Assessment of eutrophication and nitrogen and phosphorus carrying capacity before and after removing pen culture (2013–2018) in Lake Changhu, China

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Abstract

In this study, the eutrophication levels and nitrogen and phosphorus carrying capacities of Lake Changhu in Jingzhou city, Hubei province, China, were measured using the trophic level index (TLI) and Dillon model. The measurements were taken before (2013 and 2015) and after (2017 and 2018) the removal of pen aquaculture from the lake. The lake was divided into three districts: Lake Haizihu, Mahongtai Channel and Lake Dahu. The results showed total nitrogen (TN), chemical oxygen demand (COD), chlorophyll a (Chl-a), and total suspended solid (TSS) values were significantly higher in 2017 than in the other years. The Lake Haizihu district was predicted to be more seriously polluted than the other districts. In the sediment, the organic matter, STN (TN in sediment) and STP (TP in sediment) contents increased from 2013 to 2018. The mean TLI values ranged from 62.99 to 78.93 in the studied years, and the eutrophication level was highest in 2017. According to the Dillon model, when the target water quality was level III (GB 3838 – 2002, Ministry of Environmental Protection of China, 2002), the remaining TN and TP loading capacities were – 1470.72 t/a and – 182.74 t/a, respectively, in 2015, and 320.03 t/a and – 111.14 t/a, respectively, in 2018. The study provide valuable information about the actual water conditions of Lake Changhu, which will help to inform decision-making for the management of water environments.

1. Introduction

As a significant contributor to food production, fisheries accounted for 17% of the global population's intake of animal proteins in 2017. China is a major producer of fish and accounted for 35% of global fish production in 2018 (Food and Agriculture Organization, 2020). According to MAFBC (2017), freshwater aquaculture accounted for 61.8% of the total aquaculture production of 51 423 931 tonnes in 2016. With the rapid development of pond fish culture and market demand, lake fisheries in China have undergone a transformation from wild-capture fishing to culture-based fisheries. This transformation has further progressed to cage aquaculture and pen aquaculture (Zou and Huang 2015). Pen culture is one of the main forms of aquaculture in lakes and is typically conducted in shallow lakes (2–3 m) in eastern China along the Yangtze River basin, such as in Lake Taihu (Jia et al. 2013). The peak production of pen culture reached 6 624 396 tonnes in 2016, accounting for 20.84% of total freshwater aquaculture (MAFBC 2017).

The development of pen aquaculture has been a journey of exploration and discovery, but additionally, there have been challenges and various lessons have been learnt. Introducing cage and pen culture in lakes gave rise to the risk of species invasion as exotic species were introduced. Pollution and eutrophication are other problems associated with cage and pen culture in most lakes. As a semi-intensive system, it is generally believed that pen culture could accelerate eutrophication (Wu 1995). It has previously been reported that there were higher nutrient loadings and phytoplankton biomass in pen culture areas than in non-pen culture areas in Lake Honghu (Yang and Wang 2003). It has also been shown that among 40 surveyed lakes, 57.5% possessed eutrophic and hypertrophic status (Jin et al. 2005). Fortunately, with enhanced consciousness of environmental protection, an increasing amount of attention is being paid to environmentally friendly and green-growth aquaculture. For example, in order to reduce nutrient loading, there has been a requirement for the removal of pen culture in Taihu Lake since 2009, according to the documents of the government of Jiangsu Province. In 2012, the government of Hubei Province also passed a law to ban pen culture in lakes (Wang et al. 2015). Despite the fact that pen culture has been completely removed from natural lakes, little is known about the impacts that this removal has had on the trophic status and the nitrogen and phosphorus carrying capacity of the lakes.

Globally, eutrophication causes severe ecosystem degradation and abnormal ecosystem responses in lakes. The effects of eutrophication include frequent occurrences of cyanobacterial blooms and declining biodiversity. To ameliorate eutrophication, it is essential to employ appropriate methodologies to assess the trophic state of lakes. The trophic level index (TLI) was developed by Carlson (1997) as a modified trophic state index (TSI). The TLI has been recommended by the Chinese National Environment Monitoring Center for use in determining the nutrition levels in lakes (Wang et al. 2019). The TLI method has been used to evaluate lake eutrophication globally, including for lakes such as Lake Rotoru, Rotoit, Chaohu, Dongtinghu, and Timsah (Burns et al. 2005; Burns et al. 2009; Liu et al. 2012; Xiang et al. 2014; Zhi et al. 2016; El-Serehy et al. 2018). The chlorophyll a (Chl-a), Secchi disk transparency (SD), total phosphorus (TP), total nitrogen (TN) and chemical oxygen demand (COD) are five main indicators used to assess the trophic levels of lakes. The assessment of lake eutrophication is especially relevant when there is a need to balance ecological and socio-economic interests. Assessing eutrophication could also help to predict the effects of potential management interventions for improving water quality.

External nutrient loads from anthropogenic activities, such as via agricultural fertilizer and waste water discharge, are increasing due to population expansion. This should be treated as a key challenge facing water resource management and should be subjected to scientific research (Glibert et al. 2014). According to the national standards of the people's Republic of China (GB_T 25173 – 2010, Ministry of Environmental Protection of China, 2010) the Dillon model, which was developed by Dillon and Rigler (1974), should be used to calculate the nutrient budget in eutrophic lakes. Analyzing the nutrient budget is important for elucidating how anthropogenic activities affect the ecological integrity of lakes (Walter et al. 2016).

In the present study, Lake Changhu, which is located near cities, was chosen for research. The water quality of Lake Changhu is subjected to multiple impacts from human activities such as pen culture. Pen culture was popular in Lake Changhu; the pens were removed during 2016 and 2017 due to the government ban on pen culture in lakes. The actual water quality of Lake Changhu was determined by collecting samples from a total of 27 different sites, including 20, 16, 10, and 10 sampling sites in 2013, 2015, 2017, and 2018, respectively. The objectives of this study were to (1) assess the level of eutrophication using TLI; (2) evaluate the nutrient loading using the Dillon model; and (3) compare the variations in eutrophication and nutrient budget before and after the removal of pen culture, and explore the corresponding reasons. This research could provide fundamental information on the effects of banning pen culture on the eutrophication levels and nutrient budget of Lake Changhu. This information will be valuable for governments and environmental managers.

2. Materials And Methods

2.1. Study area

Lake Changhu (30°21'55.69"–30°31'36.65" N and 112° 12'14.07"–112°30'41.78" E) is the third largest freshwater lake in Hubei Province and has a surface area of 131 km^2. The mean water level is 30.5 m and the mean water depth is 2.2 m. For the convenience of management, the lake was divided into three districts from west to east: Lake Haizihu, Mahongtai Channel, and Lake Dahu (Fig. 1). With a humid subtropical monsoon climate, Lake Changhu enjoys four distinct seasons, generous sunshine, and abundant rainfall each year. The mean annual temperature and annual precipitation of Lake Changhu is 16.8℃ and 998.5 mm, respectively. The lake water comes from six main rivers: Taihugang, Shiqiaohe, Xiaqiaohe, Longhuiqiao, Tanglinhe, and Guangpinghe. The lake water outflows downstream through the Xijiakou Sluice and Liujialing Sluice (Ni 2018).

Since the 1990s, fisheries in Lake Changhu have been transformed from wild-capture fisheries to semi-intensive mode pen culture. By late 2015, the area of pen culture in Lake Changhu had reached 70.87 km^2, accounting for 54.1% of the lake area (Liang et al. 2015). External foods were being added to the lake to supplement the intake of natural food in the pen culture. This, together with surrounding pond culture and watershed pollution, caused the water quality of Lake Changhu to deteriorate and the water ecology was severely damaged. In the past two decades, the trophic state of Lake Changhu has become eutrophic and the water quality classification has changed from level II to the inferior level V (Li and Li 2009). With the enhancement of environmental awareness, it is now understood that pen culture was developed at the cost of the environment. Pen culture was banned in Lake Changhu and all pens have been removed since 2016 according to the government policy. The pen culture removal was totally completed in January 2017 (Ni 2018).

2.2 Data collection

Water samples were collected from 27 stations within Lake Changhu in four seasons (January, April, July, and October) in 2013, 2015, 2017, and 2018 (Table S1). In these four years, the sampling locations differed as follows: 2013 (sampling locations 1#, 2#, 21#, 22#, 6#, 5#, 15#, 4#, 16#, 7#, 17#, 24#, 8#, 14#, 12#, 11#, 13#, 9# and 10#), 2015 (sampling locations 3#, 5#, 15#, 4#, 7#, 8#, 23#, 14#, 20#, 26#, 19 #,11# and 18#), and 2017 and 2018 (sampling locations 21#, 22#,4#, 23#, 24#, 25#, 20#, 26#, 27# and 18#). All water samples were collected on sunny days in order to minimize the effects of the weather. The water temperature (T), dissolved oxygen (DO), and pH were measured with a multi-parameter water quality analyzer (Hach HQ40D, Hach, USA) at the water surface in situ. The transparency was measured using a Secchi disk. For each sample, 500 ml of water was filtered with a cellulose acetate membrane (0.45 μm pore size) and then extracted with hot ethanol (Lorenzen 1967) to collect Chl-a. The concentrations of Chl-a were determined via spectrophotometry using a UV-2600PC UV–Vis spectrophotometer (Shimadzu, Inc., Kyoto, Japan). Another 500 ml of water was collected at each sampling site in plastic bottles, which had been rinsed with surface water before sampling. All bottles were transferred to the laboratory, and analyzed as soon as possible. The concentrations of TN, TP, COD, ammonium (NH_4-N), nitrate (NO_3-N), nitrite (NO_2-N), phosphate (PO_4-P), and total suspended solid (TSS) were analyzed using a portable multi-parameter spectrophotometer (Hach DR1900, Hach, USA) according to the manufacturer’s manual.

Sediment samples were collected from the same sampling stations as the water samples in the four seasons (January, April, July, and October) in 2013, 2017, and 2018. A grab sampler was used to collect sediment samples from the top layer (0–5 cm). For each sampling site, 20 g of sediment was put in a self-sealing bag and transferred to the laboratory to be analyzed. The concentrations of organic matter (OC;%), TN in sediment (STN; mg/kg), and TP in sediment (STP; mg/kg) were analyzed according to the National standard method (Huang, 1999).

2.3. Trophic condition assessment of Lake Changhu

The trophic condition of Lake Changhu was assessed using the TLI (Jin and Tu 1990). The TLI is a weighted sum based on the correlations between Chl-a and other substances. The TLI values for Chl-a, TP, TN, SD, and COD, considering both qualitative and quantitative aspects, were calculated according to following equations:

TLI(Chl-a) = 10[2.5 + 1.086In(Chl-a)], (1)

TLI(TP) = 10[9.436 + 1.624In(TP)], (2)

TLI(TN) = 10[5.453 + 1.694In(TN)], (3)

TLI(SD) = 10[5.118 − 1.94In(SD)], (4)

TLI(COD) = 10[0.109 + 2.661In (COD)], (5)

where the unit of Chl-a is mg/m^3, the units of TP, TN, and COD are mg/L, and the unit of SD is m. The TLI was calculated as follows using the national standard:

$$\mathrm{TLI}(\Sigma) = \sum_{j=1}^{m} W_j \cdot \mathrm{TLI}(j)$$

6

,

$$\mathrm{W}_j = r_{ij}^2 / \sum_{j=1}^{m} r_{ij}^2$$

7

,

where TLI(j) is the composite index of j with the correlative weight W_j; m is the number of indicators; and r_{ij} is the correlation coefficients between the reference Chl-a and each parameter j (Chl-a, 1; TP, 0.84; TN, 0.82; SD, − 0.83; and COD, 0.83).

The TLI values were used to grade the water trophic status with a range from 0 to 100. High values represented high eutrophication levels. Values of < 30 correspond to oligotrophic, 30–50 to mesotrophic, 50–60 to light eutrophic, 60–70 to middle eutrophic and > 70 to hyper eutrophic.

2.4 Nutrient loading capacity

The nutrient loading capacities (TN and TP) in Lake Changhu, before and after the removal of pen culture (2015 and 2018, respectively), were calculated using the Dillon model (equations 8 and 9).

$$M = L \bullet \mathrm{A},$$

8

$$L = (Cs \bullet Z \bullet \rho) / (1 - R),$$

9

where M is the nutrient loading capacity (t/a); L is the nutrient loading rate (g/m^2 a); Cs is the target water environmental quality of TN and TP (mg/L; grade III in Lake Changhu according to GB 3838 − 2002, Ministry of Environmental Protection of China, 2002); Z is the mean depth of the lake in meters ($Z = V/A$, where V is the lake's volume in m^3 and A is the lake's surface area in m^2); ρ is the flushing rate (1/a; $\rho = Q_{in}/V$, where Q_{in} is the annual sum of the water input in m^3/a); R is retention coefficient of TN and TP (1/a). R was calculated as $R = 1 - W_{\mathrm{out}}/W_{in}$, where W_{in} is the annual inflow of TN and TP (g/a), and W_{out} is the annual outflow of TN and TP (g/a).

2.5 Statistical analyses

Statistical analyses were performed with SPSS statistical software (IBM SPSS Statistics Ver. 22.0). Significant differences between index values due to sampling locations and seasons were determined by one-way analysis of variance (ANOVA) using the least significant difference (LSD) test at a 5% significance level. Sediment variables in different years and TLI values in different seasons were compared using Kruskal-Wallis rank sum tests in R-4.0.3. Pearson correlation analysis was performed to detect relationships between TLI values and different water and sediment variables. The trophic state assessment results were interpolated using ArcGIS 10.2 (ESRI; www.esri.com/software/arcgis).

3. Results

3.1. Spatio-temporal variation trends of water and sediment quality in Lake Changhu

Temporal trends

A statistical summary of the water quality parameters measured at all sampling sites in 2013, 2015, 2017 and 2018 were shown in Table 1. Based on the One-way ANOVA results, SD, pH, T, DO, TP, NH4-N and NO_2-N showed no difference among the four years. The concentration of TN, COD and Chl-a showed significantly highest in 2017 than that in 2013, 2015 and 2018 (P< 0.05), there was no significant difference between the later three years. While TSS showed significantly highest in 2013 and 2017 than that in 2015 and 2018 (P< 0.05). PO_4-P, NO_3-N showed significantly highest in 2015 than that in 2013, 2017 and 2018 (P< 0.05), there was no significant difference between the later three years.

Table 1
Physiochemical parameters and their statistics in 2013, 2015, 2017 and 2018 (mean ± SD).

	2013	2015	2017	2018	*P*
SD (m)	0.52 ± 28	0.81 ± 0.46	0.35 ± 0.11	0.58 ± 0.33	NS
pH	7.93 ± 0.47	8.75 ± 0.44	8.41 ± 0.43	8.33 ± 1.33	NS
T (°C)	19.25 ± 9.53	20.81 ± 9.37	23.71 ± 6.38	18.03 ± 6.96	NS
DO (mg/L)	10.66 ± 2.83	10.56 ± 4.40	7.58 ± 2.35	9.78 ± 2.63	NS
TSS (mg/L)	31.23 ± 19.36^a	9.02 ± 5.26^b	20.15 ± 14.62^a	9.83 ± 5.37^b	0.000
TP (mg/L)	0.50 ± 0.34	0.62 ± 0.48	0.77 ± 0.42	0.41 ± 0.28	NS
PO_4-P (mg/L)	0.15 ± 0.09 ^{a}	0.23 ± 0.24^b	0.15 ± 0.09 ^{a}	0.12 ± 0.09 ^{a}	0.013
TN (mg/L)	2.04 ± 1.92 ^{a}	2.58 ± 2.08 ^{a}	6.54 ± 5.53 ^{b}	1.61 ± 1.21 ^{a}	0.000
NH_4-N (mg/L)	0.12 ± 0.07	0.09 ± 0.08	0.13 ± 0.12	0.12 ± 0.1	NS
NO_3-N (mg/L)	0.61 ± 0.45 ^{a}	1.02 ± 0.5 ^{b}	0.54 ± 0.28 ^{a}	0.58 ± 0.42 ^{a}	0.000
NO_2-N (mg/L)	0.01 ± 0.01	0.02 ± 0.02	0.01 ± 0.01	0.01 ± 0.01	NS
COD (mg/L)	24.81 ± 10.8 ^{a}	26.89 ± 11.45 ^{a}	36.65 ± 31.71 ^{b}	25.73 ± 22.04 ^{a}	0.007
Chl-a (mg/L)	24.95 ± 22.18 ^{a}	32.26 ± 25.2^a	72.03 ± 51.2 ^{b}	62.43 ± 21.53 ^{a}	0.000

SD, Secchi disk transparency; T, water temperature; DO, dissolved oxygen; TSS, total suspended solid; TN, total nitrogen; TP, total phosphorus; NH_4-N, ammonium; NO_3-N, nitrate; NO_2-N, nitrite; PO_4-P, phosphate; COD, chemical oxygen demand; and Chl-a, chlorophyll a concentration. NS, not significant. Different lowercase letters indicate significant differences between annual values.

To further understand the variations in water quality, water quality parameters that significantly differed among the four years were compared between wet seasons (Spring and Summer) and dry seasons (Fall and Winter) in the same year (Fig. 2). It shows that TSS and Chl-a concentration were higher in wet seasons (respectively from 8.92 to 34.13, 26.37 to126.73) than that in dry seasnons, especially TSS in 2015 and 2017 (P< 0.05) and Chl-a in four years (2013, 2015, 2017 and 2018, P< 0.05). Concentrations of PO_4-P, TN, NO_3-N and COD showed higher values in dry seasons (respectively from 0.12 to 0.34, 1.56 to 11.52, 0.59 to 1.21, 26.05 to 64.0) than that in wet seasons in the study years, especially PO_4-P in 2013, 2015 and 2017, TN in 2015 and 2017, NO_3-N in 2013, 2015 and 2017 and COD in 2017 and 2018 (P < 0.05). TN:TP ratios ranged from 1.85 to 4.43, 3.64 to 16.41 and 4.09 to 8.46, respectively in wet season, dry season and all year, and the TN:TP ratio in dry seasons was higher than that in wet seasons in 2015, 2017 and 2018 (P < 0.05).

Three sediment quality elements OC, TN and TP were analyzed in 2013, 2017 and 2018. Significant increasing trends for concentration of OC (from 2.73 to 9.32), TN (from 1007.5 to 1902.12) and TP (621.46 to 900.01) were observed from 2013 to 2018 (Fig. 3, $P < 0.05$).

Spatial trends

To clarify the spatial variation, the main water and sediment variables with significantly difference in different sampling sites in different years were interpolated with ArcGIS and the maps are presented in Fig. 4 and Fig. 5. The results revealed that TSS condition is better in Lake dahu district than that in district of Lake haizihu and Mahongtai Channel. TN and COD concentration were higher in Lake haizihu district than that in districts of Lake Dahu and Mahongtai Channel, and the phenomenon is more obvious in 2017. PO_4-P concentration was higher in district of Lake haizihu and Lake dahu than that in Mahongtai Channel district. Chl-a concentration was higher in districts of Lake dahu and Mahongtai Channel than that in Lake haizihu district and the phenomenon is more obvious in 2017.

In sediment, TP concentration was higher in districts of Lake haizihu and Mahongtai Channel than that in Lake dahu district. TN and OC concentrations were higher in districts of Lake dahu and Mahongtai Channel than that in Lake haizihu district.

3.2 Eutrophication assessment based on the TLI

TLI based on Chl-a, TP, TN, SD and COD was used to assess the trophic condition of Lake Changhu and it showed variations in average values from 65.77 to 71.64 in the wet season with middle eutropher in 2013 and 2018, while with hyper eutropher in 2015 and 2017. In the dry season, the average TLI values ranged from 62.99 to 78.93 in four years with hyper eutropher in 2017 while it were middle eutropher in other three years. The trends of trophic levels in all year is similar with the dry seasons (Fig. 6).

The TLI values of all sampling sites were interpolated with ArcGIS and the map is presented in Fig. 7. According to the maps, three districts (Lake haizihu, Mahongtai Channel and Lake dahu) all reached middle eutrophic levels in 2013, 2015 and 2018, and the eutrophic levels in Lake haizihu and Mahongtai Channel were significantly higher than that in Lake Dahu (P < 0.05). In 2017, three districts all reached hyper eutrophic levels (Fig. 7).

Pearson linear correlation generated using TLI with 13 water parameters (SD, T, pH, DO, TSS, TP, PO_4-P, TN, NH_4-N, NO_3-N, NO_2-N, COD, Chl-a) and 3 sediment parameters (OC, STN, STP) (Fig. 8). The result showed that TLI had significantly positive relationships with TN (R^2 = 0.376, P< 0.00001), TP (R^2 = 0.377, P< 0.00001) and Chl-a (R2 = 0499, P< 0.00001), while had a significantly negative relationship with STN (R^2 = 0.136, P= 0.021).

3.3 Calculation of Nutrient loading capacity

In order to determine the nutrient (TN and TP) loading capacity before (2015) and after (2018) removing pen culture in Lake Changhu, the mean annual input (W_{in}) and output (W_{out}) of nutrients (TN and TP) to and from Lake Changhu were calculated according to data provided in Conservation planning of Changhu Lake in Hubei Province (WRDHP, 2018). W_{in} included the nutrient inputs from lake precipitation, surface runoff, industrial pollution, large-scale livestock farm pollution, urban domestic sewage, and pen culture pollution. W_{out} included the nutrient outputs from outflow via sluice, the growth of fish released in Lake Dahu, the fish catch of Lake Haizihu fish farm, and pen culture. All W_{in} and W_{out} values in 2015 and 2018 are shown in Table 2. The retention of TN was 2529.34 t/a and of TP was 157.52 t/a in 2015. Meanwhile, in 2018, the retention of TN and TP was 2518.3 t/a and 118.04 t/a, respectively. The retention coefficients of TN and TP were 0.709 and 0.606, respectively, in 2015 and 0.823 and 0.613, respectively, in 2018. Approximately 82% of N and 71% of P input was from sewage outlets and land surface runoff; the rest was from pen culture pollution and precipitation. The nutrient outputs were mainly through water outflow, growth of released fish in Lake Dahu, and fish catch.

Table 2
Statistics of mean annual inputs (W_{in}) and outputs (W_{out}) of total nitrogen (TN) and total phosphorus (TP) in Lake Changhu

	2015		**2018**	
W_{in}	TN (t/a)	TP (t/a)	TN (t/a)	TP (t/a)
Lake precipitation	62.87	3.27	62.87	3.27
Land surface runoff	975.4	40.82	975.4	40.82
Industrial pollution	57.27	-	57.27	-
Large-scale livestock farm pollution	1629.82	96.93	1629.82	96.93
Urban domestic sewage	332.39	48.07	332.39	48.07
Pen culture pollution	509.52	70.65	-	-
Total	3567.27	259.74	3057.75	189.09
W_{out}	TN (t/a)	TP (t/a)	TN (t/a)	TP (t/a)
Outflow by Sluice	385.56	55.33	240.41	49.17
Growth of fish released in Lake Dahu	264.52	21.13	264.52	21.13
Fish catch of Lake Haizihu fish farm	34.52	2.75	34.52	2.75
Fish catch of pen culture	353.33	23.01	-	-
Total	1037.93	102.22	539.45	71.05
Nutrient retention	2529.34	157.52	2518.3	118.04
Retention coefficient	0.709	0.606	0.823	0.613

The permissible nutrient loading capacities in Lake Changhu were calculated using the Dillon model according to equations 8 and 9. When the target water quality was level III, the concentration of TN and TP was 1.0 mg/L and 0.05 mg/L, respectively (GB 3838 – 2002, Ministry of Environmental Protection of China, 2002). The calculated results are shown in Table 3. The predicted TN loading capacity was 2096.55 t/a and TP loading capacity was 77.55 t/a in 2015. Meanwhile, in 2018, the predicted TN and TP loading capacities were 3377.78 t/a and 77.95 t/a, respectively. The actual TN and TP loading capacities were 3567.27 t/a and 259.74 t/a, respectively, in 2015, and 3057.75 t/a and 189.09 t/a, respectively, in 2018. The remaining TN and TP loading capacities were − 1470.72 t/a and − 182.74 t/a, respectively, in 2015, and 320.03 t/a and − 111.14 t/a, respectively, in 2018.

Table 3
The permissible nutrient loading capacity for total nitrogen (TN) and total phosphorus (TP) of Lake Changhu in 2015 and 2018

	2015		2018	
	TN (t/a)	TP (t/a)	TN (t/a)	TP (t/a)
Predicted loading capacity	2096.55	77.55	3377.78	77.95
Actual loading capacity	3567.27	259.74	3057.75	189.09
Remaining loading capacity	-1470.72	-182.74	320.03	-111.14

4. Discussion

The fragile ecosystem of Lake Changhu and the proposal of development activities has aroused the need for the present study, especially as pen culture was totally removed in January 2017 (He et al. 2015; Ni et al. 2018). Lake Changhu is under increasing pressure from an increasing human population density, which is associated with reduced water resources and increasing organic pollution. It was reported that the human population of the Lake Changhu basin had increased to 1.17 million by 2017 (Conservation planning in Hubei Province, Water Resources Department of Hubei Province [WRDHP], 2018). Understanding the trophic status of Lake Changhu can provide an indication of the ecosystem's current structure and function. Such information will help to predict future trends in an ever-changing environment and will be useful for formulating appropriate mitigation strategies.

In this study, water quality elements as the TN, COD, and Chl-a values were significantly higher in 2017 than in 2013, 2015, and 2018 ($P < 0.05$). Meanwhile, the TSS concentration was significantly higher in 2013 and 2017 than in 2015 and 2018 ($P < 0.05$; Table 1). These results indicate that the nutrient and TSS concentrations were higher in 2017 than in the other years despite the fact that the pen culture was removed in the early months of 2017. A major reason for this may be that the lakebed was disturbed and stirred when the pens and cages were removed. This would have released nutrients from the sediment back into the water column. It has previously been reported that mechanically scraping the seabed when fishing can lead to a direct release of nutrients from the sediments, which can enhance primary production in the water column (Dounas et al. 2007; Couceiro et al. 2013; Tiano et al. 2019).

To further understand the variations in water quality, water quality parameters that significantly differed among the four years were compared between wet seasons (Spring and Summer) and dry seasons (Fall and Winter) in the same year (Fig. 2). The TSS and Chl-a concentrations were significantly higher in wet seasons, while the PO_4-P, TN, NO_3-N, and COD values were significantly higher in dry seasons ($P < 0.05$). In the wet seasons, the water temperature ranged from 22.7°C to 33.2°C which could enhance the growth of phytoplankton, leading to the higher Chl-a concentrations. Abundant rainfall in the wet season may wash more sediment into the lake from surrounding farmland, which would account for the higher TSS concentration. In the dry seasons, the lack of water change and low water level may lead to the higher nutrient concentrations. It has previously been reported that an increase in evaporation may also lead to higher pollution concentrations (Zhao et al. 2013). However, a previous study reported the inconsistent result that nutrient concentrations were relatively lower in estuarine areas of Lake Wuli and Lake Taihu in the dry seasons (Wang et al. 2018).

In addition, the TN:TP ratios ranged from 4.09 to 8.46 in the studied years and it was the highest in 2017. This indicates that Lake Changhu displays predictable N limitation. Downing and McCauley (1992) reported that phytoplankton in lakes are significantly more frequently N limited than P limited when the TN:TP mass ratio is below 14. In practice, TN:TP values of less than 10 indicate a N shortage and values greater than 20 indicate a P shortage. Lower TN:TP ratios are observed in eutrophic lakes and high ratio values are observed in mesotrophic and oligotrophic lakes (El-Serehy et al. 2018).

In the sediment, the OC, STN, and STP contents increased from 2013 to 2018 (Fig. 3). This indicates that nutrients accumulate in bottom sediments over time. Bottom sediments are considered as both a nutrient sink and a nutrient source. Thus, bottom sediments play an important role in the nutrient dynamics of shallow Chinese lakes (Zhang et al. 2013).

According to the spatial variation in water quality, the TSS concentration was lowest in the Lake Dahu district, and the TN and COD values were highest in the Lake Haizihu district; this phenomenon was most obvious in 2017. The PO_4-P concentration was highest in the Lake Haizihu and Lake Dahu districts. Meanwhile, the Chl-a concentration was highest in the Lake Dahu and Mahongtai Channel districts. These phenomena were most obvious in 2017. These data indicate that the Lake Haizihu district was more seriously polluted than the other districts. More than 10 industrial pollution sources related to the Lake Haizihu district may account for the higher water pollution (Conservation planning of Changhu Lake in Hubei Province, 2018). Numerous studies have demonstrated that excessive N, P, and OC are among the main causes of water pollution (Zhu, 2008; Zhi et al. 2016; Wang et al. 2018). While the OC and STN contents in sediment were higher in the Mahongtai Channel and Lake Dahu districts than in Lake Haizihu district (Fig. 5). This may be ascribed to the intensive pen culture in the Mahongtai Channel and Lake Dahu districts. The results of this report are analogous to the effects of crab pen culture in Lake Yangcheng, which caused significantly elevated sediment C and N contents (Chen et al. 2015). Marine aquaculture can also increase sediment C, N and P contents, which has been demonstrated by Das et al. (2004) and Huang et al. (2008).

The TLI was used in this study to evaluate the eutrophication status of Lake Changhu despite the fact that cyanobacterial blooms have not occurred in this lake. It showed hyper eutrophic classification in the dry season in 2017 and middle eutrophic classification in the other three years, which was similar to the all-year trends (Fig. 6). According to ArcGIS maps, three districts in Lake Changhu all reached hyper eutrophic levels (Fig. 7). These results confirmed that eutrophication is a serious and current threat in Lake Changhu. Paerl and Paul (2012) highlighted that increasing eutrophication severity will damage the functioning of the water body and may even harm the entire ecological system. Therefore, more attention should be paid to the eutrophication status of Lake Changhu in the future. Especially with respect to the

TN, TP, and Chl-a concentrations, which had a positive correlation with TLI, and STN with a negative correlation with TLI (Fig. 8).

Numerous studies have used model prediction and mass balance calculations to show that N and P are strongly retained in shallow lake ecosystems (Tang and Xie 2000; Saunders and Kalff 2001; Havens and James 2005). According to Dillon model in this study, when the target water quality was level III(GB 3838 – 2002, Ministry of Environmental Protection of China, 2002), the remaining TN and TP loading capacities were − 1470.72 t/a and − 182.74 t/a, respectively in 2015, and 320.03 t/a and − 111.14 t/a, respectively, in 2018. Indicating that Lake Changhu was rich in inorganic N and P, especially before the removal of pen culture. Further, the lake environment is still eutrophic, although it improved after the pen culture removal. From a lake management perspective, to enhance biological functions, the lake water should be replenished with relatively clean water to maintain water quality within an acceptable range. More detailed and long-term monitoring will be necessary to assess the effects of different measures.

5. Conclusions

The TLI and Dillon model were used to assess the eutrophication levels and N and P carrying capacity of Lake Changhu in Jingzhou province, China, before (2013 and 2015) and after (2017 and 2018) removing pen culture. Temporally, the TN, COD, Chl-a, and TSS values in the water column were significantly higher in 2017 than in other years. Spatially, the Lake Haizihu district was predicted to be more seriously polluted than the other two districts. In the sediment, the OC, TN, and TP contents increased from 2013 to 2018. The mean TLI values ranged from 62.99 to 78.93 in the studied years, and the eutrophication level was greatest, and thus, most serious, in 2017. According to the Dillon model, when the target water quality was level III (GB 3838 – 2002, Ministry of Environmental Protection of China, 2002), the remaining TN and TP loading capacities were − 1470.72 t/a and − 182.74 t/a, respectively in 2015, and 320.03 t/a and − 111.14 t/a, respectively, in 2018. These results will assist governments and management organizations in making evidence-based ecological water restoration decisions in Lake Changhu.

Declarations

Ethics approval and consent to participate

Not applicable

Consent for publication

Not applicable

Availability of data and materials

Not applicable

Competing interests

The authors declare that they have no competing interests

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Authors' contributions

Xuemei Li conceived and designed the experiments, performed the experiments, analyzed the data, wrote the paper, prepared figures and/or tables, reviewed drafts of the paper. Tingbing Zhu conceived and designed the experiments, reviewed drafts of the paper. Yongfeng He prepared figures and/or tables, reviewed drafts of the paper. Xingbing Wu and Yongjiu Zhu designed and performed the experiments, contributed reagents/materials/analysis tools, reviewed drafts of the paper. Deguo Yang conceived and designed the experiments, contributed reagents/materials/-analysis tools, wrote the paper, reviewed drafts of the paper. All authors commented on previous versions of the manuscript, read and approved the final manuscript.

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Figures

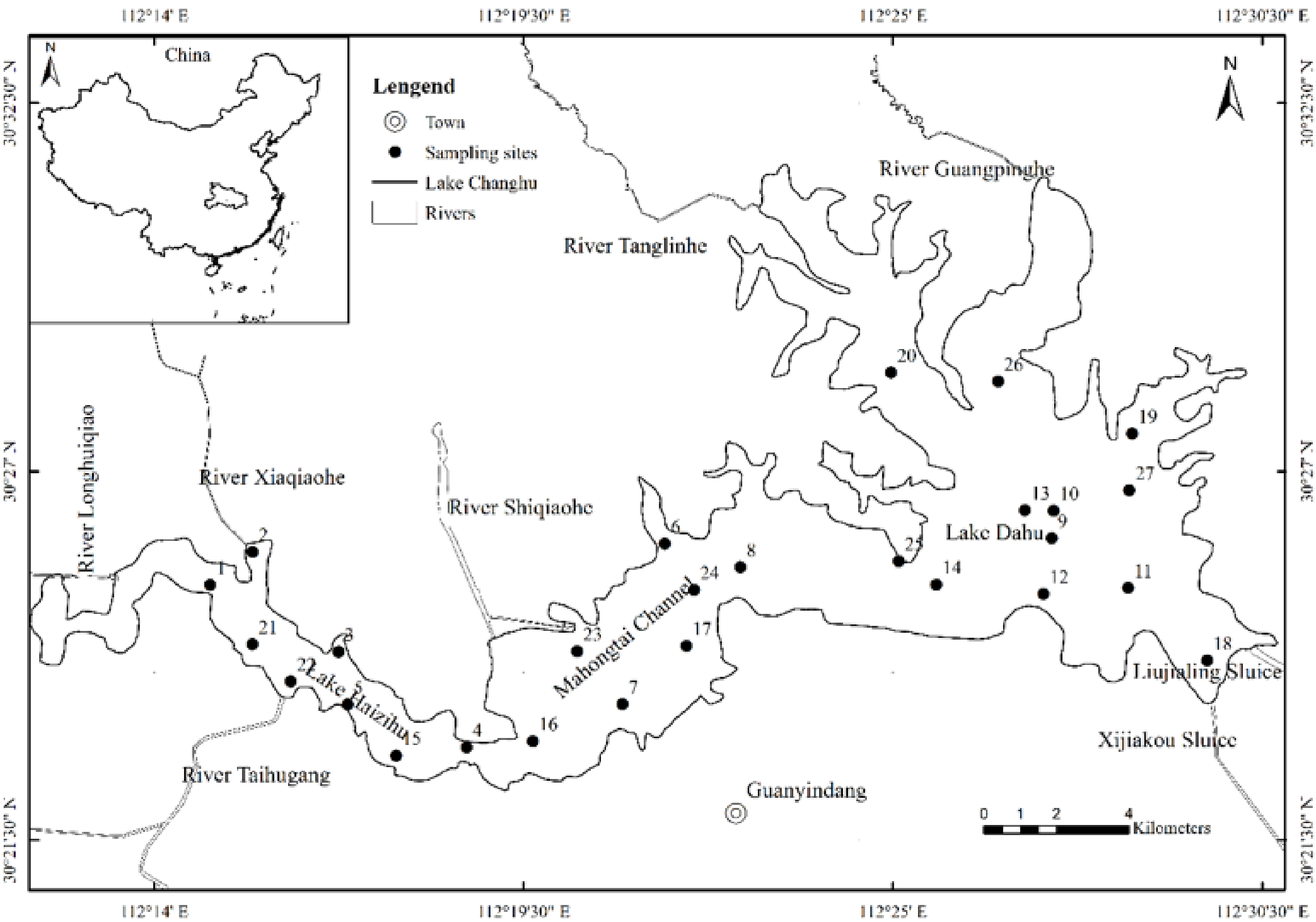

Figure 1

Location map of the study area and sampling sites in Lake Changhu, China. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

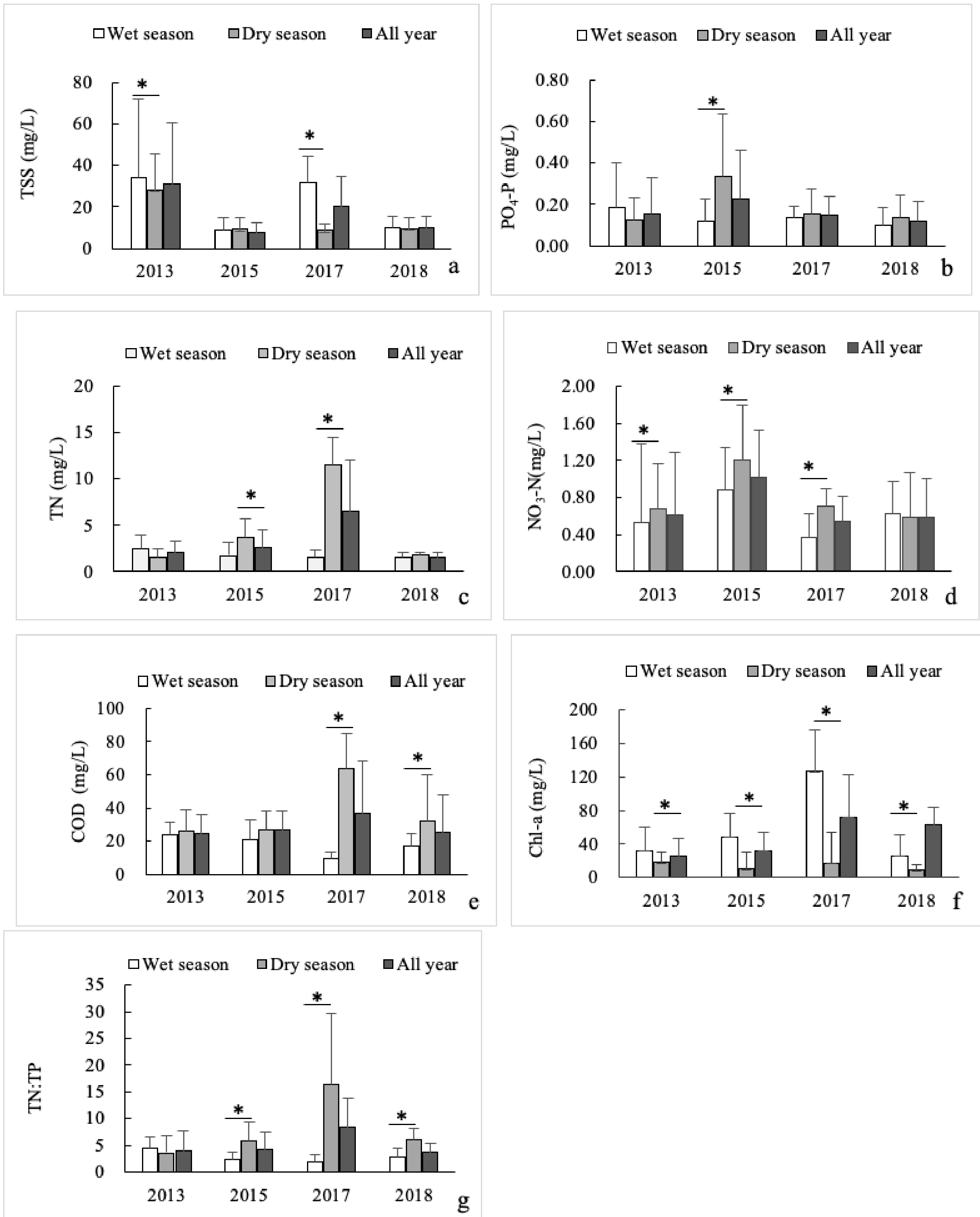

Figure 2

Seasonal variation in water physicochemical parameters in Lake Changhu. (a) The total suspended solid (TSS); (b) phosphate (PO4-P); (c) total nitrogen (TN); (d) nitrate (NO3-N); (e) chemical oxygen demand (COD); (f) chlorophyll a (Chl-a); and (g) total nitrogen to total phosphorus ratio (TN:TP).* represents the significant differences between seasons within different years.

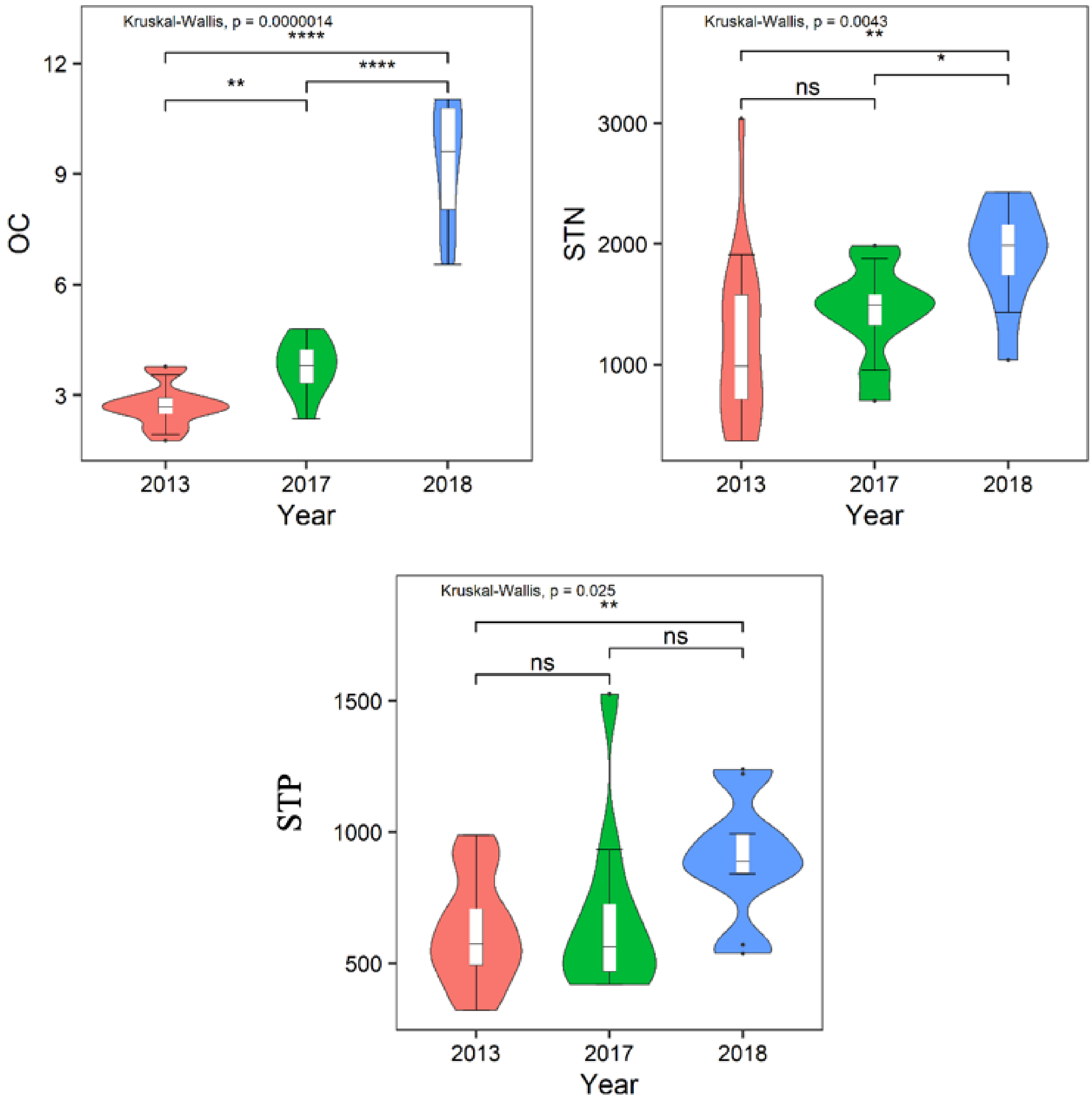

Figure 3

Sediment nutrient content variations in Lake Changhu in 2013, 2017, and 2018. OC, organic matter; STP, total phosphorus in the sediment; STN, total nitrogen in the sediment. * represent significant differences between different years

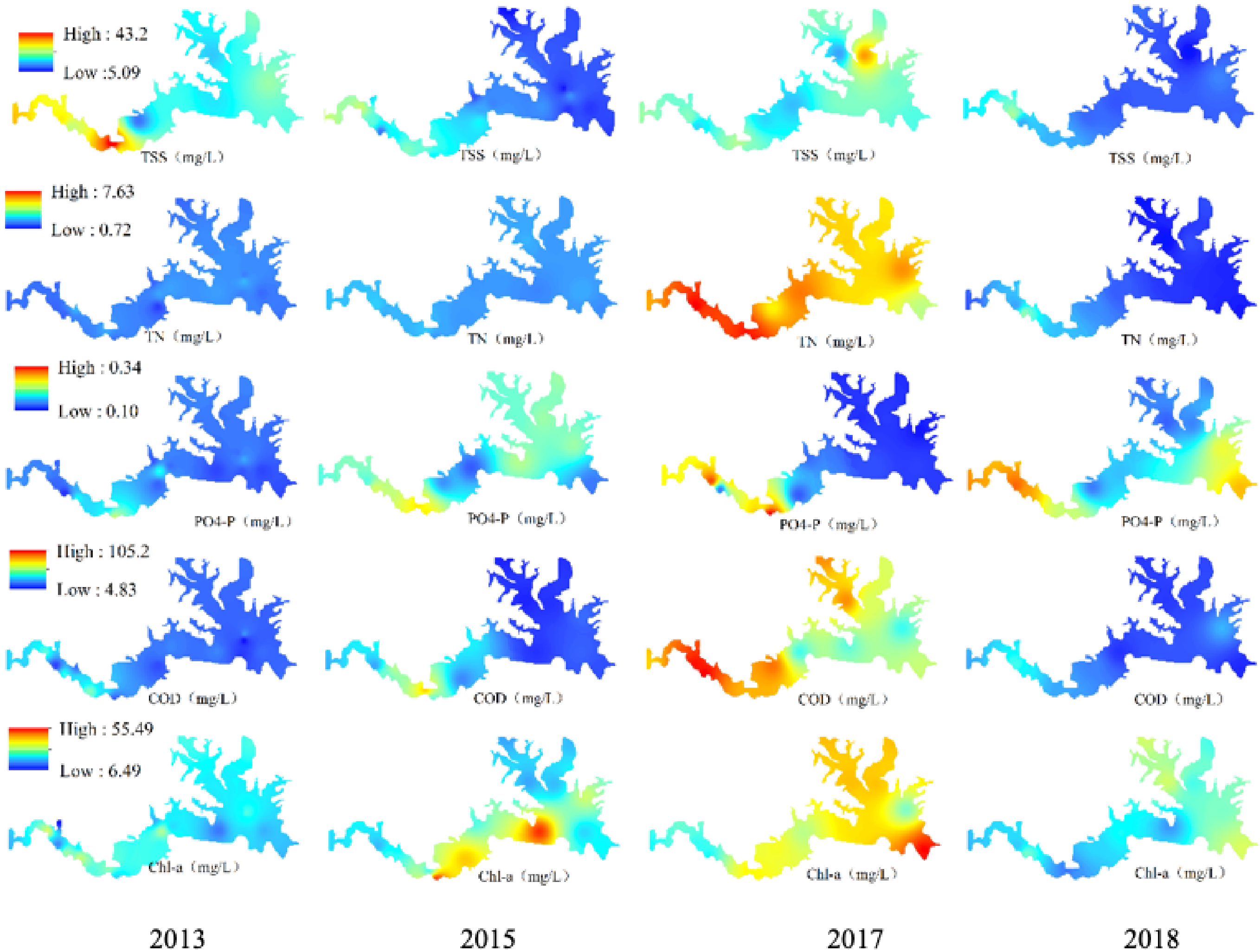

Figure 4

Spatial distribution of water physicochemical parameters that significantly differed in different years in Lake Changhu. TSS, total suspended solid; TN, total nitrogen; PO4-P, phosphate; COD, chemical oxygen demand; and Chl-a, chlorophyll a. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

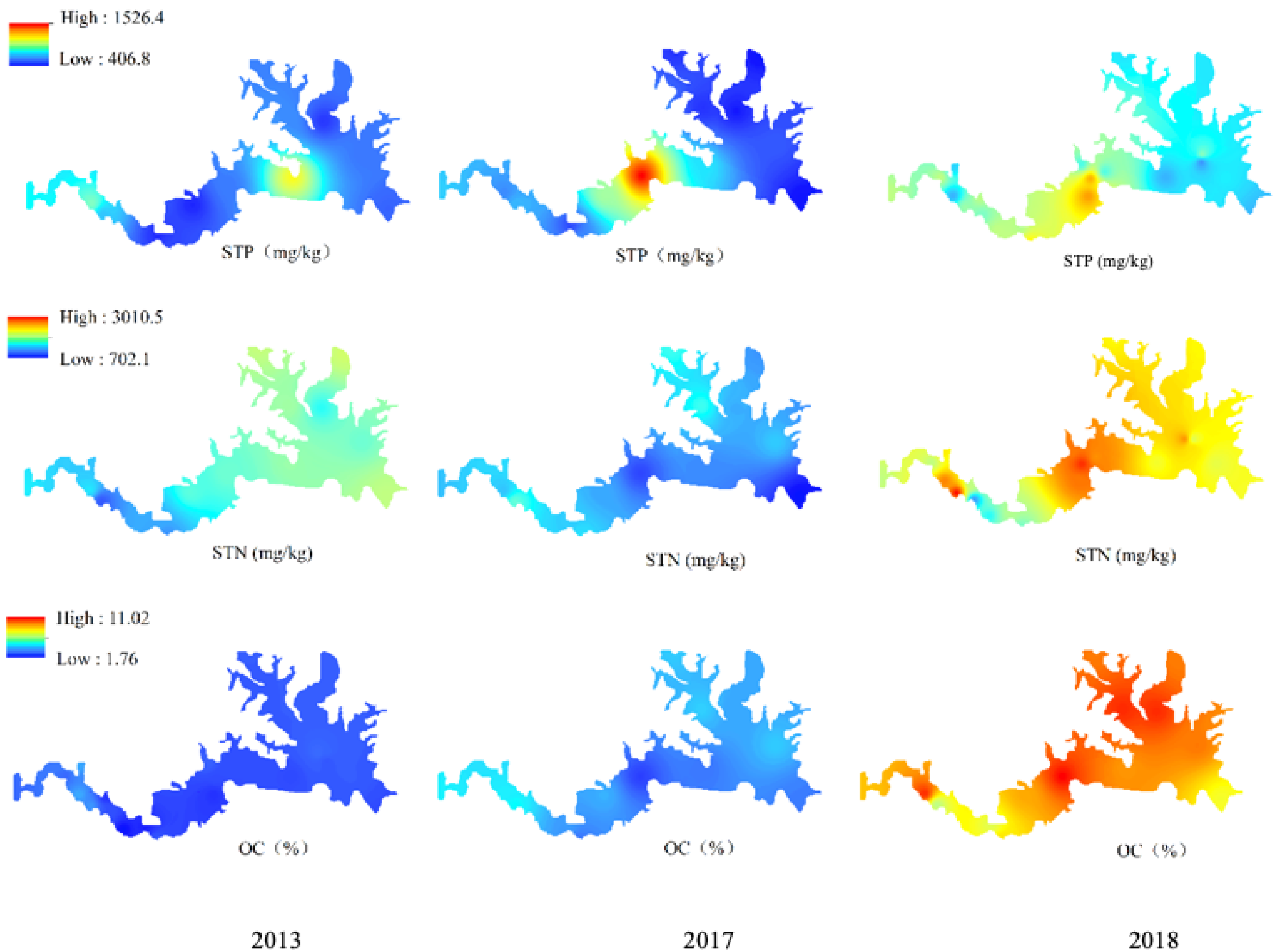

Figure 5

Spatial distribution of sediment nutrient contents in different areas of Lake Changhu in different years. STP, total phosphorus in the sediment; STN, total nitrogen in the sediment; OC, organic matter. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

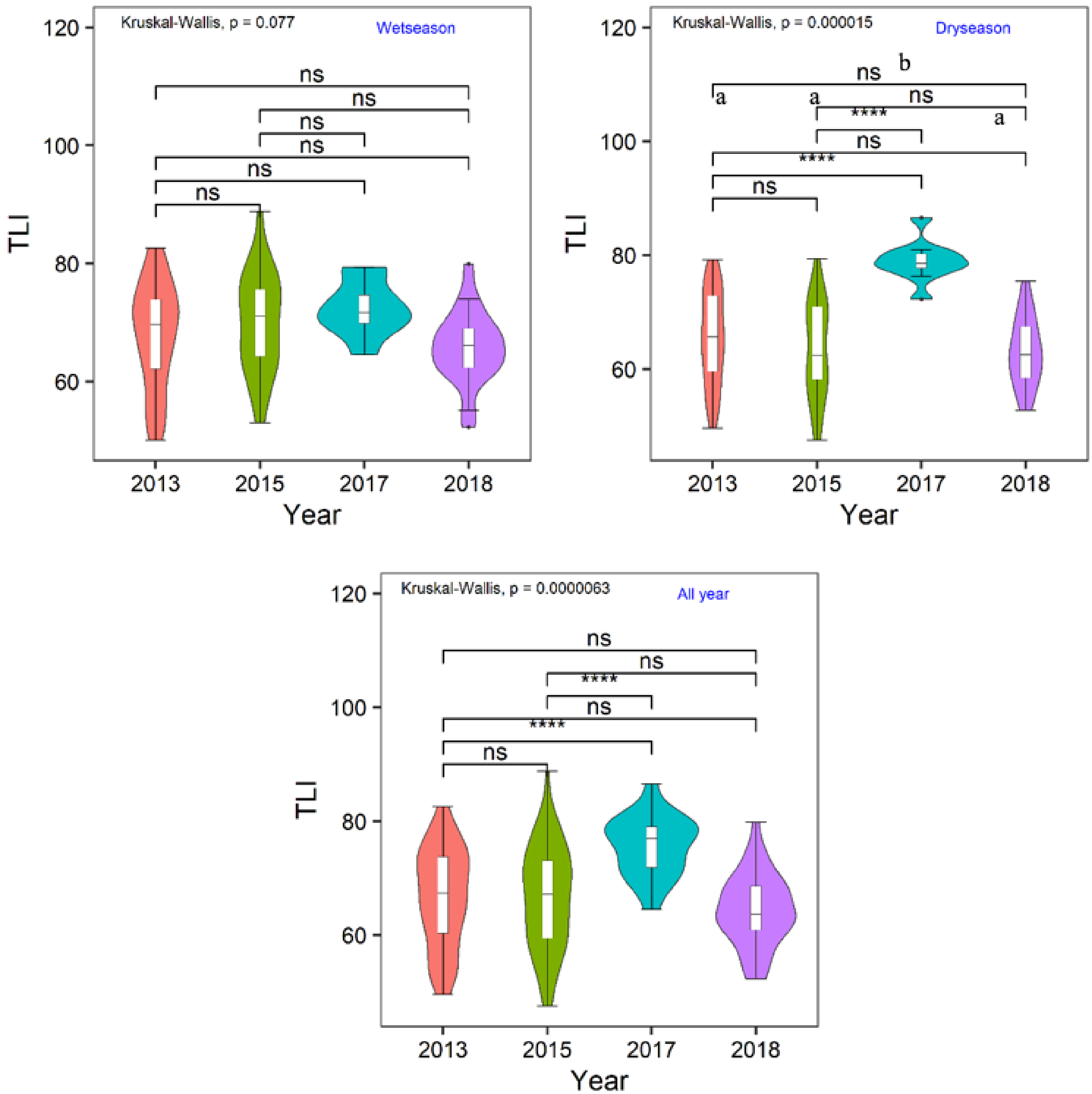

Figure 6

The changes in trophic level index (TLI) in Lake Changhu from 2013 to 2018 in the wet season, dry season and all year. * indicates significant differences between years, and “ns” indicates no significant difference.

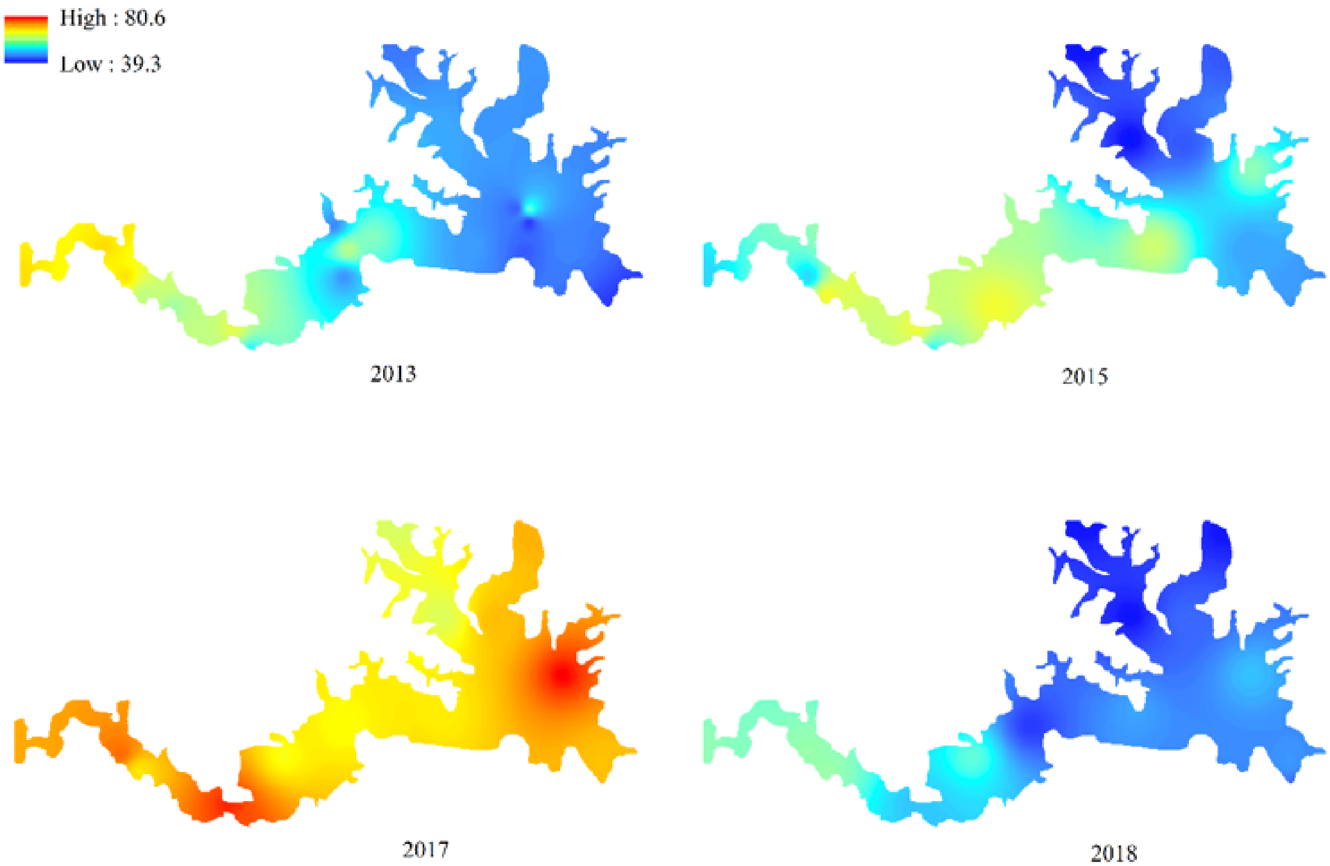

Figure 7

Spatial distribution of trophic level index (TLI) in different areas of Lake Changhu from 2013 to 2018. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

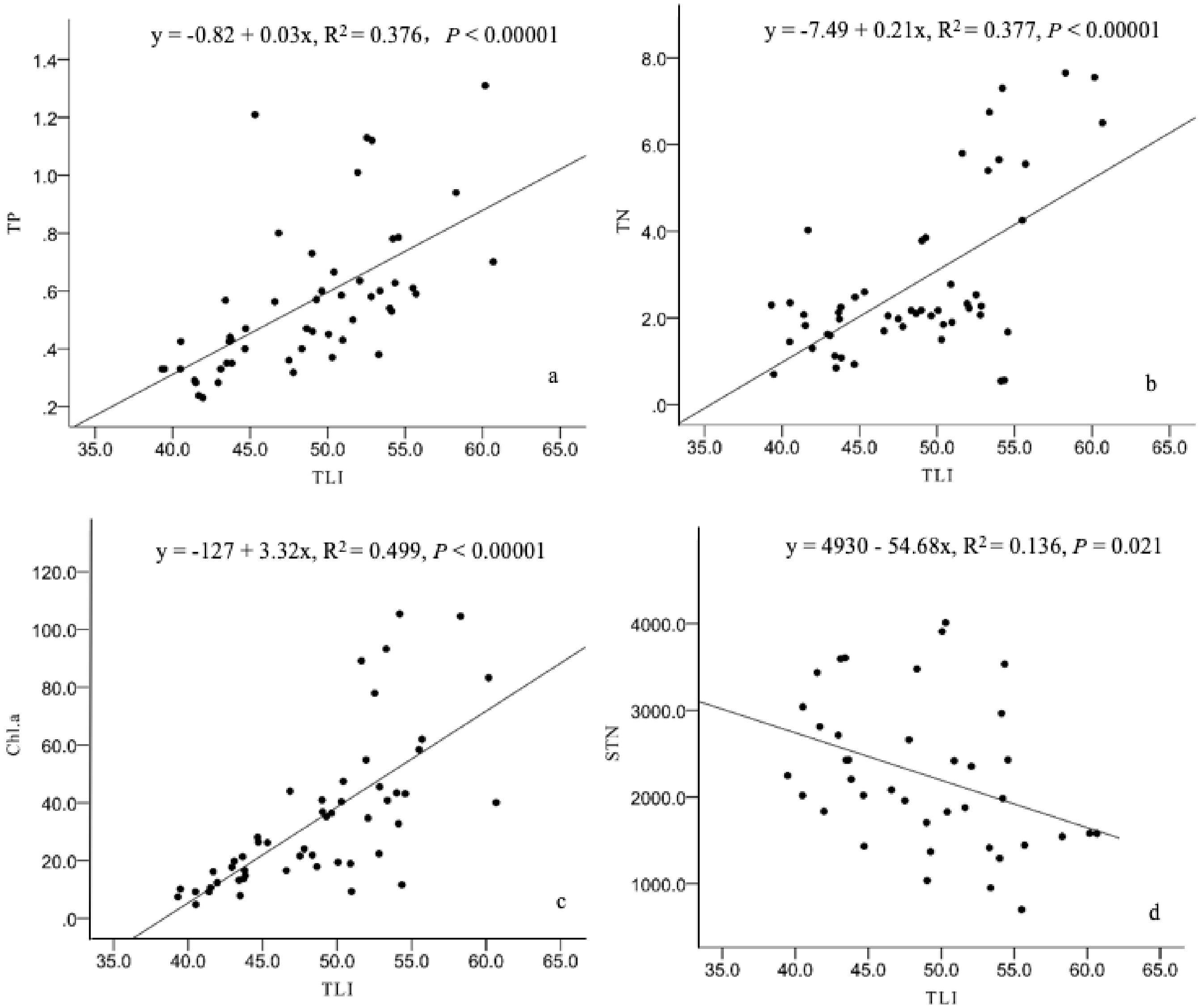

Figure 8

Relationships between trophic level index (TLI) and (a) total phosphorus (TP), (b) total nitrogen (TN), (c) chlorophyll a (Chl-a) and (d) TN in the sediment (STN) in Lake Changhu over four years.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- TableS1.docx