Soana E, Wang T, Arif M, Kavidia Muyembe D, Agboola T D. Advances in ecotechnological methods for diffuse nutrient pollution control: wicked issues in agricultural and urban watersheds. *Frontiers in Environmental Science*, 2023, **11**: 1199923
14. Wu Y L, Liu J Z, Shen R F, Fu B J. Mitigation of nonpoint source pollution in rural areas: from control to synergies of multi ecosystem services. *Science of the Total Environment*, 2017, **607–608**: 1376–1380
15. Liu X J, Chen J Y, Tang B H, He L S, Xu Y, Yang C. Eco-environmental changes due to human activities in the Erhai Lake Basin from 1990 to 2020. *Scientific Reports*, 2024, **14**(1): 8646
16. Xiao M Q, Ni Z K, Zhao H C, Wang S R. Characteristics and significance of nitrogen and phosphorus variation during high risk period of algal bloom in Lake Erhai. *Research of Environmental Sciences*, 2021, **34**(2): 294–304 (in Chinese)
17. Ji N N, Wang S R, Zhang L. Characteristics of dissolved organic phosphorus inputs to freshwater lakes: A case study of Lake Erhai, southwest China. *Science of the Total Environment*, 2017, **601–602**: 1544–1555
18. Li J H, Bai Y, Alatalo J M. Impacts of rural tourism-driven land use change on ecosystems services provision in Erhai Lake Basin, China. *Ecosystem Services*, 2020, **42**: 101081
19. He Y X, Chen Y, Zhang C, Xu Y H, Cai L Y. History of anthropogenic faece and sewage contamination to Lake Erhai in southwestern China over the past ~200 years. *Applied Geochemistry*, 2024, **164**: 105953
20. Xu W, Zhang J, Yang L, Liu X J, Zhang F S. Strengthrning non-point source pollution control to promote agricultural green development. *Frontiers of Agricultural Science and Engineering*, 2023, **10**(4): 503–509
21. Wang G W, Chen H Z. Oxygen consumption for the combustion of sewage sludge: a potential environmental parameter determined by an electrochemical YSZ oxygen sensor. *International Journal of Environmental Analytical Chemistry*, 2022, **102**(18): 6329–6338
22. Li X L, Janssen A B G, Strokal M, Kroeze C, Ma L, Zhang Y, Zheng Y. Assessing nitrogen sources in Lake Erhai: a spatially explicit modelling approach. *Agricultural Water Management*, 2023, **289**: 108549
23. Zou T T, Meng F L, Zhou J C, Ying H, Liu X J, Hou Y, Zhao Z X, Zhang F S, Xu W. Quantifying nitrogen and phosphorus losses from crop and livestock production and mitigation potentials in Erhai Lake Basin, China. *Agricultural Systems*, 2023, **211**: 103745
24. Liu X F, Wu Y, Ni Z K, Wang S R. Spatiotemporal variation of water quality and algal biomass in Erhai Lake and its environmental management implications. *Frontiers of Agricultural Science and Engineering*, 2023, **10**(4): 566–578

25. Zheng L, An Z Y, Chen X L, Liu H. Changes in water environment in Erhai Lake and its influencing factors. *Water*, 2021, **13**(10): 1362
26. Xu T B, Ma W, Chen J, Duan L Z, Li H, Zhang H C. Water quality of Lake Erhai in Southwest China and its projected status in the near future. *Water*, 2024, **16**(7): 972
27. Gong F L, Luo L C, Li H Y, Chen L, Zhang R F, Wu G Z, Zhang J, Shi W Q, Zhang F, Zhang H, Sun T. Quantitative assessment of water quality improvement by reducing external loadings at Lake Erhai, Southwest China. *International Journal of Environmental Research and Public Health*, 2023, **20**(6): 5038
28. Peng J Y, Jin C L, Wu Y, Hou Z Y, Gao S J, Chu S Z, Zheng B H. Modeling non-point source nutrient loads with different cropping systems in an agricultural lake watershed in southwestern China: from field to watershed scale. *Mathematics*, 2022, **10**(21): 4047
29. Wang J L, Lu J Z, Zhang Z, Han X X, Zhang C, Chen X L. Agricultural non-point sources and their effects on chlorophyll-a in a eutrophic lake over three decades (1985–2020). *Environmental Science and Pollution Research International*, 2022, **29**(31): 46634–46648
30. Carpenter S R, Caraco N F, Correll D L, Howarth R W, Sharpley A N, Smith V H. Nonpoint pollution of surface waters with phosphorus and nitrogen. *Ecological Applications*, 1998, **8**(3): 559–568
31. Hou Y, Velthof G L, Oenema O. Mitigation of ammonia, nitrous oxide and methane emissions from manure management chains: a meta-analysis and integrated assessment. *Global Change Biology*, 2015, **21**(3): 1293–1312
32. He Z L, Zhang Y, Liu X J, Xu W, Hou Y, Wang H L, Zhang F S. Ammonia mitigation potential in an optimized crop-layer production system. *Science of the Total Environment*, 2022, **841**: 156701
33. Najar I A, Khan A B. Assessment of water quality and identification of pollution sources of three lakes in Kashmir, India, using multivariate analysis. *Environmental Earth Sciences*, 2012, **66**(8): 2367–2378
34. Pierer M, Amon B, Winiwarter W. Adapting feeding methods for less nitrogen pollution from pig and dairy cattle farming: abatement costs and uncertainties. *Nutrient Cycling in Agroecosystems*, 2016, **104**(2): 201–220
35. Wu Y H, Hu Z Y, Yang L Z. Strategies for controlling agricultural non-point source pollution: reduce-retain-restoration (3R) theory and its practice. *Transactions of the Chinese Society of Agricultural Engineering*, 2011, **27**(5): 1–6 (in Chinese)
36. Husain A, Muneer M A, Fan W, Yin G F, Shen S, Feng W, Yuan L, Zhang K Q. Application of optimum N through different fertilizers alleviate $NH_4^+$-N, $NO_3$-N and total nitrogen losses in the surface runoff and leached water and improve nitrogen use efficiency of rice crop in Erhai Lake Basin, China. *Communications in Soil Science and Plant Analysis*, 2019, **50**(6): 716–738
37. Wang S P, Guo S F, Zhai L M, Hua L L, Khoshnevisan B, Wang H Y, Liu H B. Comprehensive effects of integrated management on reducing nitrogen and phosphorus loss under legume-rice rotations. *Journal of Cleaner Production*, 2022, **361**: 132031
38. Li R Q, Dong M, Zhao Y, Zhang L L, Cui Q G, He W M. Assessment of water quality and identification of pollution sources of plateau lakes in Yunnan (China). *Journal of Environmental Quality*, 2007, **36**(1): 291–297
39. Xu B W, Niu Y R, Zhang Y N, Chen Z F, Zhang L. China's agricultural non-point source pollution and green growth: interaction and spatial spillover. *Environmental Science and Pollution Research International*, 2022, **29**(40): 60278–60288
40. Liu J G, Zhou Z Y, Li P Y, Wang Z X, Yan Y, Yu X Z, Li W K, Zheng T L, Cao Y N, Wu W J, Cai W Q, Shi Z N, Liu J X. Characteristics of rural domestic sewage discharge and their driving mechanisms: evidence from the northern region, China. *Frontiers of Environmental Science & Engineering*, 2024, **18**(7): 83
41. Bieger K, Arnold J G, Rathjens H, White M J, Bosch D D, Allen P M, Volk M, Srinivasan R. Introduction to SWAT+, a completely restructured version of the soil and water assessment tool. *Journal of the American Water Resources Association*, 2017, **53**(1): 115–130
42. Zhang X Q, Chen P, Dai S N, Han Y H. Analysis of non-point source nitrogen pollution in watersheds based on SWAT model. *Ecological Indicators*, 2022, **138**: 108881
43. Yao J L, Guo H G, Ni X Y, Wang F, Zheng H Y, Yang H Q, Yang S S, Ren T Z. Influence of different crop rotations and fertilization methods on nitrogen and phosphorus runoff losses in Erhai Lake Basin, China. *Journal of Agricultural Resources and Environment*, 2019, **36**(5): 600–613 (in Chinese)
44. Yang F L, Zhang X Z, Li J H, Zhao H F, Jin F M, Zhou B X. Analysis and evaluation of the treatment and reuse of tailwater: a case study in Erhai Lake. *Journal of Cleaner Production*, 2021, **327**: 129435
45. Zhao H, Wang Y, Dong Y K, He Z L, Wang P, Zheng H G, He J F, Zeng W J. Modeling the response of agricultural non-point source pollution to planting structure and fertilization level in Erhai Lake Basin under low-latitude plateau climate. *Ecological Indicators*, 2023, **154**: 110829
46. Gu Y R, Shen S Z, Han B J, Tian X L, Yang F X, Zhang K Q. Family livestock waste: an ignored pollutant resource of antibiotic resistance genes. *Ecotoxicology and Environmental Safety*, 2020, **197**: 110567
47. Tang Q X, Ren T Z, Schweers W, Liu H B, Lei B K, Lin T, Zhang G L. Study on environmental risk and economic benefits of rotation systems in farmland of Erhai Lake Basin. *Journal of Integrative Agriculture*, 2012, **11**(6): 1038–1047