Effects of Fertilization of Different Crops on Non-Point Source Pollution in the Upper Reaches of Erhai Lake Basin

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Abstract The relationship between crop fertilization and non-point source (NPS) pollution is a hot topic of research on agricultural NPS pollution. In this paper, the upper reaches of Erhai Lake Basin were taken as the research area. Based on rice-broad bean and maize-potato rotation, the content of chemical oxygen demand (COD), total phosphorus (TP), ammonia nitrogen (AN), nitrate nitrogen (NO_3-N), and total nitrogen (TN) in water samples from experiment field plots under normal fertilization, 60% normal fertilization and 30% normal fertilization were measured, and the response relationship between fertilization levels and the values of the indicators was explored by using the method of split-plot experiments and statistical analysis. The experiment results are as follows: (1) The fertilization level of different crops had a significant ($P < 0.01$) effect on agricultural NPS pollution, and the effect on TP was the strongest ($R^2 = 0.550$; $P < 0.01$). COD has the second highest impact. (3) The content of AN and NO_3-N measured from field plots of maize and broad bean had no significant relationship with the fertilization level, but the content of nitrogen measured from plots of potato presented a downward trend with the increased amount of fertilizer. (4) Overall, the amount of fertilizer positively affected agricultural NPS pollution, and there was a correlation between the indicators. This study can

Highlights

1. The main crop rotations are established to be rice-fava bean and maize-potato rotations through field research in the study area.
2. The relationship between fertilizer application levels of different crops and agricultural NPS pollution in the studied basin is modelled.
3. TP, COD, NO_3-N, AN and TN are the main indicators for NPS pollution in the study area.
4. NF, 60%NF and 30%NF fertilization can effectively reveal the relationship between the fertilization level and NPS pollution.
5. The fertilization level of different crops had the most significant effect on the content of TP ($R^2 = 0.550$, $P < 0.01$). The research can provide new ideas and methods for ecological environment management of Erhai Lake Basin.

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provides new ideas for the evaluation and delineation of the spatial pattern of source-sink risk of NPS pollution in the basin, and puts forth new methods for the management of NPS pollution in the basins of low-latitude plateau fractured lakes similar to the Erhai Lake Basin.

1 Introduction

Agricultural non-point source (NPS) pollution, especially pollution caused by irrational application of chemical fertilizers, often leads to declined water quality in lakes and rivers and other environmental problems (Brett et al., 2010; Baiyegunhi et al., 2019); meanwhile, the diffusion of bacteria, pesticides, heavy metals and other pollutants accompanying fertilization treatment in agricultural production results in soil pollution and threatens ecological safety. Therefore, the key to curbing agricultural NPS pollution is the management of fertilization (Zhang et al., 2020), and this has drawn increasing attention from researchers. In China's "No. 1 Central Document for 2023", it is pointed out that the relationship between agricultural water use and agricultural fertilization should be properly managed to reach the goal of green development of agriculture. The characteristics of agricultural NPS pollution—high randomness, complexity, and uncertainty—have made it a major challenge in water pollution control initiatives across the globe (Shen et al., 2013). Therefore, quantifying the discharge of agricultural NPS pollutants and identifying the correlation between fertilization of crops and NPS pollution is the key to ecological management of the water environment in watersheds.

The upper reaches of the Erhai Lake Basin are the largest contributor of pollutants to Erhai Lake, and improper use of chemical fertilizers is the main cause of NPS pollution there (Dong et al., 2023). It was estimated that about 9,891 tons of total nitrogen (TN) and 108.1 tons of total phosphorus (TP) enter Erhai Lake every year, of which NPS pollution accounts for 97.1% and 92.5%, respectively, and point source pollution accounts for only 2.9% and

7.5% (Chen et al., 2021). Agricultural NPS nitrogen and phosphorus pollution is the main contributor to eutrophication in the Erhai Lake Basin. Among them, NPS pollution in crop farming contributes the most to water environment pollution, while the use of fertilizers is the main source (accounting for 62%) of NPS in crop farming (Lu et al., 2017). In this logic, the key to the control of water environment pollution in Erhai Lake Basin is the control of NPS pollution, the focus of NPS pollution control is the harm that crop farming may cause to the water environment, and the very solution to NPS pollution control of crop farming is optimizing the crop planting structure and proper use of fertilizers.

Many works so far have studied NPS pollution from the aspects of climate (Badrzadeh et al., 2022; Xie et al., 2019), land use (Hu et al., 2022; Qian et al., 2021), Water quality monitoring technology (Wong et al., 2021a, b), and irrigation level (Sheikhzeinoddin & Esmaeili, 2017). For example, Mouri et al. (2011) discussed the impacts of land use types on seasonal and spatial changes in biochemical oxygen demand (BOD), total nitrogen (TN), total phosphorus (TP) and suspended solids (SS) in the Shigenobu River Basin. Some other works explored the correlation between fertilization methods and the nitrogen use efficiency, nutrient accumulation and distribution of crops (Sheikhzeinoddin & Esmaeili, 2017; Adeyemi et al., 2020). Some scholars also use artificial intelligence to study the spatial variation of surface water quality and river-scale spatial classification (Wong et al., 2020 Wong et al., 2021a, b) The relationship between fertilizer application levels and surface pollution under different crop rotations has rarely been reported; therefore, this paper explores the relationship between fertilizer application levels and agricultural NPS under different crop rotations.

Most studies on agricultural NPS pollution involved analysis of precipitation and runoff (Hofmeister et al., 2016), and some discussed the effects of fertilization methods on soil nutrient distribution (Liu et al., 2021; You et al., 2019). However, current studies on the dynamics of nitrogen and phosphorus concentrations in surface water of surface runoff fields under varied levels of fertilizer application are scarce. In addition to TP and TN, other water quality indicators like BOD (Mouri et al., 2011), COD (Badrzadeh et al., 2022), NO_3-N (Chen et al., 2020) and AN (Wang et al., 2019a, b) were also measured in studies on

agricultural NPS pollution. Many pollutants are found to be contributors to agricultural NPS pollution, but few indicators of agricultural NPS pollution are studied in previous works. Thus, five typical water quality indicators of agricultural NPS pollution are selected in this paper for exploration. Based on fieldwork of the land conditions and cropping structures in the study area, experiments of varied fertilization levels in the test fields of different crop rotations were performed in our study. Specifically, field plots with regular fertilization were the control groups, and plots with reduced fertilization were the experimental groups; fertilizers were applied to crops at different stages of growth and water samples were collected after rainfall to measure five water-quality indicators: chemical oxygen demand (COD), total phosphorus (TP), ammonia nitrogen (AN), nitrate nitrogen (NO3-N) and Total nitrogen (TN). The measured indicators were then employed to decipher the relationship between fertilization levels and agricultural NPS pollution on different crops, and corresponding models were built accordingly. This study is expected to provide a theoretical basis for the evaluation and delineation of the spatial pattern of source-sink risks of NPS pollution in Erhai Lake Basin, and put forth new methods for improving the ecological well-being of the basin.

2 Materials and Methods

2.1 Overview of the Study Area

Located in Dali Bai Autonomous Prefecture, Yunnan Province, China (25°25'–26°10'N, 99°32'–100°27'E), the study area, Erhai Lake Basin, covers an area of 2607.75 km^2 and stretches along Dali City, Binchuan County, Eryuan County, and Yangbi County. Erhai Lake is a typical inland faulted lake, which mainly relies on rainfall for water supply, and the rivers that enter the lake include Haichao River, Fengwei River, Boluo River, Miju River, and Luoshi River. The upper reaches of Erhai Lake Basin cover seven towns—Shangguan Town of Dali City, Niujie Town, Sanying Town, Cibihu Town, Yousuo Town, Dengchuan Town, and Fengyu Town of Eryuan County. The Boluo River, Miju River, and Luoshi River originate from Eryuan County in the upper reaches of the Erhai Lake, providing 70% of all the water in Erhai Lake every year. The upper reaches play an important role in the ecological protection of Erhai Lake Basin. Figure 1 shows the map of the study area.

The main crops in the upper reaches of the basin under study are rice, wheat, maize, barley, beans, potato, rape, flue-cured tobacco, and vegetables. The most popular crop rotation regime there is
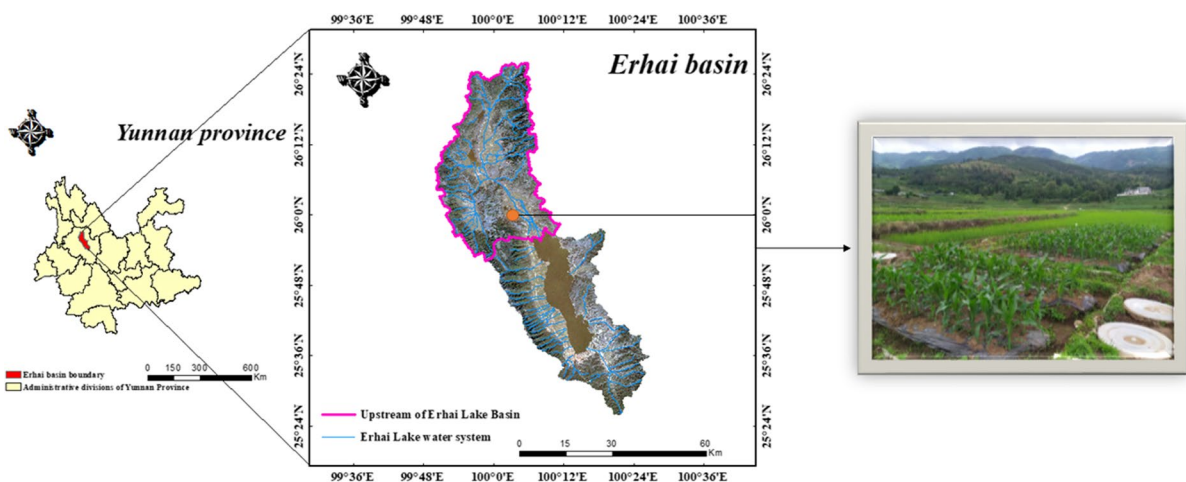

Fig. 1 Map of the study area

the rice-broad bean rotation, which accounts for about 90% of the total planting area, followed by the planting areas of maize, broad bean, and vegetables. For the time being, potato claims the largest application of chemical fertilizers among other crops in the study area. Therefore, in this study, four crops—rice, maize, broad bean, and potato were selected for analysis based on the rice-broad bean rotation in the Spring planting season and the maize-potato rotation in the Winter planting season.

2.2 Experimental Design

The experiments of this study were made in field plots in Cibihu Town, Eryuan County. Three fertilization levels were set up, with three replicates randomly arranged. In the experiments, 18 plots were used, each taking up a net area of 12m^2, totaling 216 m^2; anti-seepage treatment was also made to ensure that there was no water leakage or seepage in the plots. A runoff collection barrel with a volume of 1.0 m^3 was arranged to each runoff plot. The field for experiments took up an area of about 1,000 m^2. Two crop rotation regimes—rice-broad bean rotation and maize-potato rotation, were arranged in our experiments. Figure 2 shows the specific arrangement of our experiments.

The experiments lasted from March 2022 to April 2023, which involved two seasons of planting: the Spring planting season (from May to August) and Winter planting season (from October to December). Rice and maize are mainly planted in the Spring season, while broad beans and potatoes are mainly planted during the Winter season. A runoff collection bucket was arranged at the water inlet to the plots; the plots were numbered from #1 to #18, and the water inlet was numbered #19. The water quality at the inlet was measured to compare with that after the irrigation of plots. During Spring (from May to August, rice was planted in plots numbered #1–9, where normal fertilization was applied to plots #1–3, 60% fertilization was applied to plots #4–6, and 30% fertilization was applied to plots #7–9; maize was planted in plots #10–18, where normal fertilization was applied to plots #10–12, 60% fertilization was applied to plots #13–15, and 30% fertilization was applied to plots #16–18. Likewise, the fertilization levels on these plots remained the same when the crops for rotation, broad bean and potato, were planted during the winter season.

To ensure that each plot was not affected by the remaining plots during the experiment, we set a ridge 25 cm wide between plots under the same regime of fertilization and a 50 cm-wide ridge between plots
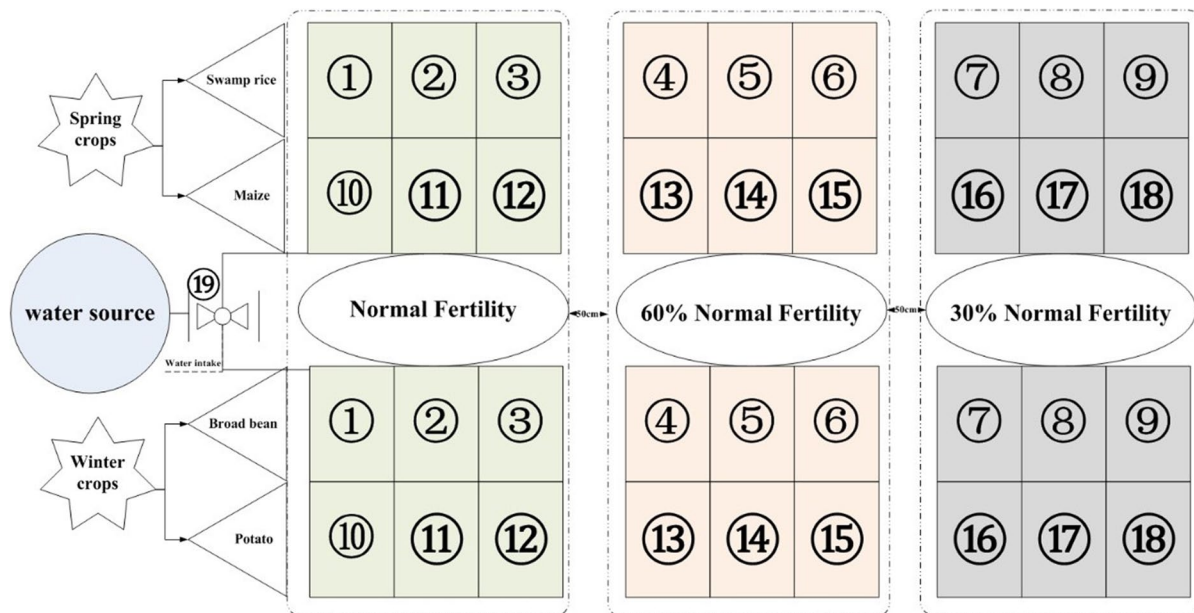

Fig. 2 Arrangement of experiments

Table 1 Fertilization regimes of different crops in our experiment

Crop	Date of fertilization	Type of fertilizer	Fertilization level	Amount of fertilizer (kg)
Rice	June 1, 2022	Compound fertilizer	NF*	0.15
			60% NF	0.1
			30% NF	0.06
	June 17,2022	Urea	NF	0.4
			60% NF	0.23
			30% NF	0.16
Maize	May 25, 2022	Compound fertilizer	NF	0.45
			60% NF	0.32
			30% NF	0.18
	June 20, 2022	Urea	NF	0.75
			60% NF	0.5
			30% NF	0.3
Broad bean	November 1, 2022	Compound fertilizer	NF	0.25
			60% NF	0.17
			30% NF	0.1
	November 29, 2022	Urea	NF	0.17
			60% NF	0.09
			30% NF	0.05
Potato	November 5, 2022	Compound fertilizer	NF	0.25
			60% NF	0.17
			30% NF	0.1
	November 29, 2022	Urea	NF	0.13
			60% NF	0.09
			30% NF	0.05

*NF indicates normal fertilization, and this applies to all figures and tables in this paper

under different fertilization regimes. Before the crops were planted, the anti-seepage mulching film was used to separate plots under different fertilization regimes to prevent mutual influence between plots and minimize experimental errors.

During the experiment, fertilization was applied through basal fertilization and top-dressing fertilization. Table 1 displays the time, amount, and level of fertilization in our experiment. The composition of the compound fertilizer is: N-P_2O_5-K_2O:19–19-19; the content of urea is greater than or equal to 46%.

2.3 Indicators and Methods for Measurement

In our experiments, all crops relied on rainfall for irrigation, except for rice which required long-term manual irrigation at different growth stages. Water quality indicators—total phosphorus (TP), total nitrogen (TN), chemical oxygen demand (COD), ammonia nitrogen (AN), and nitrate nitrogen (NO_3-N), were measured at each plot.

Preparation before sample collection: before the experimental design was laid out, a runoff bucket (with a volume of 1.0 m^3) was placed under each plot; for a total of 18 plots, 18 runoff buckets were placed. Sample collection: water samples were collected during the first rainfall after application of fertilizer into polyethylene bottles for water quality measurement. Meanwhile, a small pump was used for water sample collection to minimize experimental errors. Each bottle of water sample was 500 mL. Preservation of water samples: concentrated H_2SO_4 was added to the samples to keep the pH below 2, and sample testing was completed within 24 h. The samples were collected four times, and 19 samples were collected each time, so a total of 76 water samples were obtained.

2.3.1 Measurement of Total Phosphorus (TP)

The total phosphorus (TP) was measured by ammonium molybdate spectrophotometry GB11893-89. Specifically, the phosphorus-containing compounds in the water sample, under the action of potassium persulfate, were converted into orthophosphate, would react with ammonium molybdate and potassium antimony tartrate in the acidic medium to generate phosphomolybdic heteropoly acid, and phosphomolybdic acid could be reduced by ascorbic acid to produce dark phosphomolybdic blue. The absorbance of the sample was measured at 700 nm. The phosphorus content in the water sample was identified from the calibration curve processed by the same method, and the total phosphorus concentration was calculated (mg/L). The minimum detectable concentration measured by this method was 0.01 m/L (Agrawal & Majumdar, 1995). The analytical instrument used in our experiment was 722N spectrophotometer.

2.3.2 Measurement of Chemical Oxygen Demand (COD)

The chemical oxygen demand (COD) was measured by the dichromate method HJ828-2017. Specifically, a known amount of potassium dichromate solution was added to the water sample, and the silver salt was used as a catalyst in a strong medium; after boiling reflux, the unreduced potassium dichromate in the water sample was titrated with ammonium ferrous sulfate using the test ferrous as an indicator; the amount of ammonium ferrous sulfate consumed was converted into the mass concentration of the consumed oxygen. In acidic potassium dichromate, oxidation of aromatic hydrocarbons and pyridine is difficult to realize, with a low oxidation rate. Under the catalysis of silver sulfate, linear aliphatic compounds can be effectively oxidized. In this method, the COD digester is often required for 2 h of reflex. The minimum detectable concentration was 4 mg/L (Dedkov et al., 2000). The analytical instrument used in this experiment was the acid burette.

2.3.3 Measurement of Total Nitrogen (TN)

The total nitrogen (TN) was measured by alkaline potassium persulfate digestion ultraviolet spectrophotometry HJ636-2012. Specifically, under the condition of 120 °C ~ 124 °C, the alkaline potassium persulfate solution converted the nitrogen compounds in the sample into nitrates; the absorbance was measured by ultraviolet spectrophotometry at 220 nm and 275 nm. The minimum detectable concentration of this method was 0.05 mg/L (Wu et al., 2023). The instrument used in this experiment was UV-5500PC UV–visible spectrophotometer.

2.3.4 Measurement of Ammonia Nitrogen (AN)

Ammonia nitrogen (AN) was measured by Nessler's reagent spectrophotometry HJ535-2009. Specifically, ammonia (or ammonium) reacted with Nessler's reagent (strong alkali solution of potassium iodide) in a strong alkali solution to form colloidal compounds in the color of yellow–brown, a color of strong absorption in a wide wavelength range, and hence the compounds could be quantified through colorimetry using 410–425 nm wavelength light. This method is mostly used to measure ammonia nitrogen in water in industrial and agricultural settings. The minimum detectable concentration of this method was 0.025 mg/L (Feng et al., 2016). The instrument used in our experiment was the 722N spectrophotometer.

2.3.5 Measurement of Nitrate Nitrogen (NO_3-N)

The nitrate nitrogen (NO_3-N) was measured by phenol disulfonic acid spectrophotometry GB7480-87. The main principle is that nitrate reacts with phenol disulfonic acid in the absence of water to generate nitrodisulfonic acid phenol, which generates yellow compounds in the alkaline solution, and its absorbance is measured at 410 nm. This method is used to measure the concentration of nitrate nitrogen in water. The minimum detectable concentration of this method was 0.02 mg/L (Tong et al., 2017). The instrument used in our experiment was the 722N spectrophotometer.

In our experiment, water samples were collected four times on June 10, 2022, June 28, 2022, November 10, 2022, and December 10, 2022. The four times of sampling times were during the first rainfall after the application of base and topdressing fertilizers to the four crops in this study: rice, corn, broad beans, and vegetables because rainfall generates runoff, and the runoff after fertilizer application has a higher concentration of NPS pollution. Water samples were collected
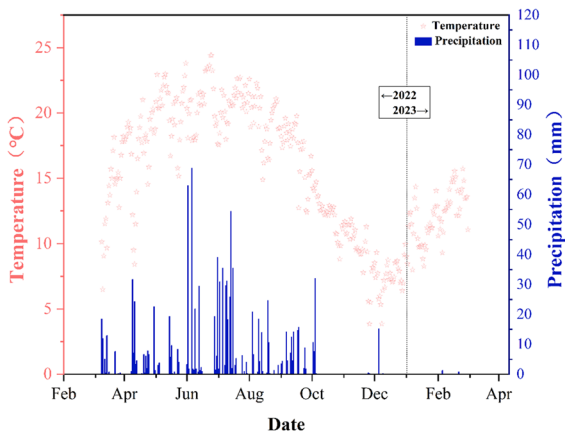
Fig. 3 Temperature and precipitation diagram of the experiment fields

from each plot to compare the varied effects of crops and fertilization levels on agricultural NPS pollution. Figure 3 shows the temperature and precipitation diagram of the experiment fields.

2.4 Statistical Analysis

In this study, one-way analysis of variance (ANOVA) was used to test the significance of the differences between the fertilization regimes of different crops. SPSS 26.0 (SPSS Inc. Chicago, USA) was used for statistical analysis (Kopriva & Shaw, 1991). When the F value in ANOVA testing was statistically significant, the least significant difference (LSD) test (significance level $P < 0.05$) was used for mean separation. Two-tailed partial correlation analysis and multiple linear regression (glm-repeat measures) were used to analyze the correlation

between the fertilization level and agricultural NPS pollution and the relationship between the amount of fertilizers and agricultural NPS pollution among different crops in the experiments. The Pearson correlation analysis was employed to analyze the correlation between indicators, and $P < 0.05$ was taken as the significant level. The OriginPro 2022 software was used for drawing of relevant maps.

3 Results

The contents of total phosphorus (TP), total nitrogen (TN), chemical oxygen demand (COD), ammonia nitrogen (AN) and nitrate nitrogen (NO_3-N) were measured by the methods and processes described above.

3.1 The content of TP, TN, COD, AN and NO_3-N Measured at the Water Inlet

The water quality indicators at the water inlet were measured to compare with the indicators of water samples from plots with fertilized crops. As Fig. 4 shows, the content of AN remained lower than that of NO_3-N at the inlet over the four times of sampling. The content of TN, AN, and NO_3-N measured during the Spring planting season (during the growth of rice and maize) was larger than that measured during the Winter planting season (during the growth of broad bean and potato), while the content of COD and TP measured during the Spring planting season was lower than that measured during the Winter planting season. The content of TP and COD varied considerably over the four times of sampling.
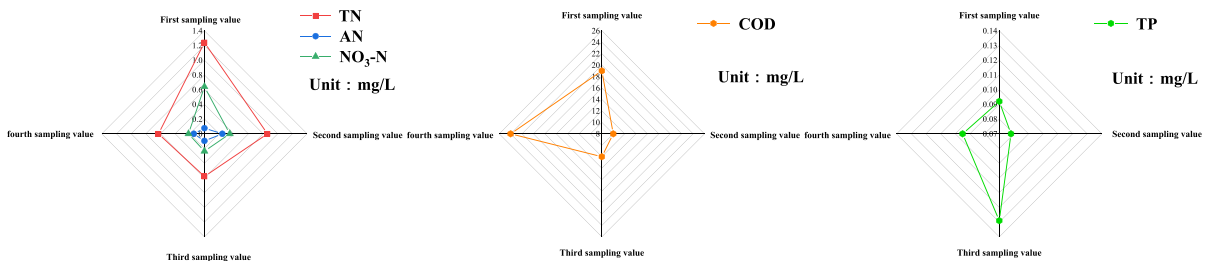

Fig. 4 Radar charts of the contents of different indicators measured at the water inlet.

Fig. 5 Total phosphorus (TP) content of crops under different fertilization levels. Note: There is no significant difference in the error column with the same letter of the same crop under different fertilization levels at the probability level of $P < 0.05$; this applies to other figures and tables throughout this paper
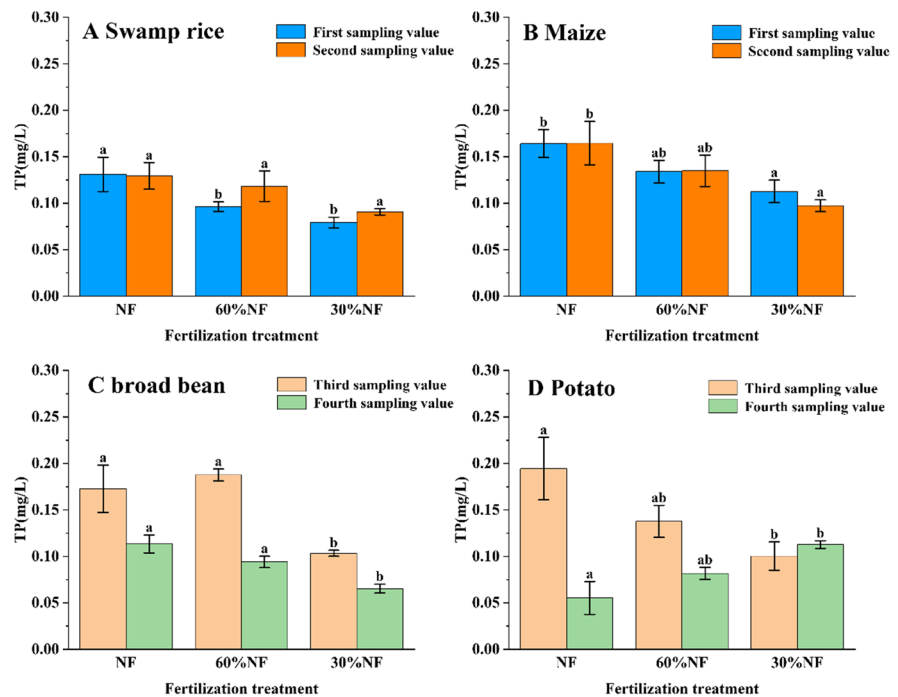
3.2 Content of TP Under Different Fertilization Levels

The content of TP under three fertilization levels of each crop was measured, as shown in Fig. 5. As the figure shows, the content of TP was considerably affected by the fertilization level, and the content of TP declined with the decreased amount of fertilizers among all four crops. For the Spring crops (rice and maize), the content of TP decreased as the amount of fertilizers declined, with little difference between the value measured after basal fertilization and that measured after topdressing fertilization. The case for the Winter crops (broad bean and potato), however, was different: after basal fertilization, the TP content in the broad bean and potato plots decreased as the amount of fertilizers reduced; but after topdressing fertilization, the TP content on the potato plot increased with the decreased amount of fertilizers.

Overall, the TP discharged from most crops after basal fertilization was generally larger than after the topdressing fertilization, but the case with the rice showed an opposite trend. The possible cause can be the high demand for phosphorus in the early growth stage of rice (Gao et al., 2020).

By comparing Figs. 4 and 5, we could found that the TP content measured at the water inlet remained smaller than that measured in the plots of crops under different fertilization levels, which indicates the influence of fertilization on the TP discharged from crops.
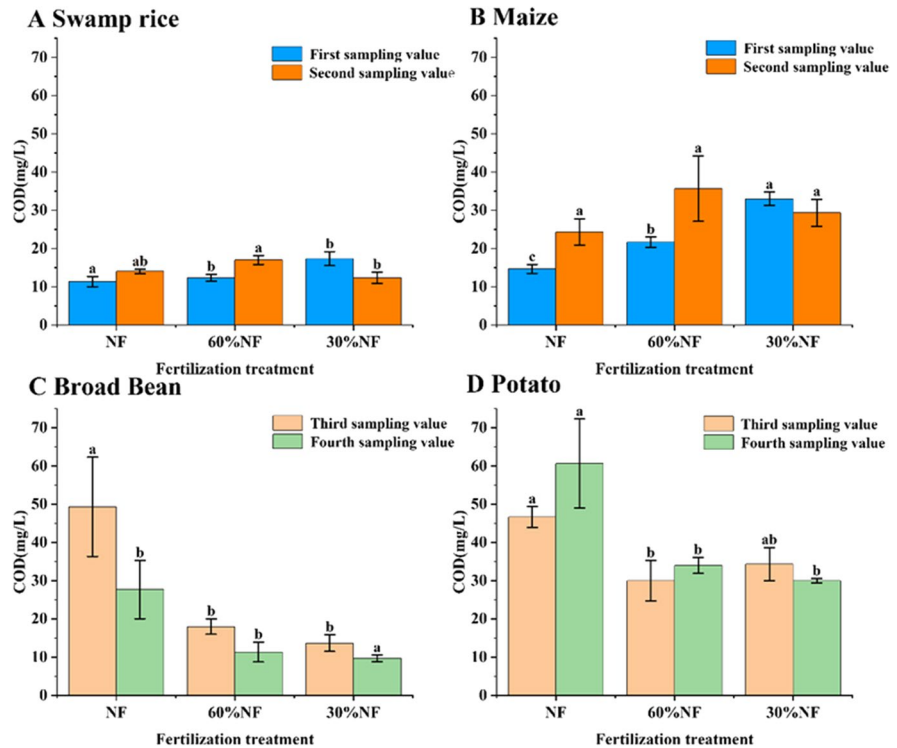
3.3 Content of COD Under Different Fertilization Levels

Figure 6 shows the correlations between fertilization levels of different crops and the COD content. As the figure shows, the COD content was greatly affected by the fertilization level and the crop planting system. Specifically, for crops planted during the Spring planting season (rice and maize), the COD content increased with the decrease of the amount of fertilizers after basal fertilization; after topdressing fertilization, however, the COD content first rose and then dropped with the decreased amount of fertilizer. For the Winter crops (broad bean and potato), the COD content displayed a decreasing trend with the reduced amount of fertilizer, and this trend was more pronounced on the broad bean plots.

Among all the crops, potato marked the highest discharge of COD, followed by maize and broad beans, and at last, rice.

By comparing Figs. 4 and 6, we could find that the COD content measured during the second and third

Fig. 6 COD content of crops under different fertilization levels

times of sampling at different plots was lower than that measured at the water inlet; the value measured from the rice plots during the first sampling time was also smaller than that measured at the water inlet; the COD content measured from broad bean plots with 60% and 30% fertilization during the fourth time of sampling was lower than the value measured at the water inlet.

3.4 Content of Nitrogen Under Different Fertilization Levels

3.4.1 Content of TN Under Different Fertilization Levels

Figure 7 shows the correlation between fertilization levels and the TN content of different crops. Figure 7 suggests the significant influence of crops and fertilization on the TN content. Specifically, the TN content from plots with rice and maize showed the same pattern of changes—after basal fertilization, the TN content first dropped and then rose with the decreased amount of fertilizer; after topdressing fertilization, the TN content increased before decreasing as the reduced amount of fertilizer. For Winter crops (broad bean and potato), the broad bean after basal fertilization witnessed an increase and then a

decrease in the TN content with decreased fertilizer; after topdressing fertilization, however, the TN content first declined and then increased with decreased fertilizer. In the case of the potato, the TN content dropped and then rose after basal fertilization with the decreased amount of fertilizer; after topdressing fertilization, however, the TN content of potato plots showed a rising trend with decreased fertilizer.

Overall, the TN content measured at plots planted with Spring crops (rice and maize) showed considerable differences after basal and topdressing fertilization, while the content measured at plots with Winter crops showed smaller differences after basal and topdressing fertilization.

By comparing Fig. 4 and 7, we could find that the TN content at the water inlet remained lower than that measured at the plots of all crops under different fertilization levels, which suggests the influence of fertilization on the TN content.

3.4.2 Content of AN Under Different Fertilization Levels

Figure 8 shows the correlation between the fertilization level and the AN content of different crops.

Fig. 7 TN content of crops under different fertilization levels
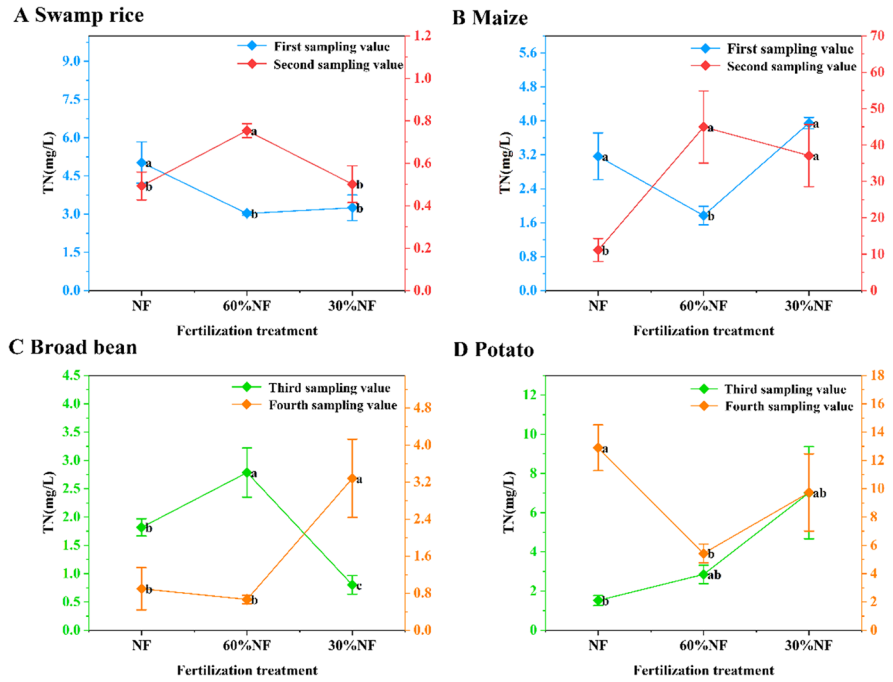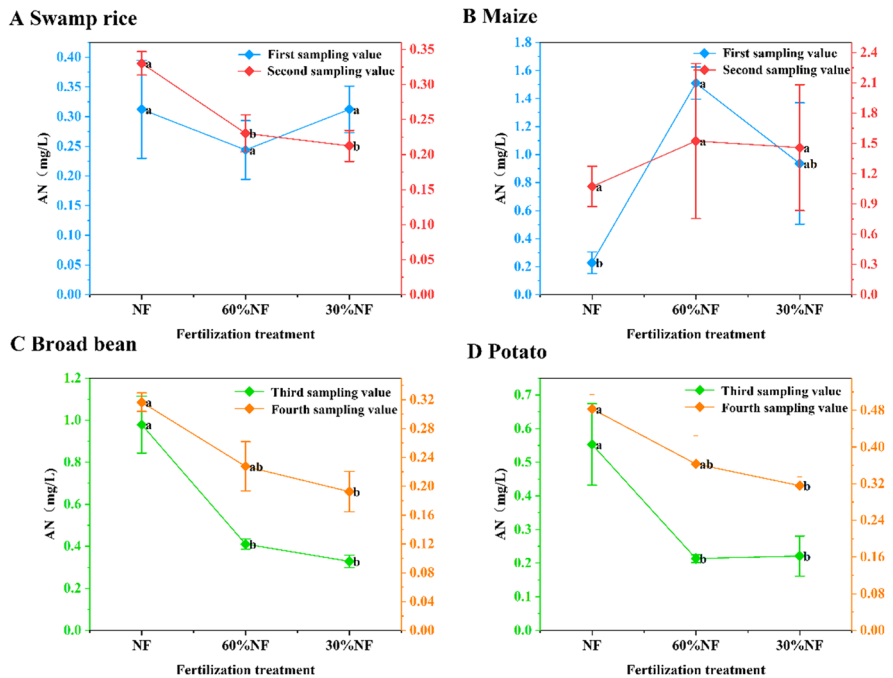

Fig. 8 AN content of crops under different fertilization levels

As Fig. 8 shows, in samples from plots with Winter crops (broad bean and potato), the AN content decreased as the amount of fertilizer reduced; the curve showed a larger gradient of slope from normal fertilization to 60% fertilization, indicating a sharp drop in the AN content, while the curve from 60% fertilization to 30% fertilization had a smaller gradient of slope, suggesting a milder drop in the AN content. The AN content measured during the third time of sampling was larger than that

Fig. 9 Content of NO_3-N of crops under different fertilization levels
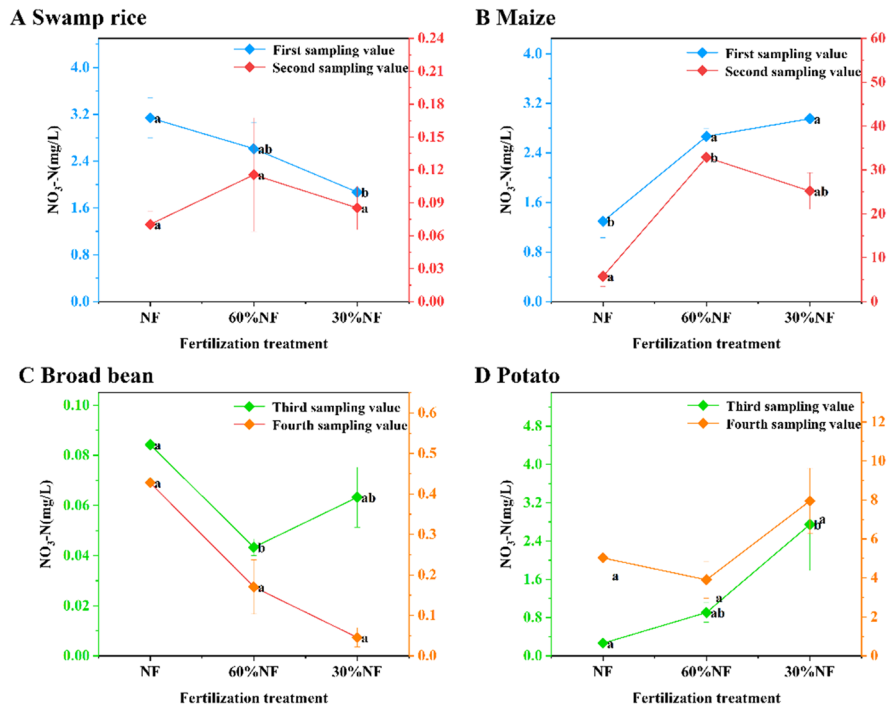
measured at the fourth time, which was correlated to the amount of fertilization around the sampling time.

On plots of Spring crops (rice and maize), the AN content of the rice plots decreased with the decreased level of fertilization during the first time of sampling; during the second sampling, however, the AN content increased and then decreased. On the rice plots, the AN content measured after basal fertilization was larger than that measured after top-dressing fertilization. In the case of maize, the AN content measured during the first time of sampling increased with the decreased fertilization level; during the second time of sampling, however, the AN content measured on the maize plots showed the same pattern of changes as that measured on the rice plots, which rose and then dropped with the decreased fertilization level. Overall, the AN content on maize plots measured after basal fertilization was lower than that measured after the application of the top-dressing fertilizer.

Comparing Figs. 4 and 8, we can see that the AN content measured at the water inlet remained lower than the values measured in plots of all the crops under different fertilization levels in the study, implying the influence of fertilization on the discharge of AN from crops.

3.4.3 Content of NO_3-N Under Different Fertilization Levels

Figure 9 shows the changes in the content of NO_3-N of crops under different fertilization levels. As the figure shows, the content of NO_3-N measured in the experiment varied with the fertilization levels of the crops, and the NO_3-N content after basal fertilization differed considerably from that measured after topdressing fertilization. On the rice plots, the NO_3-N content measured after basal fertilization decreased with the reduced amount of fertilizer; after topdressing fertilization, however, the NO_3-N content first increased before witnessing a decrease with the decreased fertilization level. In water samples from the maize plots, the NO_3-N content increased first and then decreased with the reduced fertilization level after the application of basal and topdressing fertilizers. The NO_3-N content measured in water samples from the broad bean plots decreased first and then increased with reduced fertilizer after basal fertilization, but kept declining after application of topdressing fertilizer. The NO_3-N content measured from the potato plots increased with the decreased amount of fertilizer after basal fertilization; the

Table 2 Regression analysis of agricultural NPS pollution indicators of crops under different fertilization levels

Crop	Indicator	Regression equation	R^2	Adjusted R^2	P-value
Swamp rice	TP	TP = 0.023x + 0.062	0.495	0.464	0.001
	COD	COD = 1.917x + 10.222	0.281	0.236	0.024
	AN	AN = 0.079x + 0.084	0.490	0.458	0.001
	NO_3-N	NO_3-N = 0.314x + 0.636	0.042	-0.018	0.415
	TN	TN = 0.410x + 1.336	0.035	-0.026	0.459
Maize	TP	TP = 0.030x + 0.075	0.550	0.522	0.000
	COD	COD = 5.883x + 38.111	0.266	0.221	0.028
	AN	AN = -0.273x + 1.668	0.080	0.023	0.254
	NO_3-N	NO_3-N = -5.227x + 22.014	0.098	0.042	0.206
	TN	TN = -10.019x + 9.448	0.247	0.2	0.036
Broad bean	TP	TP = 0.025x + 0.075	0.219	0.17	0.05
	COD	COD = 4.500x + 13.111	0.252	0.226	0.041
	AN	AN = 0.121x + 0.217	0.101	0.044	0.2
	NO_3-N	NO_3-N = -1.609x + 4.497	0.078	0.021	0.261
	TN	TN = -2.025x + 5.608	0.080	0.023	0.255
Potato	TP	TP = 0.038x + 0.038	0.364	0.324	0.008
	COD	COD = 9.750x + 20.444	0.357	0.317	0.009
	AN	AN = -0.019x + 0.047	0.352	0.311	0.009
	NO_3-N	NO_3-N = -1.351x + 6.167	0.294	0.237	0.017
	TN	TN = -0.584x + 7.772	0.211	0.198	0.018

measured value after topdressing fertilization of potato, however, saw a decrease and then a rise as the amount of fertilizer reduced.

By comparing Figs. 4 and 9, we could see that except maize, all other crops had a higher content of NO_3-N under the three fertilization levels than the value measured at the water inlet.

3.5 Impacts of Fertilization Levels of Crops on Agricultural NPS Pollution

Table 2 shows the result of regression analysis of the indicators measured from plots of different crops under different fertilization levels during the four times of sampling. As the table shows, with the increased level of fertilization, the values of water quality indicators of the rice plots increased as well (Intercept termd > 0, $P < 0.05$) with significant increases observed in the content of TP, COD, and AN: the influence of changes in the fertilization level was most pronounced on the content of TP ($R^2 = 0.495$) and AN ($R^2 = 0.490$), followed by the COD content ($R^2 = 0.281$), while the content of NO_3-N ($R^2 = 0.042$) and TN ($R^2 = 0.035$) was least influenced.

As with rice, the maize crop was also planted during the Spring season, but the indicators measured in the maize plots showed a different pattern of changes from those measured in the rice plots. The content of TP and COD measured in water samples from the maize plots increased with the increased fertilization level(Intercept termd > 0, $P < 0.05$), sharing the same pattern with that measured in samples from the rice plots, and the impact of fertilization levels on the TP content was found to be significant ($R^2 = 0.550$). The impact of fertilization levels on the COD content was less significant ($R^2 = 0.266$). The TN content kept decreasing with the increased fertilization, while the impact of fertilization levels on the NO_3-N and AN was not significant.

In water samples from the Winter crop of broad bean, the fertilization level was found to have positively affected the content of TP and COD, with significant impacts observed on the TP content ($R^2 = 0.219$). However, there was no significant correlation between the fertilization level and the content of NO_3-N, AN and TN. In the case of the potato, the fertilization level had significant correlations all the measured indicators for agricultural NPS pollution, with the most pronounced
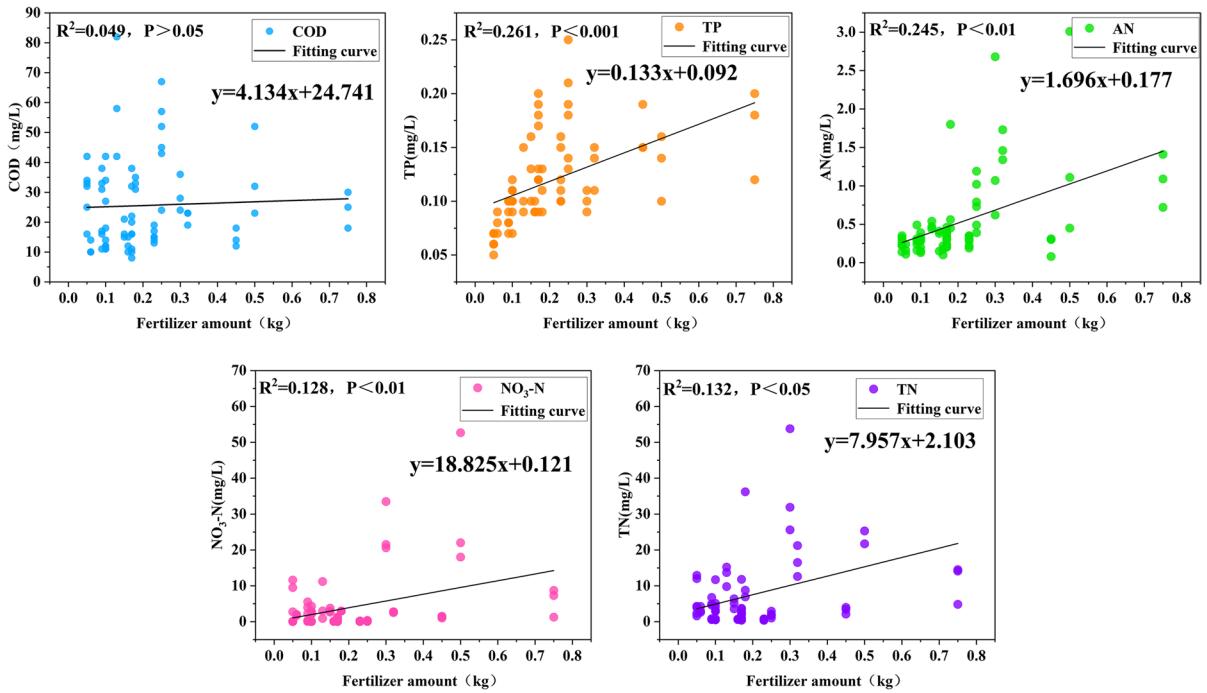
Fig. 10 Regression analysis of indicators under different amount of fertilizer

Table 3 ANOVA tests of intra-group and inter-group effects of different crops and fertilization levels on agricultural NPS pollution

Item	COD	TP	AN	NO_3-N	TN
Different crops	***	NS	***	***	***
Different fertilizer levels	NS	***	NS	NS	NS
Different crops + different fertilization levels	***	***	***	**	***

*, * *, * * * indicate statistical significance at the 0.05, 0.01, 0.001 levels; NS indicates non statistical significance at the 0.05 level

Fig. 11 Pearson correlation tests of TP, AN, NO_3-N, COD and TN indicators

correlation observed on the content of TP ($R^2 = 0.364$), followed by COD ($R^2 = 0.352$), AN ($R^2 = 0.352$), and NO_3-N ($R^2 = 0.294$), and at last, TN($R^2 = 0.211$), among which the fertilization level showed significantly negative correlations with the content of TN and NO_3-N.

Among all the four crops, the fertilization level had the largest and most significant impact on the TP content; except the case with rice, the fertilization level of the other three crops (maize, broad bean, and potato)
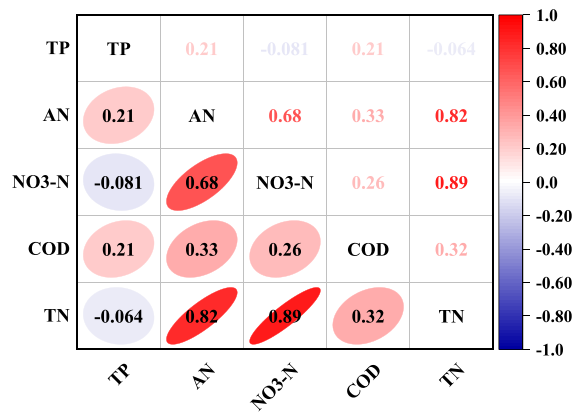
was found to have negative impacts on the nitrogen content indicators, where the TN content was most correlated to the content of NO_3-N and AN (Fig. 11). Thus, the fertilization level showed negative impacts on the content of NO_3-N and AN in some crops.

3.6 Effect of Fertilization on Agricultural NPS Pollution

To identify the effect of the fertilization level on agricultural NPS pollution, we performed stepwise regression analysis of the measured indicators of the four crops under different fertilization levels. The results are shown in Fig. 10.

As Fig. 10 shows, regardless of the type of the crop, the amount of fertilizer was found to have positively affected the measured indicators of agricultural NPS pollution, among which the TP content witnessed the most significant and largest impact ($R^2 = 0.261$; $P < 0.001$), followed by the nitrogen indicators, and the least impact was observed on the COD content ($R^2 = 0.049$; $P > 0.05$).

With the type of crop considered, it was found that the fertilization level had the largest and most significant impact on the TP content. Therefore, the discharge of TP is the main contributor to agricultural NPS pollution in Erhai Lake Basin.

4 Discussion

4.1 Correlations Between Indicators of Agricultural NPS Pollution

Table 3 shows the result of ANOVA testing. As the table shows, when only the type of crop was considered, significant impacts were observed on all indicators except the TP indicator; when only the fertilization level was considered, no significant impacts were observed on the COD, AN, NO_3-N, and TN indicators; when both the type of crop and the fertilization level were considered, significant impacts were observed on the TP, TN, COD, and AN indicators at the $p < 0.001$ level, while the impact on the NO_3-N indicator was significant at the $p < 0.01$ level.

Meanwhile, there were also correlations between the indicators of agricultural NPS pollution. The Pearson correlation test of each indicator of agricultural NPS pollution (Fig. 11) shows that the content of TN had a significant and positive correlation with AN and NO_3-N contents ($P < 0.01$), which indicates a positive impact of the TN content on the AN and NO_3-N indicators of agricultural NPS pollution; a significant and positive correlation was also observed between AN and NO_3-N ($P < 0.01$). The COD

indicator had a significant and positive correlation with TP, TN, and AN indicators ($P < 0.01$); the correlation of TP with TN and NO_3-N was not significant, the reason for which may be that the water for irrigation mainly comes from precipitation, and the water quality of water from precipitation is affected by complex factors (Badrzadeh et al., 2022).

4.2 Response of Agricultural NPS Pollution to Crops at Different Fertilization Levels

It was found in this study that TP showed the largest and most significant response to the fertilization level of the crops, which is consistent with the findings reached by Yao et al., (2010). However, no significant response was observed in the nitrogen indicators to the fertilization level, which differs from the observation by some other researchers (Wang et al., 2019a, b), and the reason for this situation may be that the transport and transformation of nitrogen in the soil is complex and subject to many external factors (Liu et al., 2013). The concentration of agricultural NPS pollutants measured at some intakes was significantly higher than those measured after the application of fertilizers, which may be due to the climate, the physicochemical properties of the fields or human disturbances (Su et al., 2022; Wang et al., 2019a, b). When it comes to the relationship between agricultural NPS pollution and the amount of fertilizer application, the content of TP remains to show the strongest and most significant response to the amount of fertilizers, which is consistent with some previous findings (Wu et al., 2021); the response relationship between COD and the amount of fertilizer application was not significant, which differs from some previous observations (Wang et al., 2019a, b), and the reason may be that the content of COD is the greatest in water and the irrigation and drainage of water in the experiment fields would affect the COD content in the sample collection bucket, resulting in a significant correlation between the COD content and the amount of fertilizer application (Choi et al., 2019).

4.3 Relationship Between Agricultural NPS Pollution and the Crop Type

Statistics in Figs. 4, 5, 6, 7 and 8 show that rice had a significantly lower regression coefficient and intercept terms than other crops. Also, the concentration of each pollutant measured at the rice plot was lower than that of other crops. The

reason may be that the rice plots have a large volume of irrigation, and increased irrigation will lead to a lower concentration of pollutants when the amount of fertilizer application remains constant (Wang et al., 2019a, b; Wu et al., 2021; Chowdary et al., 2004). The fertilization level of potatoes significantly and negatively affects TN and NO_3-N. This may be because the nitrogen fertilizer loss of vegetable crops, such as the potato, is mainly due to nitrogen leaching, while surface runoff emissions have less effects on nitrogen loss, which may be the reason for the negative correlation (Chen et al., 2018).

4.4 Research Prospects

In this paper, through experiments on plots with rice-broad bean rotation and maize-potato rotation, we studied the correlation between the fertilization level of the four crops and agricultural NPS pollution. Compared with studies that focused on singular crops, our research can more comprehensively reflect the rule of pollutant discharges of different crops (Christou et al., 2019); it also unveils the relationship between agricultural NPS pollution and the fertilization level. However, the formation mechanism of agricultural NPS pollution has a complex mechanism of formation and is subject to many factors, such as the crop planting structure (Cui et al., 2022), the irrigation amount (Xiao et al., 2019), the amount of fertilizer (Wang et al., 2019a, b) and fertilizer utilization rate (Zhou et al., 2017). Therefore, in future research, it is necessary to incorporate more contributing factors to agricultural NPS pollution into analysis.

In this study, the relationship between fertilization levels of different crops and NPS pollution was investigated to unveil the response mechanism of agricultural NPS pollution of different crop rotations to fertilizer application in the upper reaches of Erhai Lake Basin. However, the physical and chemical properties of soil in the experiment fields were not tested in this study, which may, to some degree, affect the accuracy of the measured content of phosphorus and nitrogen. Moreover, the impacts of the growth stage of the crops and the type of fertilizer on agricultural NPS pollution were not investigated here, and this can be further explored in our future studies.

5 Conclusions

Irrational application of fertilizers is one of the main causes of agricultural nonpoint source (NPS) pollution in the upper part of Erhai Lake Basin. In this study, the influence of fertilization levels of different crops on agricultural NPS pollution in the upper reaches of Erhai Lake Basin was investigated, and the conclusions are as follows:

(1) The concentration of agricultural NPS pollutants measured at the inlet was smaller than that measured after fertilization treatment, indicating the effects of fertilization on the content of agricultural NPS pollutants. Compared with the scenario when either the type of crop or the fertilization level is considered, analysis that combined both showed significant correlations ($P < 0.001$) with the content of agricultural NPS pollution.

(2) Stepwise regression analysis revealed that the fertilization level had a significant effect on the content of total phosphorus (TP) across all the four crops studied, with the largest effect observed on rice ($R^2 = 0.550$), and fertilization level had a smaller effect on the nitrogen indicators. When the type of crop is not considered, the fertilization level positively affects agricultural NPS pollution, with the largest and most significant effect observed on the content of phosphorus ($R^2 = 0.261$; $P < 0.01$). It can be concluded that the fertilization level of crops has the most pronounced effect on the emission of total phosphorus in the upper reaches of Erhai Lake Basin. Therefore, the emission of total phosphorus should be strictly controlled to curb agricultural NPS pollution in the basin.

(3) The present work clarifies the main sources of NPS pollution in Erhai Lake Basin, provides new ideas for the evaluation and delineation of the spatial pattern of source-sink risk of NPS pollution in the basin, and puts forth new methods for the management of NPS pollution in the basins of low-latitude plateau fractured lakes similar to the Erhai Lake Basin.

Declarations

Ethics Approval and Consent to Participate Not applicable.

Consent for Publication Not applicable.

Competing Interests The authors declare no competing interests.

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