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VIEWS

Unintended nutrient imbalance induced by wastewater effluent inputs to receiving water and its ecological consequences

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Abstract Eutrophication is the most widespread water quality issue globally. To date, most efforts to control eutrophication have focused on reductions of external nutrient inputs, yet importance of nutrient stoichiometry and subsequent shift in plankton composition in aquatic ecosystem has been largely neglected. To address eutrophication, improved sanitation is one of the United Nations Sustainable Development Goals, spurring the constructions of wastewater treatment facilities that have improved water quality in many lakes and rivers. However, control measures are often targeted at and effective in removing a single nutrient from sewage and thus are less effective in removing the others, resulting in the changes of nutrient stoichiometry. In general, more effective phosphorus removal relative to nitrogen has occurred in wastewater treatment leading to substantial increases in N/P ratios in effluent relative to the influent. Unfortunately, high N/P ratios in receiving waters can impose negative influences on ecosystems. Thus, long-term strategies for domestic wastewater management should not merely focus on the total reduction of nutrient discharge but also consider their stoichiometric balances in receiving waters.

Keywords Nutrient stoichiometry, Wastewater treatment, Ecosystem functioning, Water quality management

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Eutrophication due to excessive enrichments of nutrients such as nitrogen (N) and phosphorus (P) is the most widespread water quality problem (Huisman et al., 2018). For example, based on an investigation of 111 lakes in China in 2017, the mean lake TN concentration was 996 (380–2723) μg/L with mean TP concentration of 32 (7–114) μg/L (Tong et al., 2020). For comparison, typical TP concentration in a lake classified as 'eutrophic' ranges from 24 to 96 μg/L (Carlson and Simpson 1996); thus, the average lake in this large sample of lakes in China is 'eutrophic'. Lake nutrient concentrations in Europe are generally lower but both regions face increasing risk of lake degradation from algal blooms and rapid loss of aquatic biodiversity (EEA, 2018). When assessing aquatic eutrophication, most attention has been devoted to these high concentrations of nutrients but the relative balance of N with respect to P has largely been neglected (Peñuelas and Sardans, 2022). While absolute concentration of the limiting nutrients does play a key role in supporting high standing stocks of phytoplankton and driving elevates rates of primary productivity, the relative availabilities of N and P (i.e., N/P stoichiometric ratio) can also affect a range of ecological patterns and processes (Elser et al., 2000, 2022).

Among a large variety of the ongoing anthropogenic changes, imbalances between N and P in the environment, connections of this imbalance with human activities and potential consequences are much less understood (Sterner and Elser, 2002; Peñuelas and Sardans, 2022). As early as 1930s, Redfield reported the C:N:P molar ratio of 106:16:1 for marine phytoplankton which appears to reflect the elemental requirements of phytoplankton undergoing the balanced growth (Loladze and Elser, 2011). However, emerging studies indicate that anthropogenic activity has largely altered N/P ratios in water, soils and organisms in the past decades. In aquatic ecosystems, a meta-analysis indicates that 55 from a total of 66 lakes with the consistent nutrient monitoring have experienced increases in the N/P ratios (Peñuelas et al., 2020). A recent survey in China confirms that similar increases in lake N/P ratio are widespread in populated regions (Tong et al., 2020). These scenarios have also been documented in diverse lakes such as Lake Zurich in Switzerland, Lake Okeechobee in the US, Lake Superior and Lake Erie in the US and Canada, Lake Dianchi in China, and many other lakes (Tong et al., 2020). Negative influences by increased N/P ratios in aquatic ecosystems occur via impacts on the physiologic growth status of phytoplankton that makes up the base of aquatic food chain. First, N enrichment relative to P could favor the plankton species with the stronger competitive abilities for using P, particularly for the species without N-fixing ability (Sterner and Elser, 2002). Second, per cell production of N-rich toxins could be enhanced by N enrichment (Van de Waal et al., 2014; Hellweger et al., 2022). Third, the increasing N/P ratio may favor a lower number of slowly-growing plankton species of the higher optimal N/P ratios. In freshwaters, when algae are competing for limiting nutrients, limitation of algal growth is determined by N if lake N/P mass ratio is lower than 9; while P is the limiting factor when this value is above 23 (Guildford and Hecky, 2000). Thus, in water of increased N/P ratio, growth rate of phytoplankton might slow down under P limitations, disrupting phytoplankton community structures (Peñuelas et al., 2020). Furthermore, by decreasing the rate of energy transfer through food web, imbalanced N/P ratio leading to P-limited phytoplankton with high biomass C/P ratios will result in the shorter trophic webs with fewer top predators (Sterner and Elser, 2002; Peñuelas and Sardans, 2022).

Water managements and pollutant control measures could differentially change the nutrient concentrations and their stoichiometry, since some pollution control strategies are often effective in removing one nutrient but not effective in eliminating the others (Yan et al., 2016; Tong et al., 2017). As one part of the United Nations Sustainable Development Goals (‘clean water and sanitation’), many countries have implemented wastewater treatments to control nutrient pollutions. However, the technologies most often applied in wastewater treatments usually retain more P than N, and thus increase N/P ratios as the unintended consequence (Tong et al., 2020). In wastewater treatment, excessive N can be removed by the microbe-mediated nitrification and denitrification steps but implementation of these N removal steps requires a high standard of facility operations (e.g., water temperatures, aeration, and carbon sources). Removing P from the wastewaters is usually a simpler but more effective process, involving coagulation, flocculation, and sedimentation. Thus, removal efficiency in municipal wastewater by WWTPs is up to 90% for TP but less so (60%) for TN, resulting in the effluents with much higher TN/TP mass ratios than the influent. Changes in nutrient stoichiometry can cause negative impacts on plankton community in the receiving water (Fig. 1).

Now, WWTP effluent has constituted an important component in the river networks or lakes, particularly in the populated areas or in arid regions. Effluent inputs, known as unintended wastewater reuse, can generate the physical or chemical discontinuities along the fluvial continua (Rice and Westerhoff, 2017). These disruptions can damage water quality, threaten securities of water supply and affect river ecosystem structures and function. However, the potential impacts of wastewater nutrient effluents in river networks have not been well characterized. In the Yangtze River estuary, the WWTP

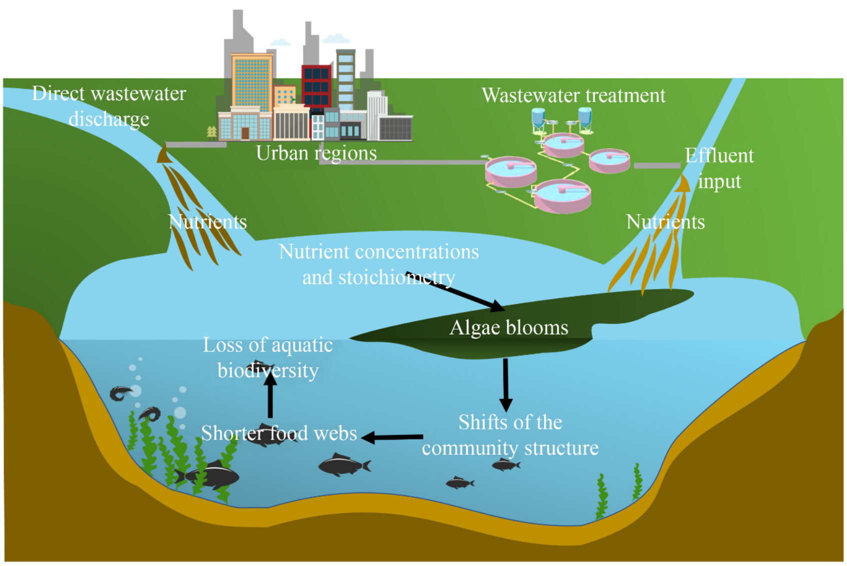

Fig. 1 Impacts of municipal wastewater input on nutrient concentrations in receiving water.

effluent inputs can contribute 14% of total flow during periods of low streamflow and contribution can be even up to 20% in the Han River, a large tributary of the Yangtze River (Wang et al., 2017). In more arid regions in Northern China, this contribution could be even higher. Since the 2000, China has made large progresses in improving wastewater treatment. However, little attention has been paid to disruption of nutrient dynamics in receiving waters, particularly negative impacts on nutrient stoichiometry and aquatic communities. In China, about 60 billion m^3 of effluent is discharged every year (Tong et al., 2017). Existing effluent discharge standards have limits on N and P concentrations before discharges (GB18918-2002), but these limits are mainly set by technical feasibility or operation cost. To achieve sustainable wastewater management, ecological consequences induced by the N over-enrichment relative to the P should be considered in future sanitation approaches in which N and P removals are considered in a holistic way. The time has come for environmental agencies and policy-makers to recognize the risks of unbalanced N/P ratios as well as other imbalances in elemental stoichiometry (e.g., C, Si, and S) imposed on biosphere. This strategy should begin by quantifying the contributions of WWTP effluents in river networks, their N/P balance, and subsequent effects on the ecology of recipient lakes, rivers or estuaries. Doing so will be a major undertaking which would requires close cooperation among ecologists, environmental engineers and management agencies.

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