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Nitrogen concentration response to the decline in atmospheric nitrogen deposition in a hypereutrophic lake☆

Xingyu Jiang, Guang Gao *, Jianming Deng, Guangwei Zhu, Xiangming Tang, Keqiang Shao, Yang Hu

State Key Laboratory of Lake Science and Environment, Nanjing Institute of Geography and Limnology, Chinese Academy of Sciences, Nanjing, 210008, China

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ABSTRACT

Atmospheric nitrogen (N) deposition is becoming an increasingly important factor affecting the nutrient level of lakes, especially considering the long-term control measures for external N inputs in developed regions. However, few studies have investigated the effects of atmospheric N deposition and the respective ecological significance in eutrophic waters. In this study, bulk and wet deposition rates of all N species and water N concentrations in Lake Taihu were determined based on the long-term (2010–2018) high-resolution (weekly or monthly) systematic observations. The results indicated that the decline in wind speed and change in land-use type likely decreased the N deposition rate. The bulk N deposition rates decreased from 45.77 kg N ha^{-1} yr^{-1} in 2012 to 22.06 kg N ha^{-1} yr^{-1} in 2018, which could account for decrease of 1.01 mg N L^{-1} in the lake N concentrations via a rough estimation, and this value was close to the actual variation in N concentration in Lake Taihu. The correlation between N concentrations and atmospheric deposition fluxes was stronger than that between N concentrations and riverine N inputs or lake storage, which further indicated that change in atmospheric N deposition was the key reason for the variation in N concentrations. The direct bulk N deposition into Lake Taihu accounted for 17.5% and 51.4% of the riverine N inputs and lake N inventory, respectively. Moreover, atmospheric N deposition was concentrated in summer, which was dominated by reduced N, and it may be important for the duration of algal blooms. Therefore, external N inputs, including atmospheric N deposition, should be further controlled for an effective mitigation of eutrophication and algal blooms in Lake Taihu.

1. Introduction

Anthropogenic activities have increased the amount of nitrogen (N) circulating in the biosphere by more than 100%, which has led to a shift from N loads improvement for food production to environmental damage (Elser et al., 2009; Vitousek et al., 1997). This alteration is considered as one of the most serious threats to the global ecosystem (Camarero and Catalan, 2012). Atmosphere deposition is a major pathway of anthropogenic N input into ecosystems (Elser et al., 2009). Atmosphere N deposition has increased by approximately 300% since preindustrial times, especially in East and South Asia (Galloway et al., 2004; Wang et al., 2015a). Reactive N, deposited in aquatic ecosystems via wet and dry deposition, can alter the biogeochemical cycling and affect the nutrient levels (Elser et al., 2009; Liu et al., 2013). Therefore, a reliable estimation of the contribution and influence of atmospheric N deposition is fundamental to understand the N budget and eutrophication of water bodies (Castro and Driscoll, 2002; Zhan et al., 2017).

Previous studies have shown that atmospheric N deposition significantly affects water N concentrations and the stoichiometric ratio of N to phosphorus (P) (Camarero and Catalan, 2012; Guieu et al., 2014). Especially in oligotrophic waters, nutrient levels can be closely related to atmospheric deposition. In Europe and north America, there is a good correlation between water N concentration and atmospheric N deposition flux (Crowley et al., 2012; Elser et al., 2009; Meunier et al., 2016). However, the effects of atmospheric N deposition on eutrophic lakes have not been widely studied, because external N inputs from watersheds are normally considered the primary causes of changes in nutrient levels of eutrophic waters. Recent studies have reported that lakes tend to show an increasing propensity for N limitation as they become more eutrophic (Paerl et al., 2015; Sterner, 2008). Especially in shallow

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* Corresponding author.
E-mail address: guanggao@niglas.ac.cn (G. Gao).

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eutrophic lakes, algal blooms can amplify the N loss via denitrification by providing abundant organic carbon sources (Qin et al., 2020). Furthermore, as developed regions increasingly apply long-term control of point and nonpoint pollution sources, atmospheric N deposition is becoming an increasingly dominant N source to these eutrophic waters (Zhan et al., 2017).

Atmospheric N deposition, especially wet deposition of inorganic N, has been systematically measured in China (Jia et al., 2014). However, it is difficult to compare or evaluate the temporal characteristics of N deposition, because of the differences in sampling and analytical methods (Chen et al., 2018; Ti et al., 2018; Zhan et al., 2017). In addition, it is also difficult to establish the relationship between N deposition and the nutrient level of lakes, and evaluate the respective ecological effects based on short-term observations. Short-term observations have a high uncertainty, because atmospheric N deposition is especially susceptible to occasional or extreme meteorological events (Rojas and Venegas, 2010; Simkin et al., 2016). Therefore, long-term monitoring data with high-resolution are of great importance for such assessments.

In Lake Taihu, China, a series of nutrient management strategies to prevent harmful algal blooms have been implemented since the 2007 drinking water crisis (Paerl et al., 2011; Reidsma et al., 2012). However, the algal biomass has increased, and the extent and maximum area of algal blooms have not shown decreasing trends in the last decade (Qin et al., 2019). Although climate warming and lower wind speeds in winter and spring can promote algal blooms (Deng et al., 2020; Qin et al., 2021), these algal growths have been mainly attributed to high nutrient levels. In this context, previous studies have shown that atmospheric N deposition can significantly affect N loads and algal growth in lake ecosystems such as Taihu (Zhai et al., 2009), Dianchi (Zhan et al., 2017), and Victoria (Bakayoko et al., 2021). Therefore, in Lake Taihu, the contribution of atmospheric N deposition for the occurrence and intensity of algal blooms may be increasing, especially considering the reduction in external N inputs through the established measures to control eutrophication.

The primary objective of this study is to test the hypothesis that the changes in atmospheric N deposition affects N concentrations in the eutrophic Lake Taihu. The study is based on long-term (2010–2018) high-resolution (weekly or monthly) systematic observations of atmospheric N deposition and water nutrients concentration. Bulk and wet deposition rates of all N species and lake N concentrations were determined to estimate the response of nutrient dynamic to atmospheric deposition. Furthermore, we analyzed the contribution of atmospheric N deposition to lake N budget and its implications for the nutrient management of eutrophic lakes.

2. Materials and methods

2.1. Description of study area

Lake Taihu is located in the central area of the Yangtze River delta and is the third largest freshwater lake in China, with an area of approximately 2,338 km^2. It is a typical shallow (mean depth <3 m) and hypereutrophic lake with frequent and intense algal blooms (mostly cyanobacteria) (Qin et al., 2010; Qin et al., 2019). The annual average temperature in 2018 was 17.8 °C, and the lowest and highest temperatures occurred in January (3.7 °C) and July (29.5 °C), respectively. The mean annual precipitation in the Lake Taihu Basin from 2010 to 2018 was 1281 mm, and rainfall intensity is normally higher in summer. The daily average and maximum wind speed during the study period was 2.66 and 5.18 m s^{-1}, respectively. The prevailing wind direction is southeast wind in summer, and the prevailing wind direction is northwest wind in winter.

The monitoring sites of atmospheric N deposition were established in the northern part of Lake Taihu, at the pier of the Taihu Laboratory for Lake Ecosystem Research (TLLER), Nanjing Institute of Geography and Limnology, Chinese Academy of Sciences (31.419N, 120.214E). Three parallel sampling sites were set on the shore of Lake Taihu (Fig. 1).

2.2. Sample collection

Precipitation samples were collected for all rainfall or snow events >5 mm from January 2010 to December 2018. Plastic buckets (20 cm inner diameter, 28 cm height) were placed at the sampling sites within 5–10 min of the start of the precipitation event and were removed after each event. The precipitation and other meteorological data were monitored simultaneously. Throughout the study period, 345 precipitation events were monitored. Bulk deposition was monitored using the standard method in GB/T15265-94 published by the Ministry of Ecology and Environment of the People's Republic of China. The sampler consisted of a glass beaker (14 cm inner diameter, 26 cm height) and a mesh (1 mm pore size) to avoid contamination. The beakers were washed and filled with deionized water to maintain a water level of approximately 3–5 cm. The water volume was monitored regularly and deionized water was supplied to ensure that there was enough water to intercept dry deposition. Samples were collected approximate 1–3 times each month according to the number of raining days. After sampling, precipitation and bulk samples were immediately transported to the nearby laboratory for analysis of total nitrogen (TN), total dissolved nitrogen (TDN), ammonium (NH_4^+-N), and the sum of nitrate and nitrite (NO_x^--N). All buckets and beakers were cleaned with deionized water and stored in plastic bags for the next use.

A long-term water quality monitoring was conducted based on the routine cruises of TLLER throughout the same study period. In the northern part of Lake Taihu, water samples were collected monthly at 13 sites to determine the TN concentrations. Details on the sampling procedure have been described by Qin et al. (2019).

2.3. Chemical analysis

The samples retrieved were divided in two parts. One part was immediately filtered through Whatman GF/F glass fiber filters (47 mm diameter) to determine the concentrations of TDN, NH_4^+-N, and NO_x^--N. Subsequently, all samples were refrigerated at 4 °C and analyzed within 48 h of sampling. The concentrations of TN, TDN, NH_4^+-N, and NO_x^--N were analyzed using standard methods for observation of lake eutrophication (Jiang et al., 2019). The concentrations of TN and TDN were determined by spectrophotometry after digestion with alkaline potassium persulfate. The concentrations of NH_4^+-N were determined using the nesslerization colorimetric method. The concentrations of NO_x^--N were determined using the phenol disulfonic acid ultraviolet spectrophotometric method.

2.4. Calculation of wet and bulk N deposition rates

The monthly wet deposition rate was calculated using Eq. (1):

$$R_{wet} = k\left(\sum_{i=1}^{n} C_i P_i\right) \quad (1)$$

where R_{wet} is the monthly wet deposition rate (kg N ha^{-1} mo^{-1}), k is the constant for unit conversion ($k = 10^{-2}$), n is the number of precipitation events in one month, C_i is the measured N concentration (mg N L^{-1}) in collected rainwater, and P_i is the amount of precipitation (mm) in event i.

The monthly bulk deposition rate was calculated using Eq. (2):

$$R_{bulk} = k\left(\sum_{i=1}^{n} C_i V_i\right) \Big/ S \quad (2)$$

where R_{bulk} is the monthly bulk deposition rate (kg N ha^{-1} mo^{-1}), k is the constant for unit conversion ($k = 10^{-2}$), n is the number of samplings in one month, C_i is the measured N concentration (mg N L^{-1}) in collected

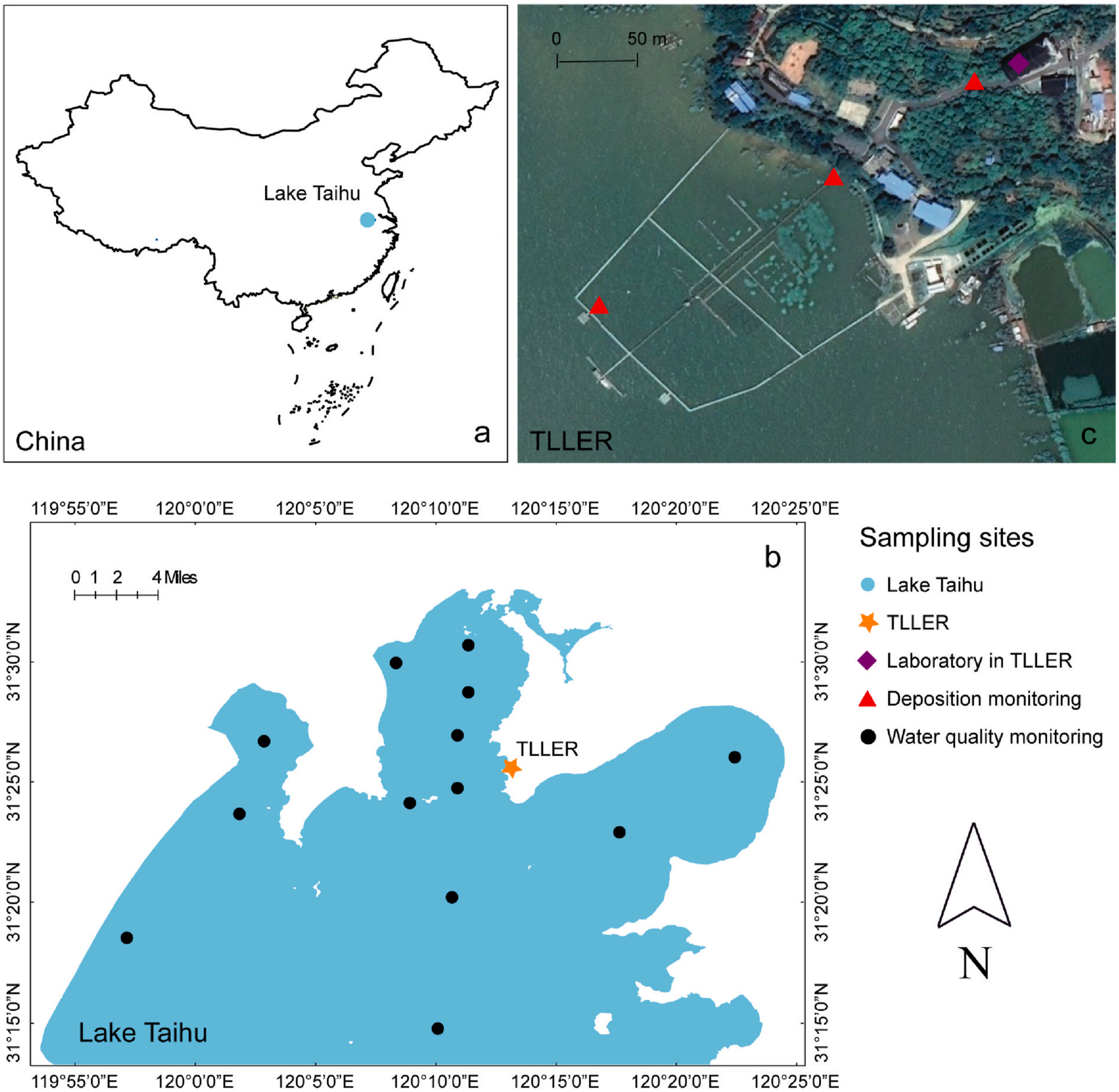

Fig. 1. Map of sampling sites: (a) China, (b) northern area of Lake Taihu, and (c) Taihu Laboratory for Lake Ecosystem Research (TLLER).

samples, V_i is the volume of samples (L) in each sampling, and S is the surface area of the bucket (m^2). The annual N deposition rates (kg N ha^{-1} yr^{-1}) were calculated as the sum of the monthly deposition rates in a year.

2.5. Mass balance analyses in Lake Taihu

According to the area of Lake Taihu and the annual rates of bulk TN deposition, the annual fluxes of TN deposited into the lake were calculated. The annual TN inputs and outputs from rivers in Lake Taihu throughout the study period were obtained from the Taihu Health Report of the Taihu Basin Authority (http://www.tba.gov.cn/). According to the monthly average concentrations of TN and lake storage, a TN inventory was created for Lake Taihu. The monthly average storages were obtained from the Monthly Report of Water Regime in Taihu Basin between January 2010 and December 2018 (http://www.tba.gov.cn/). The changes in the TN inventory ($\Delta TN_{inventory}$) of the water column of Lake Taihu were calculated according to the values obtained in the beginning and end of a year. Ecosystem N retention ($TN_{retention}$) was assessed based on the mass balances of the inputs (TN_{in}: riverine inputs and atmospheric deposition), outputs (TN_{out}: riverine outputs), and $\Delta TN_{inventory}$.

$$TN_{retention} = TN_{in} - TN_{out} - \Delta TN_{inventory} \quad (3)$$

2.6. Statistical analyses

The statistical analyses were performed using R 3.5.3 and the RStudio 1.1.462 interface. The trends were obtained using Kendall's coefficient and local regression (Loess) smoothing for straight lines and curves, respectively. The significance of linear trends was tested based on the mean result of the nonparametric Mann–Kendall test. Independent-samples t-test (2-tailed) was used to evaluate the differences between group means at the 95% confidence interval ($p < 0.05$). Pearson correlation was used to examine the relationships between N deposition rates and meteorological factors. Significance was determined at $p < 0.05$. Data visualization was performed using the package "ggplot 2" in R.

3. Results and discussion

3.1. Factors influencing atmospheric N deposition

The basin of Lake Taihu is one of the hot areas for atmospheric N deposition (Han et al., 2014; Zhu et al., 2015), and the annual bulk deposition rates ranged from 22.06 kg N ha^{-1} yr^{-1} in 2018 to 45.77 kg N ha^{-1} yr^{-1} in 2012 (Fig. 2a). These values were substantially higher than those in most areas of China (Han et al., 2014; Zhu et al., 2015). Atmospheric N deposition has been widely reported in Lake Taihu Basin, but most studies focused on wet deposition (Luo et al., 2007; Wang et al., 2015b). In this study, the annual wet deposition rates ranged from 16.37 kg N ha^{-1} yr^{-1} in 2013 to 28.73 kg N ha^{-1} yr^{-1} in 2010 (Fig. 2b), which was close to most values nearby Lake Taihu, such as 20.0 kg N ha^{-1} yr^{-1} in 2002–2003 (Luo et al., 2007), 19.9 kg N ha^{-1} yr^{-1} in 2007 (Zhai et al., 2009), 16.7 kg N ha^{-1} yr^{-1} in 2013–2014 (Wang et al., 2015b) and 19.3 kg N ha^{-1} yr^{-1} in 2018 (Xu et al., 2019). In this study, the proportion of wet deposition accounting for bulk deposition fluctuated from 43.55% to 87.90% (average of 68.09%), which was similar to the values from May to November 2007 in TLLER (Zhai et al., 2009) and North China Plain (Liu et al., 2006; Zhang et al., 2008). Ti et al. (2018) reported that wet N deposition accounted for 45.5% on average of the total deposition in the Lake Taihu region. Bulk deposition denotes the deposition flux from wet and partial dry deposition (Liu et al., 2015). Therefore, the proportion of wet deposition in this study was higher than the values reported by Ti et al. (2018).

Factors such as wind speed and land-use type can significantly influence atmospheric N deposition (Han et al., 2014; Liu et al., 2013; Ti et al., 2018; Zhu et al., 2015). The mean and maximum wind speeds in the Lake Taihu Basin decreased by approximately 10% from 2010 to 2018 (Fig. 2c and d). Meanwhile, the bulk and wet N deposition at the monitoring sites showed a decreasing trend, which was closely associated with the changes in wind speeds (Fig. 3a and b). The production and emission of aerosols usually depend on wind speed (Meira et al., 2007; Huang et al., 2018). Therefore, a decrease in wind speed leads to the reduction in N emission flux and transmission distance. Accordingly, changes in wind speed might decrease the N deposition rates in Lake Taihu Basin.

In addition to wind speed, changes in land-use type can significantly affect N deposition rates. In this study, reduced N was dominant among the deposited atmospheric N (Fig. S1). Deposited NH_4^+-N mainly derives from ammonia emissions by agricultural sources, such as cultivated land, gardens and pasture land (Elser et al., 2009; Geng et al., 2021). The government encouraged the change in land-use type from agricultural land to forestland or wetland to improve water quality since 2007. In the surrounding areas of Lake Taihu (Jiangsu Province, Zhejiang Province and Shanghai Municipality), wetland areas, including natural and constructed wetlands, increased from 27,966 km^2 in 1995–2003 to 43,975 km^2 in 2013 (National Bureau of Statistics, 2009−2013). In addition, parks and green land areas in cities gradually increased from 2009 to

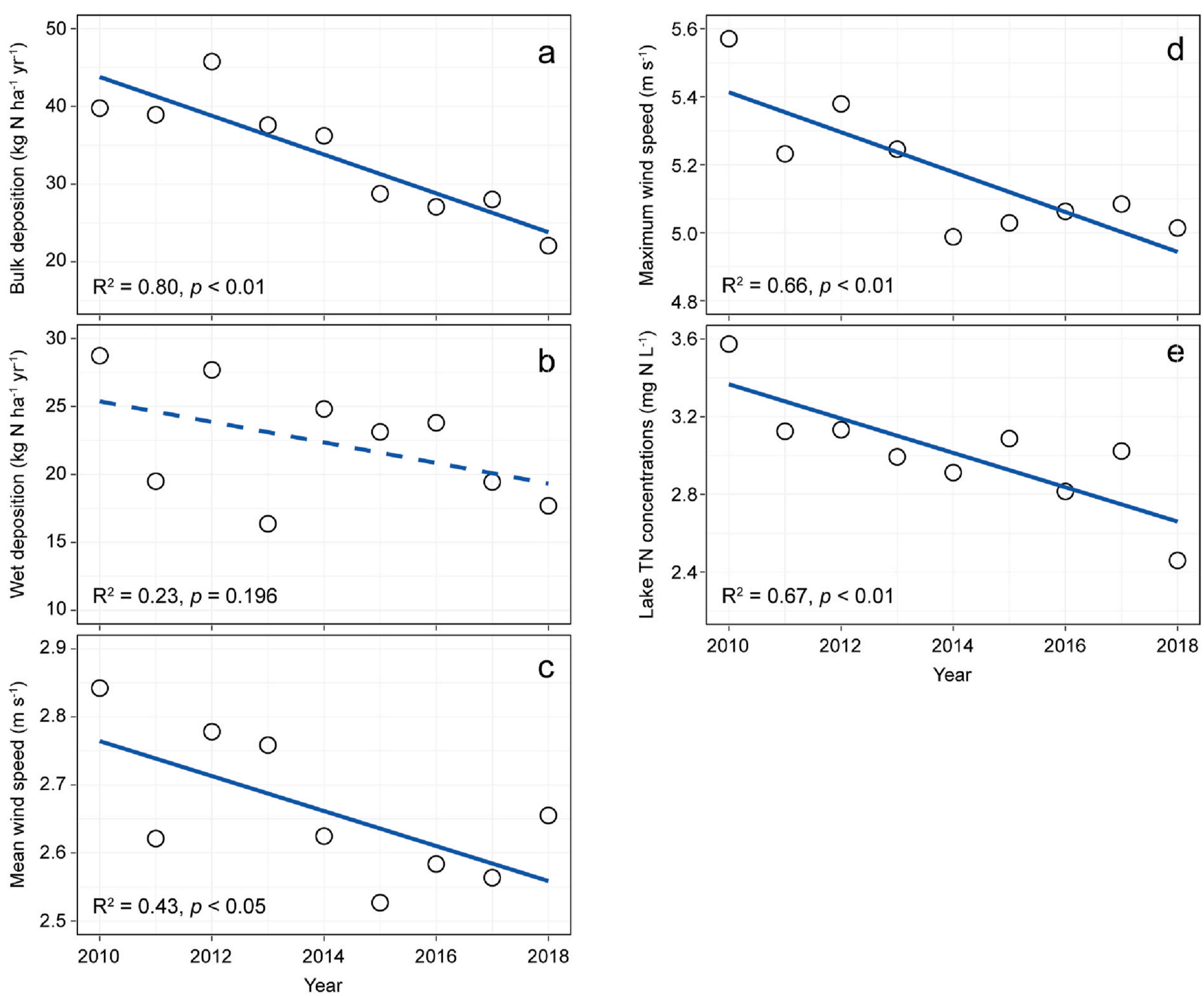

Fig. 2. Annual (a) bulk and (b) wet deposition of total nitrogen (TN); annual (c) mean and (d) maximum wind speeds; and (e) TN concentration in Lake Taihu. Solid and dashed blue lines are significant ($P < 0.05$) and nonsignificant ($P > 0.05$) Kendall's overall trend lines, respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

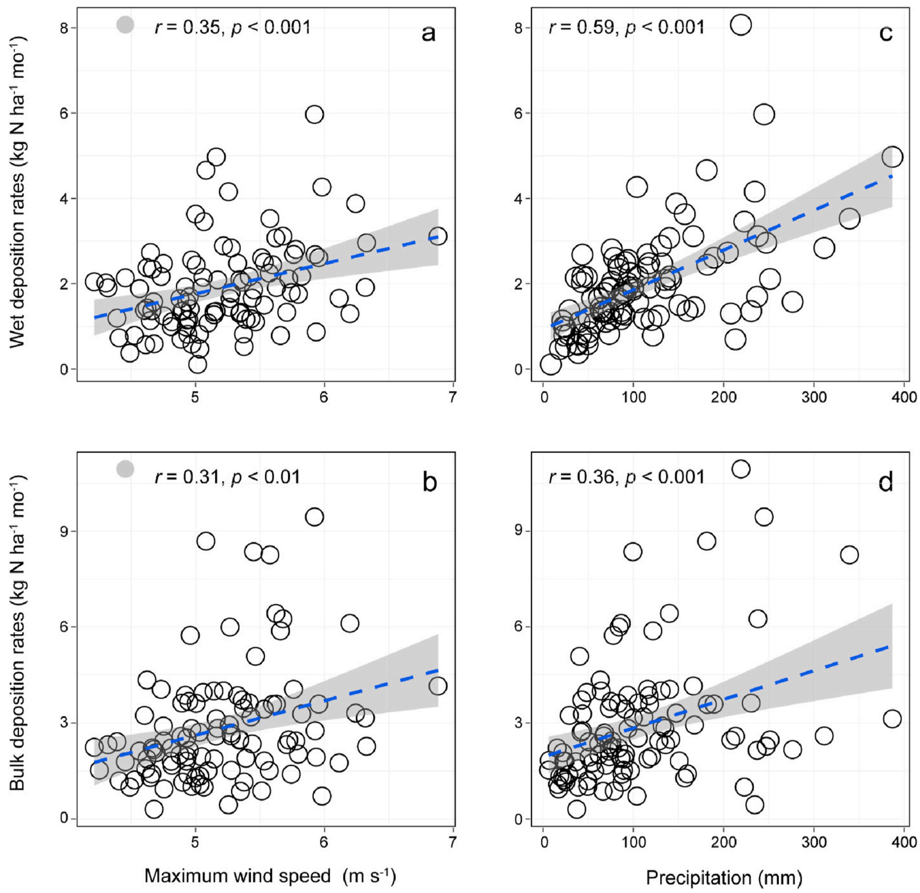

Fig. 3. Correlation between N deposition rates and meteorological factors (precipitation and maximum wind speed). Linear fits were performed (dashed blue lines), and the gray areas represent 95% confidential intervals. Gray solid circles were considered abnormal values and removed from the analysis of Pearson correlation in a and b. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

2016 (Fig. S2). Geng et al. (2021) recently reported that agricultural expansion in northwest Taihu Basin reached its peak in 2013, and then gradually decreased. These changes were likely crucial to the decrease in atmospheric N deposition (Lu et al., 2016).

3.2. Responses of lake TN concentrations to interannual variations in N deposition

The long-term and high-resolution observations of atmospheric N deposition and the simultaneous measurements of N concentrations in Lake Taihu provide a new insight into the influence of N deposition to the nutrient level of a typical hypereutrophic lake. Data from routine cruises in Lake Taihu from 2010 to 2018 show a clear shift toward lower N concentrations, in which TN decreased by 1.11 mg N L^{-1} (Fig. 2e). The atmospheric N deposition flux was significantly correlated with the N concentration in Lake Taihu (Fig. 4). In addition, TN deposition fluxes decreased by 0.58 kton yr^{-1} (1 kton = 10^6 kg). The decline in atmospheric N deposition from 2010 to 2018 could cause a decrease in TN of approximately 1.01 mg L^{-1}, which was close to the actual variation in N concentration. Therefore, the decrease in atmospheric N deposition is a plausible explanation for the observed pattern of decreasing N concentrations in Lake Taihu.

Riverine N inputs and outputs are normally considered the primary causes of the variation in lake N loads (Chen et al., 2011; Mooney et al., 2020). Annual N loading in and out of Lake Taihu from rivers showed a high fluctuation (Table 1), which was closely associated with discharge in inflow (Fig. S3). Riverine N inputs can directly affect lake N concentrations over riverine N outputs. However, lake N concentration was weakly correlated with riverine N input from 2010 to 2018 compared to its correlation with atmospheric N deposition (Fig. 4). Consequently, although external N inputs from rivers are high compared to atmospheric N deposition, riverine inputs might not be the major factor causing the decrease in N concentrations of Lake Taihu.

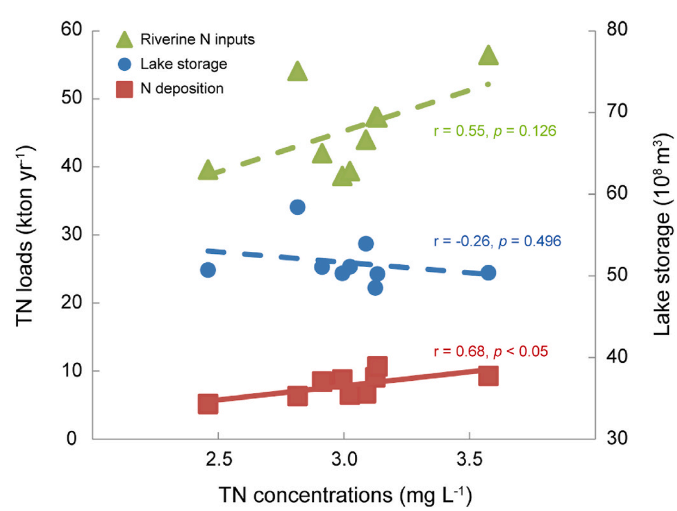

Fig. 4. Correlation between total nitrogen (TN) and influencing factors (riverine TN inputs, TN deposition, and lake storage). Linear fits were performed, and solid and dashed lines indicate significant ($P < 0.05$) and nonsignificant ($P > 0.05$) correlations, respectively.

Nitrogen retention includes denitrification, N sedimentation, and

Table 1
Mass balances of total nitrogen (TN) inputs, outputs, and changes in inventory ($\Delta TN_{inventory}$) in the water column of Lake Taihu at annual scales. TN inputs include hydrologic transport from surrounding rivers ($TN_{riverine\ inputs}$) and direct deposition to the lake surface ($TN_{deposition}$). TN outputs include those occurring via river outflow ($TN_{riverine\ outputs}$) and retention by sediments and aquatic organisms ($TN_{retention}$). Units are kton yr^{-1} (1 kton = 10^6 kg).

Year	$TN_{deposition}$	$TN_{river\ inputs}$	$TN_{river\ outputs}$	$\Delta TN_{inventory}$	$TN_{retention}$
2010	9.30	56.44	25.04	−6.47	47.17
2011	9.10	47.41	16.97	−4.46	44.00
2012	10.70	47.30	17.37	−3.69	44.32
2013	8.79	38.69	14.29	−2.83	36.03
2014	8.47	42.01	13.00	−0.60	38.08
2015	6.72	44.00	15.10	0.31	35.31
2016	6.33	54.10	24.10	−2.11	38.43
2017	6.55	39.40	12.79	−3.00	36.15
2018	5.16	39.61	10.99	−0.75	34.52
Mean value	7.90 ± 1.69	45.44 ± 6.09	16.63 ± 4.65	−2.62 ± 2.00	39.34 ± 4.36

uptake by aquatic organism, and it represents an alternative hypothesis to explain the variation in lake N concentrations. Denitrification is the primary mechanism of N retention in freshwater lakes, and changes in denitrification capacity can lead to alterations in nutrient levels (Bernhardt, 2013; Saunders and Kalff, 2001). Previous studies usually indicated that the decay of algal blooms can supply fresh organic carbon and deplete oxygen, thus creating favorable conditions for denitrification and N retention (Bernhardt, 2013; Finlay et al., 2013). However, a recent study indicated that this decay, which likely depletes dissolved oxygen, might have inhibited nitrification and thereby denitrification in Lake Taihu (Zhu et al., 2020). Jiang et al. (2020) also reported that low nitrate availability limited the N removal during the summer in the northern area of Lake Taihu. Moreover, the N retention in Lake Taihu assessed based on mass balances presented a decreasing trend from 2010 to 2018 (Table 1). Therefore, it is unlikely that N retention is a major factor involved in the decrease of N concentration in this ecosystem.

We propose that the decrease in atmospheric N deposition is a plausible explanation for the variations in N concentration in the lake. However, not all signals of N deposition were responded by the N concentrations in Lake Taihu. For instance, atmospheric N deposition is highly episodic based on extreme meteorological events, and not all episodes influence the lake in the same way or with the same intensity (Camarero and Catalan, 2012). Moreover, the water residence time of Lake Taihu is approximately 180 d. Therefore, the changes in lake N concentrations observed in this study integrates the values of a previous period. This might lead to an interannual or delayed response of lake nutrient to the changes in atmospheric deposition. In addition, the spatial differences in atmospheric deposition should also be considered. Luo et al. (2007) collected and measured the wet N deposition rates in cities around Lake Taihu. The results showed that the eastern (Suzhou), northern (Wuxi), and northwestern cities (Changzhou and Jintan) presented the largest, moderate, and lowest wet deposition rates, respectively. Whereas considering different land uses, Ti et al. (2018) observed no significant differences in the deposition rates among three main land-use types (rural, suburban, and urban) in the Taihu Basin. Although the contribution of atmospheric deposition should not be ignored, it would be arbitrary to attribute the changes in lake N concentration entirely to the decrease in atmospheric N deposition.

3.3. *Implication of N deposition for nutrient management in eutrophic lake*

Precipitation can significantly affect wet and bulk N deposition rates (Fig. 3c and d), thereby shaping the seasonal patterns of N deposition (Geng et al., 2021; Zhu et al., 2015). In this study, the highest wet deposition was observed in late summer along with extreme rainfall

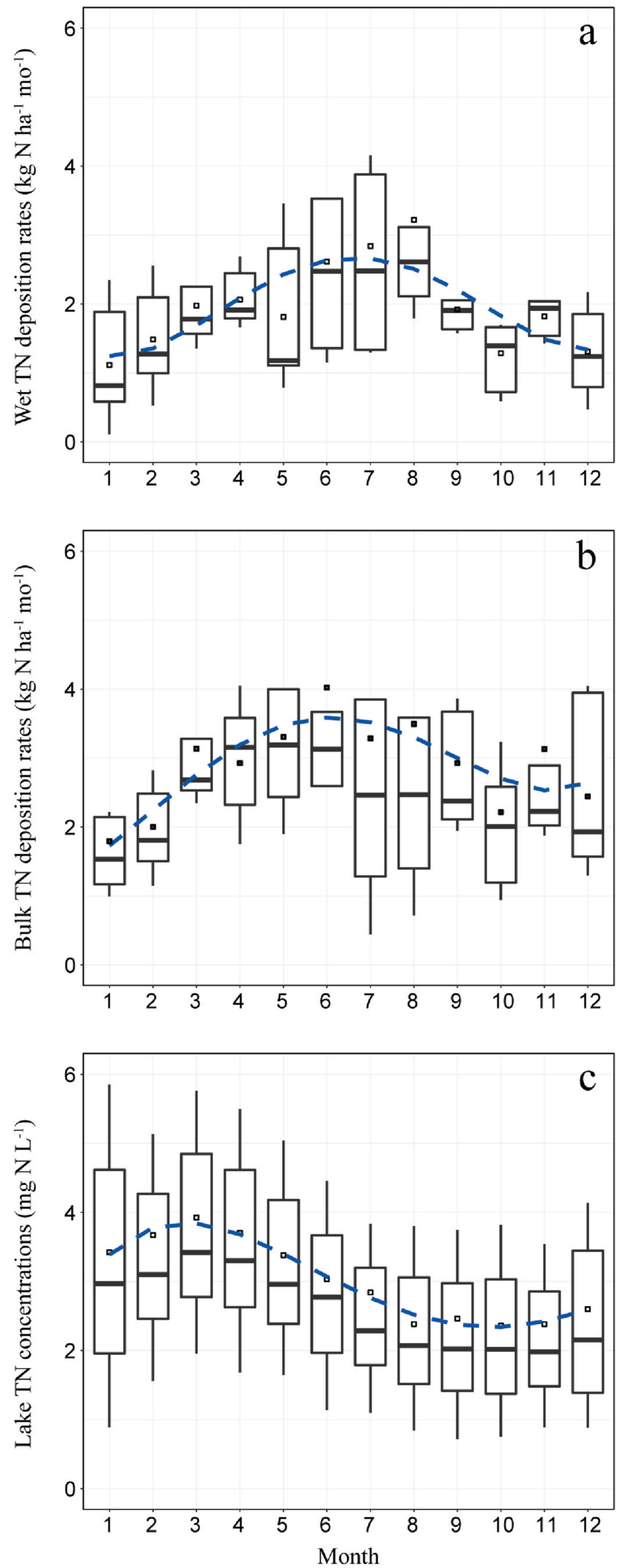

Fig. 5. Monthly (a) wet and (b) bulk deposition rates of total nitrogen (TN) at the monitoring sites (n = 9), and (c) TN concentrations in Lake Taihu (n = 126) between 2010 and 2018. Curves are local regression (Loess) smoothing trend lines of mean values.

(Fig. 5a). Whereas dry deposition was usually higher in late spring and early summer (Fig. 5b), which was likely caused by the intensive application of chemical N fertilizer during this period in the Lake Taihu Basin (Luo et al., 2007; Ti et al., 2018). Overall, atmospheric N deposition was mainly concentrated in the summer. The seasonal variation in N concentration was contrary to the trend of atmospheric N deposition. The minimum values of N concentrations usually occurred in late summer to early fall (Fig. 5c), which was mostly attributed to the high N demand of cyanobacterial blooms (Jiang et al., 2019). As blooms fully matured and persisted through the summer into fall, N and P co-limitation or N limitation tended to become more usual in the northern part of Lake Taihu (Paerl et al., 2015; Xu et al., 2010). This led to a higher dependence on atmospheric N deposition.

In Lake Taihu, non-N_2-fixing *Microcystis* spp. is generally the primary contributor to the algal blooms (Paerl et al., 2014; Qin et al., 2018; Xu et al., 2013; Zhang et al., 2018). *Microcystis* have a general preference for reduced N, and they have the ability to effectively compete for dwindling N sources (Huisman et al., 2018; Paerl et al., 2014). These advantages led *Microcystis* to compete well with other cyanobacteria, such as those of N_2-fixing genera (Paerl et al., 2015). Our results revealed that reduced N contributed more to inorganic N deposition than oxidized N in Lake Taihu (Fig. S1). Especially for wet deposition, the relative contribution of NH_4^+-N to TN deposition exceeded 80% in the summer (Fig. S4), which coincided with the period of maximum algal demand (Jiang et al., 2019; Gardner et al., 2017). Therefore, atmospheric N deposition can play an important role in the duration of *Microcystis* blooms.

Excessive N deposition is known as a significant threat to water quality (Gao et al., 2019; Liu et al., 2013; Zhan et al., 2017). In this study, the direct bulk N deposition into Lake Taihu accounted for 17.5% and 51.4% on average of the riverine N inputs and lake N inventory, respectively, which indicates that atmospheric N deposition was a quantitatively important source of external N loading. Furthermore, the seasonal results indicate that atmospheric N deposition has become more important for the duration of algal blooms in the summer. Although current strategies for nutrient management have led to the decrease in N concentrations, TN concentrations still exceeded 2 mg N L^{-1} in most of the time (Fig. 5c), and cyanobacterial blooms have not been effectively controlled in Lake Taihu (Qin et al., 2019). As the N to P ratio in Lake Taihu gradually decreased because of the variations in N concentrations, the N-dependency of algal growth is expected to become increasingly clear. Therefore, external N inputs, including atmospheric N deposition, should be further controlled to effectively mitigate eutrophication and algal blooms in Lake Taihu.

4. Conclusions

Atmospheric N deposition can significantly affect aquatic ecosystems, especially regarding their nutrient levels and phytoplankton growth. Although several studies have investigated atmospheric deposition in eutrophic lakes, little evidence for the relationship between nutrient concentration and atmospheric deposition has been published. Through long-term (2010–2018) and high-resolution (weekly or monthly) systematic observations in Lake Taihu, our results revealed the interannual and seasonal variations in the N deposition of a recent decade. The changes in atmospheric N deposition were a key reason for the decrease in N concentrations in this hypereutrophic lake. Moreover, the seasonal results indicated that atmospheric N deposition has become more important in supporting algal blooms of the summer. This study provides a deeper insight into the response of N concentrations to changes in atmospheric N deposition, and the results strengthen awareness for the adequate control of N inputs in eutrophic lakes.

Author contribution

Xingyu Jiang: Conceptualization, Investigation, Writing – original draft, Visualization, Funding acquisition. **Guang Gao**: Conceptualization, Methodology, Writing – review & editing, Funding acquisition. **Jianming Deng**: Conceptualization, Methodology, Investigation. **Guangwei Zhu**: Methodology, Investigation, Writing – review & editing. **Xiangming Tang**: Investigation, Data curation. **Keqiang Shao**: Formal analysis, Project administration. **Yang Hu**: Investigation, Funding acquisition.

Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envpol.2022.118952.

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