Wu, Mingqian; Zhang, Xiuming; Reis, Stefan; Ge, Shengxiu; Gu, Baojing. 2022. **Pollution controls in Lake Tai with the reduction of the watershed nitrogen footprint.**

The definitive version was published in *Journal of Cleaner Production*, 332, 130132. https://doi.org/10.1016/j.jclepro.2021.130132

The definitive version is available at https://www.elsevier.com/

Pollution controls in Lake Tai with the reduction of the watershed nitrogen footprint

Abstract

To feed an increasingly affluent population, the nitrogen input into global food production systems is currently two times the safe planetary boundary leading to adverse impacts on the local and global environments. The nitrogen footprint is an important index to understand the impact of human activities on the environment, however, it is rarely applied at a watershed scale. By using the Coupled Human And Natural System (CHANS) model, it was found that the total nitrogen input to the Lake Tai watershed has increased from 141.1 Gg N yr^{-1} in 1995 to 244.3 Gg N yr^{-1} in 2010, and then decreased again to 201.2 Gg N yr^{-1} in 2015. The study findings are consistent with the change in the total nitrogen concentration observed in Lake Tai. While the per capita nitrogen footprint remained stable at around 30 kg N yr^{-1} before 2010, a substantial decrease to approximately 25 and 20 kg N yr^{-1} in 2010 and 2015, respectively, has occurred. Dominant sources of nitrogen emissions contributing to the nitrogen footprint gradually have changed from agricultural production to wastewater and nitrogen oxides emissions from fossil fuel combustion. A reduction of the nitrogen footprint is beneficial for effective nitrogen pollution control strategies and better wastewater treatment techniques should be prioritized for future policymaking.

Key words: Water pollution, Nitrogen footprint, Agriculture, Wastewater, Land use, Watershed, Lake Tai

1. Introduction

China is the most populous country in the world, and in recent years, rapid economic development also has changed the dietary structure to more animal-product based nutrition, leading to substantial pressures on food security (Zhai et al., 2014). To produce sufficient food and animal feed, China uses about 30% of the global nitrogen fertilizers, and raises about 30-40% of the global livestock (FAO, 2020). However, due to the small farm size, nitrogen is not well managed on cropland, and two thirds of animal manure nitrogen also is lost to the environment due to decoupling of livestock and cropland (Wu et al., 2018; Zhang et al., 2019; Zhang and Hu, 2020). These factors have contributed to a rapid increase of nitrogen pollution across China, resulting in water and air pollution, with consequences for biodiversity loss due to nitrogen deposition (Zhang et al., 2015).

Besides the nitrogen losses during food production, nitrogen losses as a result of food consumption, i.e., via domestic wastewater, is another important emission source. With the increase of population and per capita consumption, wastewater including effluents of wastewater treatment plants (WWTP) (Yu et al., 2019) has become a dominant source of water pollution in many watersheds. In rural China, however, wastewater is rarely treated at all and sludge from septic tanks is not reused as manure (MHURDPRC, 2005; Deng and Wheatley, 2016). This wastewater makes a significant contribution to the increase of nitrogen pollution. Nitrogen oxide (NO_x) emissions from fossil fuel combustion are another important emission source of nitrogen (Zhang et al., 2007). The increase in energy demand has led to a rapid growth of fossil fuel usage in China. NO_x emissions have become increasingly important as a driver of atmospheric nitrogen deposition and contribute to biodiversity loss in sensitive regions and also nitrogen input to lakes in urbanized regions (Bobbink et al., 2010; Hobbs et al., 2016). This atmospheric pathway can add up to 30% of the total nitrogen input to lakes, substantially affecting water quality (Ti et al., 2018). Understanding the contribution of nitrogen losses during wastewater discharge after food consumption and energy production has, thus, become increasingly important for nitrogen management.

The nitrogen footprint is defined as the total amount of nitrogen released to the environment as a result of individual or collective activities (Leach et al., 2012). It is used to calculate the loss of reactive nitrogen (Nr; all species of nitrogen except N_2) from human activities to the environment, providing information on how to reduce Nr losses (Ti et al., 2018). Previous studies have calculated the national nitrogen footprint, e.g., for Australia (Liang et al., 2016), China (Gu et al., 2013), and the United Kingdom (Stevens et al., 2014). In addition, nitrogen footprints also can be used by institutions to improve their sustainability in nitrogen consumption (Leach et al., 2013). The success of the universities of Virginia (Leach et al., 2013) and Australia (Liang et al., 2018) shows that the nitrogen footprint can be used not only for nitrogen evaluation at the national scale, but also for nitrogen analysis at the local scale. A new study has applied a nitrogen footprint calculation approach at the city scale to understand how to manage nitrogen regionally (Huang et al., 2019). However, nitrogen pollution is typically constrained by natural boundaries such as watersheds, not administrative boundaries. Linking administrative boundaries and natural boundaries on nitrogen management using a nitrogen footprint is important.

In this paper, a new watershed-scale nitrogen footprint is developed taking into consideration changes in land use and water quality. By using the Coupled Human And Natural System (CHANS) model (Gu et al., 2015), which is a conceptual model that identifies the main nitrogen fluxes in a given physical system, this study quantifies the contribution of different sources to the nitrogen footprint for the Lake Tai watershed. This model has advantages in mass balance calculation, which is beneficial to nitrogen management. Previous studies have proved that it is feasible to calculate the nitrogen footprint through the CHANS model (Gu et al., 2015). Meanwhile, the spatial variation of different sources contributing to the nitrogen footprint also were estimated based on the land use changes to identify hotspots of nitrogen use and losses within the watershed. The relationship between the overall nitrogen footprint and water quality then is analyzed in particular to reveal the driving forces of human activities on the aquatic environment. Finally, aspects relevant to policy implementation emerging from this study are discussed to identify better management options for nitrogen to contribute to the attainment of the sustainable development goals.

2. Materials and Methods

2.1 Study area

The Lake Tai watershed located in East China (30°05′-32°08′N, 119°08′-121°55′E) was used as a case study. The lake has an area of 2,427 km^2, and the whole watershed area is about 36,900 km^2 (see Fig. 3 for more geographical information). The Lake Tai watershed is one of the most developed regions in China, with a high population density and well-developed industrial and agricultural production. The watershed includes part of Jiangsu, Zhejiang, and Anhui provinces and Shanghai city. In 2015, the total population of the Lake Tai watershed was about 60 million, accounting for 4.4% of the total population of China. The total gross domestic product (GDP) is US$ 945.9 billion, accounting for 9.9% of the national GDP. Since the 1990s, water pollution events have frequently occurred in Lake Tai. One particular event in 2007 was marked by a large scale cyanobacteria outbreak, which seriously affected drinking water quality and aquaculture production.

2.2 Land use analysis

Land use maps for the Lake Tai watershed for the years 1995, 2000, 2005, and 2010 with a resolution of 1 km were derived from Landsat TM/ETM, and for 2015, from Landsat 8 remote-sensing data. All data were provided by the Data Center for Resources and Environmental Sciences, Chinese Academy of Sciences (RESDC) (http://www.resdc.cn). The land use types were divided into cropland, forest, grassland, water, and residential and commercial land to analyze the change of land use types across the Lake Tai watershed over the period 1995 to 2015. In addition, the nitrogen footprint calculations were associated with land use types to explore the change of the per capita nitrogen footprint during the study period.

2.3 Nitrogen flow analysis.

In order to quantify the nitrogen flows, the CHANS model was used to extract related flows for the Lake Tai watershed (Fig. 1). The system boundary follows the watershed boundary (Fig. 3), which includes the main channel and tributaries. Based on the relation between Nr flows, the CHANS model is divided into four functional groups, which is further divided into 14 subsystems (Gu et al., 2015). The concept of subsystem and ecosystem is similar. Taking the cropland subsystem as an example, it refers to biological (including human) activities and natural activities on cropland. The nitrogen cycle for the Lake Tai watershed is primarily based on the surface water subsystem. There are nine subsystems which directly interact with the surface water subsystem through nitrogen flows: cropland, forest, livestock, aquaculture, urban greenspace, industry, residential and commercial, wastewater treatment, and near-surface atmosphere.

2.4 Mass balance calculation

Land use change and nitrogen flow analysis are related. The China Land Use/Land Cover Remote Sensing Monitoring Database provides Chinese land use change data at intervals for five years. The basic data for the Lake Tai watershed were collected for 5-year intervals for 1995, 2000, 2005, 2010, and 2015, and these were processed through the CHANS model to calculate the local nitrogen flows (Fig. 1). Data used in this study can be divided into two categories: (1) socioeconomic information for the Lake Tai watershed, such as cropland area, urban/rural population, crop/livestock production, fertilizer usage, and sewage discharge, which were mainly obtained from the annual statistics provided by yearbooks and bulletins, more details can be found in the SI Appendix of Gu et al. (2015); and (2) coefficients and parameters used for the calculation of nitrogen input to the surface water subsystem were adopted from the CHANS model (Gu et al., 2015) with some modification for local parameters such as nitrogen deposition (Liu et al., 2013) for each year.

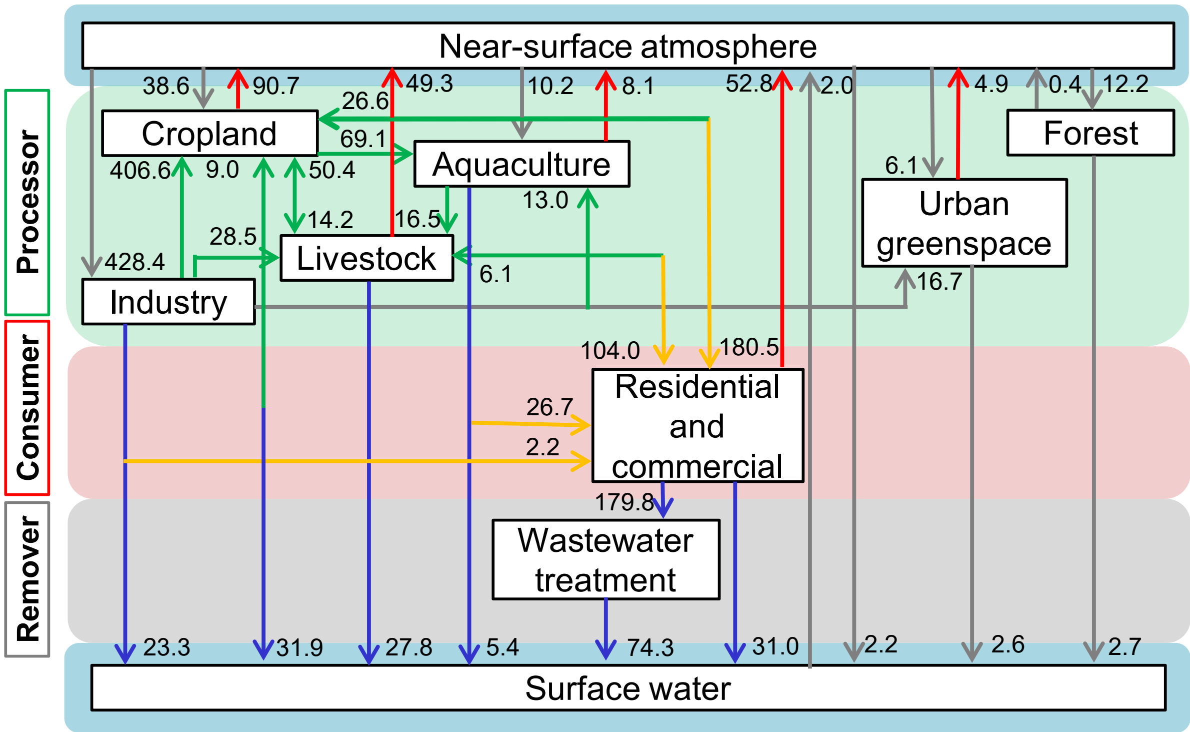


Fig. 1 Nitrogen cycle in the CHANS model used to calculate nitrogen fluxes. Data represent the N fluxes in 2015 with units of Gg N. The background colors represent different functional groups: blue represents life-supporter; green represents processor; red represents consumer; and gray represents remover. Arrows represent nitrogen (N) flows, which are all included in the calculation of the N cycle in this study. Blue arrows represent Nr discharge to the surface water; green arrows represent Nr flows associated with agricultural production; red arrows represent Nr emission to the atmosphere; and orange arrows represent Nr flows associated with human consumption and gray arrows mainly represent natural nitrogen processes. The two-way arrow indicates that the nitrogen flow is two-way. Taking the two arrows pointing to cropland and residential and commercial subsystems for example, the green arrow represents 27.2 Gg N from residential and commercial subsystem is input to cropland for agricultural production, and the orange arrow represents 184.3 Gg N from cropland subsystem is used by human residential and commercial activities. The natural nitrogen processes related to the nitrogen flow from industry to urban greenspace subsystems represent fertilization in urban greenspace.

The basic principle of the CHANS model is a mass balance approach, which is applicable to the whole system and subsystems (Gu et al., 2015):

$$\sum_{h=1}^{m} IN_h = \sum_{g=1}^{n} OUT_g + \sum_{k=1}^{p} ACC_k \quad (1)$$

where IN_h and OUT_g represent the different nitrogen inputs and outputs, respectively, and ACC_k represents the different nitrogen accumulations. In the current study, this principle postulates that the nitrogen input from other subsystems to the surface water subsystem is equal to the sum of nitrogen output from the surface water subsystem to other subsystems and the amount of nitrogen accumulated by the surface water subsystem itself.

2.5 Nitrogen footprint calculation

The nitrogen footprint is defined as the total amount of nitrogen released to the environment as a result of individual or collective activities, expressed in total units of Nr (unit: kg N capita^{-1} year^{-1}), which provides a novel method to link consumption behavior and management behavior to the nitrogen cycle (Leach et al., 2012). Based on the mass balance approach embedded in the CHANS model (eq.1), the data of nitrogen flows was calculated, and the data related to the system level nitrogen footprint (NF_{system}) of the Lake Tai watershed was extracted to calculate the footprint for a certain year as follows (Gu et al., 2013):

$$NF_{system} = N_{BNF} + N_{CFA} + N_{FFC} + N_{FI} \quad (2)$$

where N_{BNF} indicates nitrogen from biological nitrogen fixation, N_{CFA} indicates chemical fertilizer application, N_{FFC} indicates NO_x emission from fossil fuel combustion, and N_{FI} indicates feed and food import from other regions (estimated based on the differences between consumption and production). In the calculation of the nitrogen footprint in the Lake Tai watershed, N_{BNF} mainly includes cropland BNF, aquaculture BNF, grassland BNF, forest BNF, and urban greenspace BNF.

3. Results

3.1 Nitrogen input and nitrogen footprint for the Lake Tai watershed

The nitrogen input to the surface water subsystem Lake Tai watershed (including main channel and tributaries) increased by over 70% from 141.1 Gg N yr^{-1} in 1995 to 244.3 Gg N yr^{-1} in 2010, and then declined to 201.2 Gg N yr^{-1} in 2015 (Fig. 2a). Cropland runoff was the largest component of nitrogen input in 1995, while wastewater treatment plant (WWTP) effluent has replaced cropland runoff as the largest source since about 2010, which was consistent with the changes in the socio-economic structure, industrial development, and population growth in the watershed. Cropland runoff decreased from 58.4 to 31.9 Gg N yr^{-1} between 1995 and 2015, mainly due to a reduction in fertilizer use. The Lake Tai watershed has attracted a large number of immigrants because of its well-developed economy and convenient transportation, leading to substantial population growth. These changes increased the amount of WWTP effluent, challenging the nitrogen removal rate of the WWTPs in the future.

A system-level nitrogen footprint for the Lake Tai watershed was estimated, with the per-capita footprint remaining relatively stable at around 30 kg N yr^{-1} before 2010, and then reducing markedly to approximately 25 and 20 kg N yr^{-1} in 2010 and 2015, respectively (Fig. 2b). This change mainly occurs due to the decrease of N input and increase of population that results in a dilution effect. Chemical fertilizer application has decreased by 63.9% during the period from 1995 to 2015 because of the changes in agricultural production. The decrease of cropland area and fertilizer use per hectare led to an increased nitrogen use efficiency (NUE, harvested crop Nr divided by total Nr input), from 29% to 35% between 1995 and 2015, which reduced overall nitrogen fertilizer use. Meanwhile, an increase of animal feed and food import transferred part of the nitrogen footprint outside of the region (Fig. 2b).

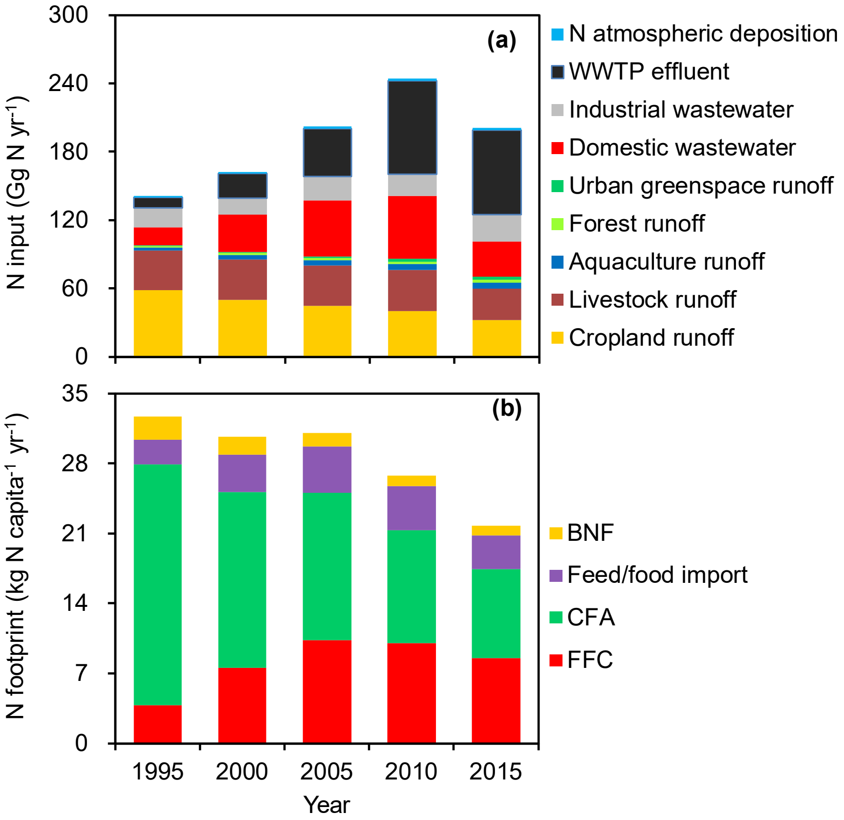
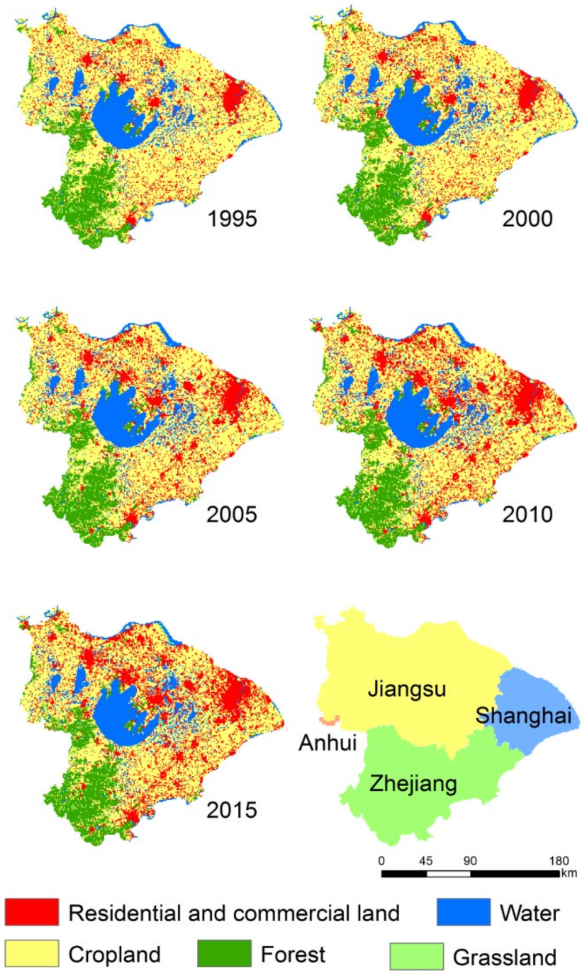


Fig. 2 Changes of nitrogen input and nitrogen footprint from 1995 to 2015. (a) Nitrogen input. (b) Nitrogen footprint. WWTP refers to wastewater treatment plant; BNF refers to biological nitrogen fixation; CFA refers to chemical fertilizer application; FFC refers to NO_x emission during fossil fuel combustion.

3.2 Land use change and socioeconomic development

The land-use types in the Lake Tai watershed were divided into five basic categories: cropland, forest, grassland, water, and residential and commercial land to analyze of land use changes from 1995 to 2015 (Fig. 3). Cropland, forest and grassland only consider nitrogen input from their own subsystem in the CHANS model; water includes the aquacultural and surface water subsystems; and residential and commercial land include nitrogen input from industry, urban greenland, pet, livestock (animals raising normally used built-up area which is classified in residential and commercial land), and wastewater treatment subsystems. Forest is mainly distributed in the southwest of the Lake Tai watershed (within Zhejiang province), accounting for 13% of the total watershed area. Water surface is mainly from Lake Tai, surrounded by some smaller lakes and rivers (14%). Grassland area is relatively small (0.4%) and scattered around other land use types. In the past 20 years, the area and distribution of forest, water, and grassland have not changed significantly. On the other hand, cropland and residential and commercial land have changed substantially. Between 1995 and 2015, about 16 percentage points of cropland were converted into residential and commercial land. Residential and commercial land was mainly distributed in the northeast of the watershed (within Shanghai city) in 1995, and there were also small-scale residential and commercial land clusters in Jiangsu, Zhejiang, and Anhui provinces. By 2015, not only had the area of the original residential and commercial area become larger, but also many new residential and commercial areas had developed.



3.3 Nitrogen footprint spatial intensity

In order to analyze the nitrogen footprint spatial intensity (NFSI), each source of the nitrogen footprint was assigned to different land use types (for example, the cropland BNF occurred on cropland, NO_x emission during fossil fuel combustion occurred on residential and commercial land), and the annual per capita nitrogen footprint per hectare of land was computed (Fig. 4). Because the nitrogen footprint of forest, grassland, and water is relatively small and has not changed much, Fig. 4 focuses on the analysis of the nitrogen footprint for cropland and residential and commercial land only.

As a whole, the per capita NFSI of cropland has gradually declined from 1995 to 2015, starting from between 0.3 and 2 kg N ha^{-1} yr^{-1} $capita^{-1}$ in 1995, with a decreasing gradient from west to east and the highest values in the northwest. By 2015, the NFSI of cropland was 0-0.3

kg N ha^{-1} yr^{-1} capita^{-1} in the northeast of the watershed, 1-2 kg N ha^{-1} yr^{-1} capita^{-1} in the northwest, and 0.3-1 kg N ha^{-1} yr^{-1} capita^{-1} in the remaining areas. In contrast, the per capita NFSI of residential and commercial land showed an upward trend. With the continuous expansion of the residential and commercial land areas, most have an NFSI higher than 1-2 kg N ha^{-1} yr^{-1} capita^{-1}, which indicates that those areas have become nitrogen footprint hotspots over the period from 1995 to 2015.

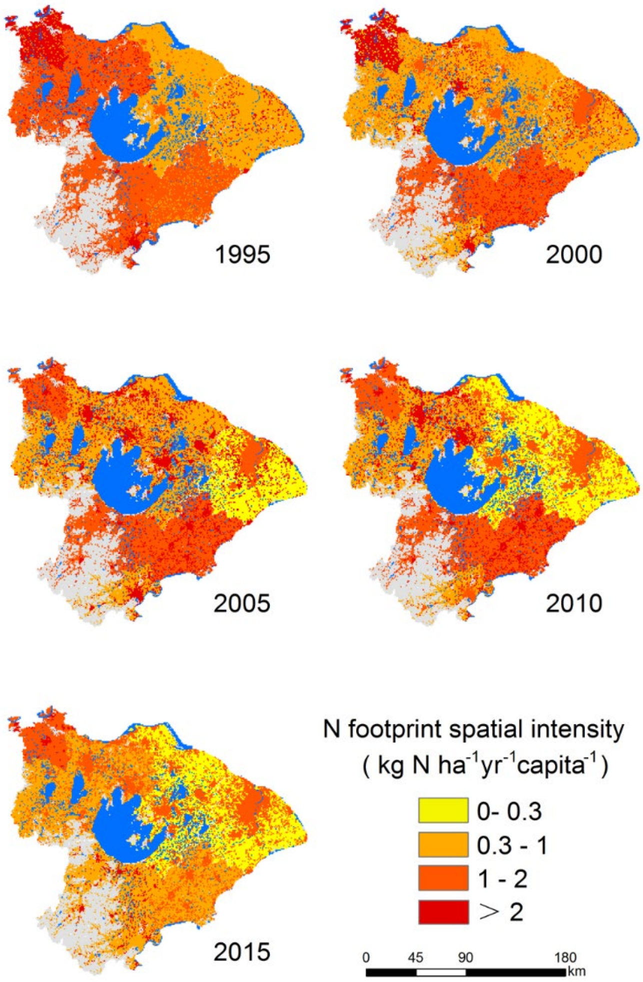


Fig. 4 Spatial distribution of per capita nitrogen (N) footprint from 1995 to 2015. Yellow represents low nitrogen footprint regions, red represents high nitrogen footprint regions. The more substantial the color change, the greater the change in the nitrogen footprint. Blue refers to the water, and gray refers to forest and grassland, and their nitrogen footprints are small, and the changes are slight, which are not identified in the figure. The base map is derived from GADM data (https://gadm.org/).

4. Discussion

Generally, a substantial transition in the main flows of nitrogen use and loss within the Lake Tai watershed was found over the study period. The improvement of Nr management for cropland and the import of feed and food substantially reduced the nitrogen footprint of food production, despite the population increasing by 20 million, for a growth of 53% compared with the 1995 population levels. This illustrates that environmental improvements can be realized despite increased population densities and food demand through better agricultural management. The farm size in many regions within the Lake Tai watershed increased with the implementation of the land transfer system (Ju et al., 2016). However, part of the region's footprint has been transferred to other regions, with the food and feed imports. Information on the origins of these imports currently is not available, which limits the ability to do a comprehensive estimation of the Nr footprint change due to trade.

With the reduction in the relative share of agricultural land, more land areas were converted to urban residential and commercial areas. As a result, a shift of increasing the nitrogen footprint of urban land use is found, mainly corresponding to Nr emissions from food and fossil fuel consumption. This is not only indicated by the total Nr losses to water bodies, but also by the detailed analysis of the spatial distribution of Nr losses from different land use types. Areas with urban land use have become the new hotspots compared to emissions from cropland and natural land. This highlights the growing importance of an efficient management of Nr for urban land use.

In the current study, a watershed nitrogen footprint based on the consumer side was initiated. To directly link the nitrogen input and water pollution, the total nitrogen (TN) index was used to analyze the nitrogen concentrations in water. It was found that the TN index and Nr input in the watershed had the same trend over a 15-year period (Fig. 5): increasing from 2000 to 2010 and subsequently decreasing after 2010. The increasing demand for daily life needs and industrial production has made the nitrogen input in the Lake Tai watershed increase since 1995. This increase made the Chinese government realize the urgency and necessity of controlling water pollution in the Lake Tai watershed. Since then, the government has invested around US$ 50 billion to reduce pollutant (e.g., nitrogen and phosphorus) input into the watershed. The decline of nitrogen pollution from 2010 to 2015 directly reflects the government's effectiveness in controlling nitrogen losses.

In addition, the water quality of Lake Tai also was mapped, and it followed a similar trend: from 1995 to 2010, the proportion of water quality of Grade IV, Grade V, and worse than Grade V continued to increase and by 2005 the worst category could be attributed to 75% of the watershed. Starting around 2010, water quality gradually improved with the proportion of Grade IV, Grade V, and worse than Grade V reducing, and a water quality level of Grade I being observed for the first time (Fig. 5). In the current study, it is found that despite the timeline of nitrogen input not being completely consistent with respect to the TN index and water quality in the Lake Tai watershed, their overall patterns are similar on a two-decade scale. Therefore, these can be used to quantify the impact of different human activities, providing detailed data to support policy-makers in identifying suitable measures to control Nr pollution.

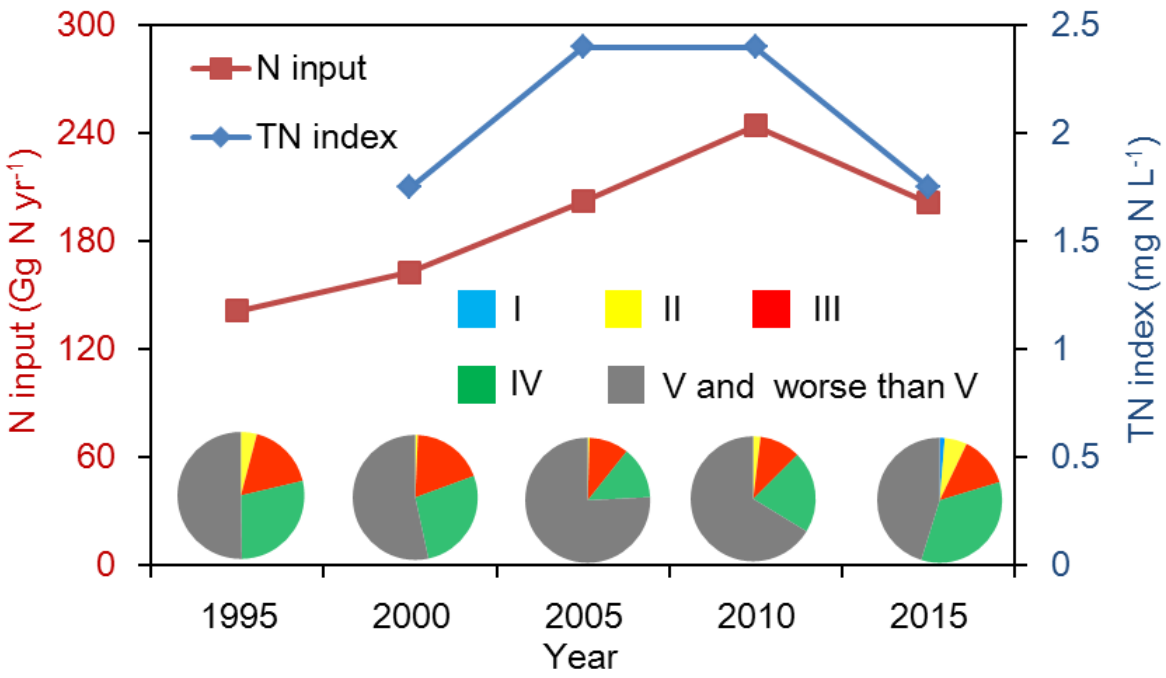


Fig. 5 Temporal trend of the nitrogen input and water quality from 1995 to 2015. The total nitrogen (TN) index in Fig. 5 represents the level of nitrogen concentration as an indicator of water quality, which includes nitrate nitrogen, ammonia nitrogen, organic nitrogen, etc. According to the Chinese classification of surface water environmental quality standard GB3838-2002, the middle value of the TN index range is taken as the value for the Lake Tai watershed (for example, the TN index in 2000 was class V, the range of class V is 1.5-2.0 mg N L^{-1}, and the middle value is taken as 1.75 mg L^{-1} in the figure). The TN index in 2000 and 2005 was from the literature (Qian and He, 2009), and the TN index in 2010 and 2015 was obtained from the Lake Tai health status report published by the Lake Tai Basin Authority of the Ministry of Water Resources (the TN index in 1995 was not available). The pie chart in Fig. 5 shows the change of water quality in Lake Tai watershed from 1995 to 2015. The colors of the pie charts represent different water quality grades: blue, yellow, red, green, and gray represent Grades I, II, III, IV, and V and worse than V, respectively. According to GB3838-2002, Grades I-III are suitable for water supply, Grade IV waters are suitable for industrial water use and non-contact recreation areas, and Grade V waters are only suitable for agricultural water use and landscaping requirements, furthermore, the water worse than Grade V is not suitable

for any use. The data in 1995 and 2000 are from the literature (Jin et al., 2006), and the data of 2005, 2010, and 2015 were from the Lake Tai Watershed & Southeast Rivers Water Resources Bulletin.

The Chinese government has paid close attention to nitrogen pollution in the Lake Tai watershed, with substantial polices for the treatment of Nr pollution in the basin since 1995 (Fig. 6). These policies not only include the five-year plan, but also additional management in combination with the actual situation of the Lake Tai watershed. Despite these actions, a large cyanobacteria bloom occurred in 2007, causing irreparable damage to the livelihood of local residents and biodiversity in the watershed, which reflects certain shortcomings in the governance measures. Taking "zero o'clock" action in 1998 as an example (Fig. 6), although it controlled the sewage discharge of industrial enterprises in the watershed, this action lasted for a very short time, which was not conducive to the sustainable development of the Lake Tai watershed.

In the aftermath of the 2007 cyanobacteria bloom, the government not only increased the attention in environmental protection for the Lake Tai watershed, but also adjusted the focus of the policy (Fig. 6). These policies not only require attention to agricultural non-point source pollution, but also require the control of urban sewage discharge, taking the treatment of point source pollution and non-point source pollution into account. During the past two decades, over US$ 50 billion has been invested by governments to control the water pollution in Lake Tai. Although the pollution is reduced with the decline in the nitrogen footprint, still more effort is needed to further reduce the Nr loading and other elements such as phosphorus (Gu et al., 2021). Considering that the nitrogen footprint in residential and commercial land is higher than cropland, the treatment of Nr pollution in the Lake Tai watershed needs to further reduce the nitrogen input from residential and commercial lands, such as WWTP effluent in urban areas and direct discharge of domestic wastewater from rural settlements.

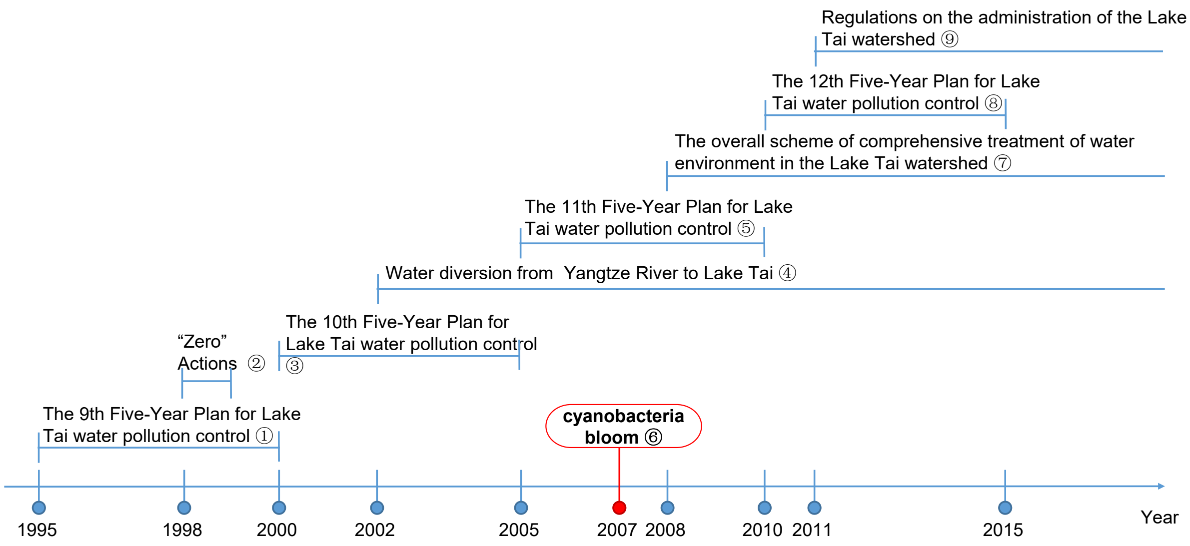


Fig. 6 The policy in nitrogen governance from 1995 to 2015. All information is from Lake Tai Comprehensive Treatment Phase I Project, the overall plan of water environment comprehensive treatment in the Lake Tai watershed, the Five-Year Plan of China, and other public documents. ① In 1995, the 9th Five-Year Plan set the goal of total water pollutant discharge control in the Lake Tai watershed in 2000, and proposed a long-term goal was to solve the problem of eutrophication in Lake Tai by 2010. ② On December 31, 1998, nearly 1,000 law enforcement officers conducted on-site inspections and enforcement of the industrial pollution from polluting enterprises in the Lake Tai watershed, known as the "zero" actions. ③ In 2000, the 10th Five-Year Plan proposed to implement cleaner production in the Lake Tai watershed to control the total amount of pollutants entering the lake. The responsibility for the prevention and control of water pollution in Lake Tai was assigned to the people's governments at all levels to control water pollution. ④ In 2002, water from the Yangtze River was transferred from other areas to Lake Tai, which accelerated the flow in the water body of Lake Tai, improving the self-purification ability of the water body, and reducing the pollution. ⑤ In 2005, the 11th Five-Year Plan carried out point source pollution control for heavily polluting industries, upgrading urban sewage treatment plants, implementing rural non-point source pollution control, and comprehensive improvement of rivers as part of the lake and ecological restoration work to improve the water quality in the Lake Tai watershed. ⑥ In 2007, a cyanobacteria bloom broke out in the Lake Tai watershed, affecting the normal supply of drinking water for residents and shutting down a large number of factories in the basin. ⑦ In 2008, the overall scheme proposed industrial point source treatment and agricultural non-point source pollution treatment, implemented in the river chief system. ⑧ In 2010, the 12th Five-Year Plan proposed to harness the Lake Tai watershed for the following five aspects: promoting economic transformation and upgrading; controlling agricultural non-point source and urban

domestic pollution; restoring the Lake Tai ecosystem; promoting the collaborative management of river basin; and advocating the construction of a water-saving society. ⑨ In 2011, regulations were proposed to ensure drinking water safety, protection of water resources and prevention of water pollution in the Lake Tai watershed through supervision and clear legal responsibilities.

5. Conclusions

Nitrogen pollution has undergone marked changes with socioeconomic development. Calculating a nitrogen footprint is a useful tool to link water pollution and human activities. In this paper, a turning point of water quality in the Lake Tai watershed was identified around the mid-2000s, which is well illustrated by the total nitrogen footprint despite an increase in the overall population in this region. With urbanization, urban residential and commercial areas have become new hotspots of the nitrogen footprint compared to agricultural land uses. Meanwhile, part of the nitrogen footprint derived from agricultural production has been exported to other regions with urbanization and land use change reducing the availability of agricultural land. Therefore, government policies should focus on reducing the per capita nitrogen footprint of residential and commercial areas going forward. Increasing the number and effectiveness of WWTPs to reduce the direct discharge of Nr through wastewater should be done, hence, improving and enforcing the standards of WWTPs to reduce the nitrogen emissions in the effluent. Sustainable development at the watershed scale can be realized through optimizing the nitrogen footprint across all relevant sources, as illustrated by this study.

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