Nitrogen removal by different riparian vegetation buffer strips with different stand densities and widths
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ABSTRACT

The migration of nitrogen (N) from farmland to lake aggravates eutrophication. Riparian buffer strips (RBSs) are crucial in alleviating nitrogen into water bodies. This study examined the impacts of different RBS patterns on nitrogen removal. The effects of different RBSs of various widths (5, 15, 30, and 40 m), with different vegetation types (Taxodium hybrid 'Zhongshanshan', poplar (Nanlin-95), and a mixed forest of T. hybrid 'Zhongshanshan' and poplar) and at different densities (400, 1,000, and 1,600 plants·hm⁻²) on the TN, NH₄⁺-N and NO₃⁻-N removal rates in different depths of runoff water were studied. The results showed that the 15 m-wide RBS removed nitrogen the most effectively, with average removal rates of NH₄⁺-N, NO₃⁻-N and TN reaching 67.79%, 65.93% and 65.08%, respectively. Among the RBSs with different vegetation types, the poplar forest RBS removed the most NH₄⁺-N (74.28%) and NO₃⁻-N (61.71%). The mixed-forest RBS removed the most TN (65.57%). The RBS with 1,000 plants·hm⁻² was more suitable in terms of the removal of NH₄⁺-N (74.25%), NO₃⁻-N (71.08%) and TN (62.67%). The conclusion can provide the basis of vegetation and width optimization for the design and construction of an RBS for maximum eutrophication nutrient removal.

Key words | nitrogen removal, nonpoint source pollution, riparian buffer strip, Taihu Lake, water quality

HIGHLIGHTS

- Construction and stability of different RBS patterns were operated for around three years.
- Removal capacity of N pollutants from runoff by different patterns was compared quantitatively.
- The 15 m-wide RBS with 1,000 stem·hm⁻² poplar plantation removed nitrogen the most effectively.

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INTRODUCTION

Due to the rapid development of industry and agriculture and increase in the usage of chemical fertilizers, pollution of surface waters such as lakes and rivers with nitrogen pollutants has become increasingly severe (Zhang et al. 2011). The RBS, a banded vegetation zone between polluted water bodies and pollution sources, serves as a buffer transition zone closely connected with aquatic ecosystems and terrestrial ecosystems (Glenn 2005). The RBS is also an important link for the exchange of energy, material and information between river ecosystems and terrestrial ecosystems (Casey & Klaine 2004). Currently, construction of RBSs is emphasized in lake eutrophication management to reduce the nitrogen content of lake water that occurs through surface runoff and underground runoff (Hefting et al. 2008). To protect river banks and water bodies, the New Zealand government has established regulations, including the restoration of river banks using riparian vegetation buffer strips (RBSs) (Yuan et al. 2002). RBSs have been considered the best management measure for soil and water in Canada (Lorion & Kennedy 2009), and other European countries are initiating research on RBS technology and actively promoting the application of this technology (Phillips 1989; Smith 1989).

In China, the level of eutrophication of lakes and reservoirs has exceeded 66%, of which approximately 22% of lakes experienced severe eutrophication and ultra-eutrophication, indicating that eutrophication of lakes and rivers has been a significant aquatic environmental problem for a long time (Guo et al. 2014). Water eutrophication not only severely affects the environment and health but also restricts the utilization of water resources (Abu-Zreig et al. 2004; Vymazal & Kröpfelová 2011). Taihu Lake, the third largest freshwater lake in China, plays a significant role in the economy and daily life of its surrounding residents (Qin et al. 2007). In May 2007, a large-scale outbreak of cyanobacteria in Taihu Lake caused widespread concern in society and among scholars, which resulted in the problem of eutrophication of lakes becoming recognized by the public as an urgent issue of the aquatic environment (Qin et al. 2010). Due to the universally wide range of agricultural production activities, agricultural nonpoint source pollution has become an important cause of the deteriorating water quality of lakes and rivers (Hazlett et al. 2008). The study showed that the most important form of water pollution in Taihu Lake is agricultural nonpoint source pollution, in which nitrogen pollution is up to 56% (Borin et al. 2010).

The width of an RBS determines whether it can fully exert its ecological service function (Lee et al. 2004; Chung et al. 2012; Valente-Neto et al. 2015). The ability of an RBS to remove nitrogen is generally considered to be positively correlated with its width (Mayer et al. 2007). The abilities of RBSs with widths of 3 and 6 m to retain nutrients and sediments were significantly different. A 6 m-wide RBS removed total nitrogen and nitrate-nitrogen from surface runoff at rates of 43% and 46%, respectively, while a 3 m-wide RBS removed TN and NO₃⁻N at rates of 66% and 28%, respectively (Lee et al. 1998). A 9.1 m-wide grassland buffer zone could remove 84% of the suspended particulate matter in surface runoff. However, when the width of this buffer was reduced to 4.6 m, the removal rate of the suspended particulate matter was 70%, and the efficiency of the interception and conversion of TN in surface runoff...
decreased from 73% to 54% (Dillaha et al. 1989). In the same study, the optimum width of the riparian buffer zone was 5–12 m, and the optimum width was greater than 15 m in field application (Kiffney et al. 2003). The minimum width of the RBS widely used in the United States is 30 m. In general, the width of the RBS is more than 30 m, which has a significant effect on the removal of pollutants (Hickey & Doran 2004). There have been many studies on the optimum width of an RBS, but to date, there has been no consensus on the optimum width, especially on a slight slope.

In an RBS, nitrogen pollutants in surface runoff are mainly intercepted by physical processes, such as sedimentation and infiltration (Li et al. 2014) through a series of biological and biochemical processes, including the adsorption of soil and plants (Mander et al. 2005), denitrification (Groffman et al. 1992), and microbial fixation (Hill 1996). One of the most important removal mechanisms is plant absorption (Groffman et al. 1992; Li et al. 2009; Tompkins et al. 2001). Moreover, the effect of the interception of pollutants by an RBS is largely dependent on its vegetation composition, so determining the optimal vegetation types of an RBS is particularly important (Blanco-Canqui et al. 2004). Studying the effects of plant composition on the interception ability of an RBS usually involves a combination of one or several vegetation types such as trees, shrubs and herbs. Different types of vegetation all have the ability to remove nitrogenous contaminants (Wu et al. 2020). RBSs covering vegetation are more effective in intercepting pollution (Dukes et al. 2002). However, woody plants and herbaceous plants have comparable abilities to remove pollutants (Hill & Jung 1975). The more developed roots of a tree can stabilize a river bank and prevent scour and erosion caused by water, while plants can increase the infiltration capacity of the surface runoff by increasing the surface roughness of the soil, thereby reducing runoff velocity and improving interception of sediment by the RBSs (Hogarth et al. 2003). A mixed RBS of grassland and grassland forest can reduce the TN content of surface runoff by 50% (Al-Wadaey et al. 2012). Planting shade-tolerant plants under trees can enhance the ability of an RBS to intercept pollutants (Duchemin & Hogue 2009). A study has shown that a perennial plant can absorb and assimilate nitrogen in amounts up to 400 kg·hm⁻² per year (Daniels & Gilliam 1996). However, most nitrogen will return to the soil with the aging and apoptosis of plant tissues (Wenger 1999). The absorption of nitrogen by plants causes nitrogen to be transferred from the soil to plant biomass, transported to the surface after wilting and death, and then converted into the large amount of inorganic nitrogen and organic carbon required for microbial denitrification by mineralization, and these processes play a key role in the circulation and transformation of nitrogen in an RBS (Sabater et al. 2003).

Currently, there have been few studies on the relationship between stand density and nitrogen removal capacity given different widths and plant composition in RBSs. An RBS can effectively filter sediment continuously, and its filtration capacity increases with increasing stand density (Anderson et al. 2007). In comparison with other combinations, a combination of woody plants and dense native warm-season plants would be more effective in intercepting nonpoint source pollutants (Cissel et al. 2006). By estimating a model of stand density and water quality in an RBS, the optimal density of an RBS for pollutant removal was determined to be 1,074 stem·hm⁻² (Song 2012).

Many studies have been carried out on the optimum pattern of the RBS by adjusting widths and vegetation. However, there has been no consensus on the optimum RBS pattern in removing N pollutants. This study intends to focus on the different RBS patterns to derive detailed quantitative analysis on the removal of N pollutants in runoff. To explore better design of RBSs using various widths, vegetation types and densities, a research project was designed in Yixing City of China. The test facility was constructed including buffer strip test bases and runoff collection devices. This research intends to compare and analyze the N pollutant removal effect of a typical vegetation buffer, in order to find the removal capacities of different RBS patterns for non-point source pollutants, and determine the best RBS pattern.

The research can furnish a technical basis for the prevention and control of non-point source pollution in Taihu Lake or similar plain river network areas. In addition, it can provide technical support for the design and construction of an RBS.

**MATERIALS AND METHODS**

**Study area**

This study was conducted in Zhoutie town adjacent to Taihu Lake, southeastern Yixing City, Jiangsu Province, China.
(31°07′N to 31°37′N, 119°31′E to 120°03′E) (Figure 1). The selected site is in an area with a subtropical monsoon climate and abundant annual rainfall (1,276.6 mm). The frost-free period is 239 d. The average annual temperature of the area is 15.7 °C, and the average annual sunshine duration is as long as 1,924.2 h. The accumulated temperature of the crop growth season is 5,475.8 °C (www.yixing.gov.cn).

The rainwater in the area was concentrated in spring and summer and the early summer was the rainy season. The annual average number of rainy days in the area was 136.6 d, and the annual average precipitation was 1,177.1 mm. The heavy rain in June and September was more frequent. The soil had a pH of 6.8, 24.1 g·kg⁻¹ organic matter, 0.2 g·kg⁻¹ TP and 9.7 g·kg⁻¹ TN, respectively (http://vdb3.soil.csdb.cn). The average slope of the soil surface was 2%.

**Plot setting**

There were eight plots of 20 m long × 40 m wide at the experimental site. The tree species were poplar (Nanlin-95) and *T. hybrid* ‘Zhongshanshan’, which are the main plantation species in the Taihu Lake Basin (Figure 2). The ages of the trees were five years old with good growth. The average height of the poplars was 4.0 m. The diameter at breast height (DBH) was 5.0 cm, and the average crown height was 135 cm. The average height of the *T. hybrid* ‘Zhongshanshan’ was 3.0 m, its DBH was 4.0 cm, and its average crown height was 105 cm.

Plots of a total of four different vegetation-types were established in the spring of 2010, including wasteland, *T. hybrid* ‘Zhongshanshan’, poplars, and mixed forests of *T. hybrid* ‘Zhongshanshan’ and poplars. The stand densities were 400 stem·hm⁻², 1,000 stem·hm⁻² and 1,600 stem·hm⁻² (Figure 2, Table 1). The widths of the different RBSs (5, 15, 30 and 40 m) corresponded to the distance from the front of the RBS parallel to the runoff direction (Figure 3).

The PVC leaching pipes were buried at widths of 0, 5, 15, 30 and 40 m in each plot, and three groups of leaching pipes were set at each width as replicates. The depths of each group of pipes were set at 20, 40 and 60 cm to serve as runoff collection devices at different depths. The interval between each leaching pipe was 1 m, and the interval between groups was 3 m (Figure 3).

Fertilization was carried out at 0–0.5 m in each plot. The amount of fertilization was the amount used on local farmland (48 kg·hm⁻²). The fertilization method was spreading, and the specification was a nitrogen–phosphorus–potassium (N-P-K) compound fertilizer ratio of 16:8:16. The basic properties of the soil are shown in Table 2. The test samples were collected during the local rainy season (April–September). The three sampling times were April 21–23, 2016; July 9–11, 2016; and September 23–24, 2016. Fertilization occurred...
one week apart from the sampling time. The rainfall during the period is shown in Table 3 (www.yixing.gov.cn).

### Chemical analysis

Three different depths of water samples were collected at different widths in each plot. The leaching water was extracted with a small plastic water pump and filled a 250 mL plastic bottle. Samples were brought back to the laboratory and stored in a $-4^\circ$C refrigerator. The different forms of nitrogen in the water samples were determined as soon as possible. After each sampling was completed, the

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Table 1 | The features of the experimental plots

| Plot number | Vegetation types                  | Stand density (stem·hm$^{-2}$) |
|-------------|-----------------------------------|-------------------------------|
| 1           | Wasteland                          | —                             |
| 2           | *T. hybrid* 'Zhongshanshan'        | 400                           |
| 3           | Poplar (Nanlin-95)                 | 400                           |
| 4           | Poplar (Nanlin-95) × *T. hybrid* 'Zhongshanshan' | 1,000                       |
| 5           | *T. hybrid* 'Zhongshanshan'        | 1,000                         |
| 6           | Poplar (Nanlin-95)                 | 1,000                         |
| 7           | *T. hybrid* 'Zhongshanshan'        | 1,600                         |
| 8           | Poplar (Nanlin-95)                 | 1,600                         |

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**Figure 2** | Layout of experimental plots.

**Figure 3** | The test plots and installation of water collection pipes.
water in the water pipe was drained and emptied far from the sample plot.

We used a carbon–hydrogen–nitrogen (CHN) elemental analyzer (2,400 II CHN elemental analyzer; Perkin Elmer, Boston, MA, USA) to determine the TN. The water samples of NH₄⁺-N and NO₃⁻-N first needed to be filtered by a 0.45 μm filter membrane and then determined using an ultraviolet visible spectrophotometer (UV-2550; Shimadzu, Kyoto, Japan). TN, NH₄⁺-N and NO₃⁻-N were analyzed according to standard protocols (APHA 2014).

The rate of nitrogen removal from runoff is based on Equation (1):

\[
r_{Ni} = \frac{(N_0 - N_i)}{N_0} \cdot 100\%,
\]

where \(i\) is the RBS width (5, 15, 30 and 40 m), \(r_{Ni}\) is the cumulative removal rate of nitrogen at different widths (%), \(N_i\) is the concentration of nitrogen at the width of \(i\) (mg·L⁻¹), and \(N_0\) is the concentration of nitrogen in runoff water at the 0 m width (mg·L⁻¹). If \(r_{Ni}\) is greater than zero, the concentration of nitrogen at \(i\) width is higher than that at the initial width. If \(r_{Ni}\) is less than zero, the concentration of nitrogen at \(i\) width is lower than that at the initial width.

### Statistical analyses

All data were expressed as the observed mean, followed by its standard error (±SE). Statistical analyses were performed using SPSS Version 19.0 software (SPSS Inc., Chicago, USA). Means were compared using the least significant difference (LSD) determined by a one-way ANOVA, and differences were considered statistically significant at \(p < 0.05\).

### RESULTS AND DISCUSSION

#### Differences in nitrogen interception and absorption in the RBS with different widths

**The effect of the RBSs with different widths on runoff NH₄⁺-N removal**

In the case of NH₄⁺-N, the mass concentration of runoff NH₄⁺-N decreased as the depth of the runoff deepened and width increased within the first 15 m width, which generally occurred in the order of 20 cm (0.549 mg·L⁻¹) > 40 cm (0.552 mg·L⁻¹) > 60 cm (0.393 mg·L⁻¹) (Figure 4(a)). The NH₄⁺-N removal efficiencies of the RBSs for runoff depths of 20 cm (63.76%) and 40 cm (68.49%) were higher than that of 60 cm (60.14%). The reason for this result may be that on the one hand, the NH₄⁺-N leached into the deep soil continuously while moving horizontally through the RBS, thus causing the runoff nitrogen concentration at the shallower depths to gradually decrease and rapidly be intercepted and transformed; on the other hand, the capillary roots of the buffer plants and the root system of the ground vegetation were densely distributed in the soil at depths of 15–40 cm. The abundant roots are deemed to have well created the underground soil environment for a long time and provided the inhabitation conditions for microfauna, and further carried out plant uptake well.

The ANOVA indicated that in the runoff at various depths, the NH₄⁺-N concentrations at widths of 0 m (0.73 mg·L⁻¹), 5 m (0.35 mg·L⁻¹) and 15 m (0.23 mg·L⁻¹) were obviously different \((p < 0.05)\), while at widths greater than 15 m, the NH₄⁺-N concentrations showed no significant difference \((p > 0.05)\). The RBS at the width of 40 m and
The concentration and removal efficiency of N in runoff at different widths of RBSs, and the removal efficiency of runoff N in RBSs with the same widths but different depths; the different letters indicate significant differences at the $p < 0.05$ level.
depths of 20, 40 and 60 cm resulted in average NH$_4$-N concentrations of 0.275, 0.219, and 0.201 mg·L$^{-1}$ and removal efficiencies of 65.76%, 68.49% and 60.14%, respectively. The removal efficiency of runoff NH$_4$-N was not only affected by the various depths of the RBS, with an order of increasing efficiency of 40 cm > 20 cm > 60 cm, but also changed with widths from 0 to 40 m, showing a trend of increasing first and then decreasing. In comparison with the RBSs with other widths, the RBSs with widths of 15 m (67.79%), 30 m (68.81%) and 40 m (68.13%) had better removal rates, which were not significantly different ($p > 0.05$).

The effect of the RBSs of different widths on runoff NO$_3$-N removal

Figure 4(b) shows that after flowing through an RBS of a certain width, the concentration of runoff NO$_3$-N continually decreased, and the removal efficiency of NO$_3$-N increased as the width of the RBS increased. The RBSs with widths of 15 m (65.93%), 30 m (68.58%) and 40 m (68.69%) showed higher removal efficiencies, which were not significantly different ($p > 0.05$). At the width of 5 m, the removal efficiency (53.56%) was lower by 23.6%, 28.1% and 28.7% than those of RBSs with widths 15 m, 30 m, and 40 m and the differences were significant ($p < 0.05$). These results were similar to those for the removal of NH$_4$-N, which indicated that the removal efficiencies of NH$_4$-N and NO$_3$-N were higher in the RBS with a width of 15 m than in RBSs with other widths. The concentration of NH$_4$-N in the RBS with different widths was in the following order: 20 cm > 40 cm > 60 cm, while the concentration of NO$_3$-N at the widths of 5 and 15 m was 20 cm > 40 cm.

A one-way ANOVA showed that the runoff NO$_3$-N concentration at different widths differed significantly ($p < 0.05$) within the first 15 m width of the RBS, which indicated that NO$_3$-N interception and transformation mainly occurred at the smaller widths of the RBS, and as the width of the RBS increased, the removal effect became increasingly weak. The results above are similar to the results of many previous studies (Jacobs & Gilliam 1985; Lowrance 1992; Wenger 1999; Abu-Zreig et al. 2004). At the far end of the RBS, the average concentrations of NO$_3$-N in the runoff at the three depths of 20, 40 and 60 cm were 0.232, 0.224 and 0.211 mg·L$^{-1}$, while the removal efficiencies were 67.76%, 65.69% and 64.58%, respectively.

The effect of the RBSs of different widths on runoff TN removal

As the width of the RBS increased, the runoff TN concentration decreased continually (Figure 4(c)). At the far end of the RBS, the average TN concentration decreased to 1.63, 1.34, and 1.20 mg·L$^{-1}$ at depths of 20, 40 and 60 cm, respectively, which were significantly lower concentrations than those at the beginning of the RBS ($p < 0.05$). The maximum TN removal efficiency from runoff was 64.40% at a depth of 40 cm, while the minimum removal efficiency from runoff of 57.53% was at a depth of 60 cm. The variance analysis of runoff TN concentration at different widths showed that in runoff of various depths, the TN concentration varied significantly ($p < 0.05$) at the RBS widths of 0 m (4.11 mg·L$^{-1}$), 5 m (1.96 mg·L$^{-1}$) and 15 m (1.43 mg·L$^{-1}$), while there were no significant differences after 15 m. The removal efficiencies at RBS widths of 15, 30 and 40 m differed minimally and were as high as 65.08%, 65.02% and 66.01%, respectively, which indicated that the runoff TN concentration decreased as the width of the RBS increased (within a 15 m width), while after a width of 15 m, the TN concentration did not substantially change.

One of the important functions of an RBS in agricultural nonpoint source pollution control is to intercept nitrogen pollutants in surface runoff (Borin et al. 2010). An RBS can reduce the impacts of runoff by sedimentation, interception, and adsorption of nitrogenous contaminants through vegetation as well as interception in soil (Lin et al. 2004). On the one hand, the vegetation and soil in an RBS can intercept and adsorb some nitrogen particles in runoff water; on the other hand, soil particles and colloids adsorb some nitrogen on the soil surface, and plants can absorb and assimilate some nitrogen to form their own compounds (Cors & Tychon 2007). Width was an important factor affecting the nitrogen removal ability of an RBS (Hefting et al. 2005). A reasonable width of an RBS was advantageous for improving the interception efficiency of nitrogen pollutants. The present study showed that with an increase in RBS width, the concentrations of NH$_4$-N, NO$_3$-N and TN in
runoff water decreased. The most significant nitrogen removal was at 15 m width, however the increases after 15 m were less effective.

The results of this study showed that the concentrations of $\text{NH}_4^+\text{-N}$, $\text{NO}_3^-\text{-N}$ and TN in the RBS with a width of 15 m varied significantly with the width of the RBS ($p < 0.05$), and the removal rate increased significantly. At widths greater than 15 m, there was no significant variation among the different widths. The increasing trend in removal rate slowed down or dropped to a certain extent. The concentrations of $\text{NH}_4^+\text{-N}$ and TN in the runoff water at the three depths decreased in the order of $20 \text{ cm} > 40 \text{ cm} > 60 \text{ cm}$. The nitrogen moved horizontally through the RBS and leached to the deep soil, which caused the concentration of nitrogen in the runoff water at shallower depths to decrease gradually; thus, nitrogen was intercepted and transformed rapidly (Chung et al. 2010). In addition, the root system of shallow soil vegetation was densely distributed, and soil microbial activity was higher, mainly due to the interaction of wetland vegetation absorption and microbial denitrification. During rainfall, the $\text{NO}_3^-\text{-N}$ applied to the fertilization area was rapidly transferred into the deep soil layer at a depth of 40 cm or deeper and then moved horizontally in the soil layer and gradually moved into the water. The $\text{NO}_3^-\text{-N}$ was removed during its transfer process through various effective mechanisms of the RBS, and while the $\text{NO}_3^-\text{-N}$ leached into the soil layer at a depth of 20 cm, the $\text{NO}_3^-\text{-N}$ approached the riparian buffer in a horizontal direction and constantly leached into the deep soil at the same time. Thus, the concentration of $\text{NO}_3^-\text{-N}$ that horizontally moved within the soil layer at a depth of 20 cm gradually decreased, and after moving in the horizontal direction over a very short distance, the $\text{NO}_3^-\text{-N}$ was quickly intercepted and transformed. On the other hand, at the front end of the RBS, the runoff water flowed faster, which led to a faster migration of $\text{NO}_3^-\text{-N}$ in the vertical direction, while at the backend at widths of 30 and 40 m, the runoff velocity slowed, which led to a decrease in the $\text{NO}_3^-\text{-N}$ concentration; thus, the migration velocity slowed (Cey et al. 1999).

When surface runoff occurred, the flow velocity of the runoff was greater at the closest of the RBS than at the farthest of the RBS, and the nitrogen adsorbed by the surface soil particles went through the RBS with the surface runoff. As the vegetation increased runoff resistance and reduced the velocity of flow, some of the nitrogen-containing particulate matter in the runoff was gradually retained at a width of approximately 15 m.

Differences in nitrogen interception and absorption in the RBSs with different stand densities

The effect of the RBSs with different stand densities on runoff $\text{NH}_4^+\text{-N}$ removal

The $\text{NH}_4^+\text{-N}$ concentrations in the RBSs with the three different stand densities were significantly different at the beginning and end of RBSs ($p < 0.05$), and in addition, the RBSs with different stand densities had different effects on the removal efficiency of $\text{NH}_4^+\text{-N}$. In comparison with the other RBS stand densities, the RBS with 1,000 stem·hm$^{-2}$ had the highest removal rate of $\text{NH}_4^+\text{-N}$ from runoff, at an average removal efficiency of 74.25%, and the RBS with 1,600 stem·hm$^{-2}$ had the next highest removal rate at an average removal efficiency of 69.56%. The RBS with 400 stem·hm$^{-2}$ had the lowest removal efficiency at 63.65% and lower by 16.7% and 9.3% than that of the RBSs with 1,000 stem·hm$^{-2}$ and 1,600 stem·hm$^{-2}$, respectively. At a width of 15 m, the RBS with a density of 1,000 stem·hm$^{-2}$ (81.00%) had a higher removal efficiency than that of the RBS with 1,600 stem·hm$^{-2}$ (67.55%), and the difference was significant ($p < 0.05$). At the other widths, the removal efficiencies were almost the same. In the four RBSs with different widths, the RBS with a density of 1,000 stem·hm$^{-2}$ had a significantly higher removal efficiency than that of the RBS with 400 stem·hm$^{-2}$ ($p < 0.05$, except at a width of 30 m).

The effect of the RBSs with different stand densities on runoff $\text{NO}_3^-\text{-N}$ removal

The three RBSs with different stand densities showed high and different $\text{NO}_3^-\text{-N}$ removal efficiencies from runoff
The RBS with 1,000 stem·hm\(^{-2}\) showed the highest average removal efficiency of NO\(_3\)\(-N\) (71.08\%). The average removal efficiency of the RBSs with 1,600 stem·hm\(^{-2}\) (70.08\%) and 400 stem·hm\(^{-2}\) (61.37\%) was lower by 1.4\% and 15.8\% than that of the RBS with 1,000 stem·hm\(^{-2}\). At a width of 50 m, the RBS with a density of 1,000 stem·hm\(^{-2}\) (70.66\%) had a lower removal efficiency of NO\(_3\)\(-N\) than that of the RBS with 1,600 stem·hm\(^{-2}\) (75.19\%); while at other widths, the RBS with a density of 1,000 stem·hm\(^{-2}\) showed a higher NO\(_3\)\(-N\) removal efficiency than those of the RBSs with different densities, and the difference was not obvious. Of the four RBSs with different densities, the RBS with 1,600 stem·hm\(^{-2}\) had a higher average removal efficiency than that of the RBS with 400 stem·hm\(^{-2}\), and the difference was significant at widths of 5 and 15 m (\(p < 0.05\)).

**The effect of the RBSs with different stand densities on runoff TN removal**

Figure 5(c) shows the effects of the three RBSs with different vegetation densities on the removal of runoff TN. The three different stand densities of the RBS all showed high and clearly different removal efficiencies of runoff TN. Of the three RBSs with different vegetation densities, the RBS with 1,600 stem·hm\(^{-2}\) showed the highest average efficiency of TN (64.05\%) and was significantly higher than that of the RBS with 400 stem·hm\(^{-2}\) (\(p < 0.05\)). When the density of the RBS decreased from 1,000 to 400 stem·hm\(^{-2}\), the average removal efficiency of runoff TN decreased from 62.67\% to 50.60\%. At widths of 5 m (55.26\%) and 15 m (65.35\%), the removal rate of TN in the RBS with 1,000 stem·hm\(^{-2}\) was clearly different than that in the RBS with a density of 400 stem·hm\(^{-2}\) (34.83\%, 53.22\%, respectively) (\(p < 0.05\), while there was no obvious difference between the removal rate of TN at widths of 50 and 40 m. In addition, there was no significant difference in the removal rates of TN between the RBSs of 1,600 stem·hm\(^{-2}\) and 1,000 stem·hm\(^{-2}\) at different widths.

With the increase in stand density, the amount of nitrogen entering the RBSs decreased. However, there was no significant difference in the removal rates of different fractions of nitrogen between the RBS with 1,600 stem·hm\(^{-2}\) and the RBS with 1,000 stem·hm\(^{-2}\), which may have been because although the stand density was high enough to absorb nitrogen, there was more vegetation litter in the RBS with high stand density and more nitrogen recycling to the soil through senescence and decay of leaves (Rutherford & Nguyen 2004). Studies have shown that approximately 80\% of the nitrogen absorbed by a deciduous forest RBS will return nitrogen to the soil as plant litter and decay (Nilsson & Svedmark 2002).

**Difference in nitrogen interception and absorption in the RBSs with various types of vegetation**

**The effect of the RBSs with various vegetation types on runoff NH\(_4\)\(-N\) removal**

The removal effects of the RBSs with the different vegetation types (\(T\). \(hybrid\) ‘Zhongshanshan’ forest, poplar forest, and mixed forests) on NH\(_4\)\(-N\) in runoff are shown in Figure 6(a). After passing through these RBSs buffers, the NH\(_4\)\(-N\) concentration in runoff was significantly reduced, and the RBSs with various vegetation types showed clear differences in NH\(_4\)\(-N\) removal efficiencies. Of the three riparian vegetation buffer system vegetation types, the average removal efficiency of the poplar forest (74.28\%) was higher by 25.6\%, 7.5\% and 59.8\% than that of the \(T\). \(hybrid\) ‘Zhongshanshan’ forests (59.13\%), mixed forests (69.05\%) and the wasteland (control) (46.47\%), respectively. In the runoff of forested RBSs with the three types of vegetation, the NH\(_4\)\(-N\) removal efficiency occurred as follows: poplar forests > \(T\). \(hybrid\) ‘Zhongshanshan’ forests > mixed forests. In the 5 m (67.13\%) and 30 m (73.69\%)-wide RBSs, the NH\(_4\)\(-N\) removal efficiencies of the poplar forest RBS were significantly different from those of the RBSs with the other two vegetation types (\(p < 0.05\)), and the removal efficiencies of the three vegetation types were all higher than that of the wasteland (control).

**The effect of the RBSs with various vegetation types on runoff NO\(_3\)\(-N\) removal**

The removal effects of the RBSs with various vegetation types on NO\(_3\)\(-N\) in runoff are shown in Figure 6(b). The NO\(_3\)\(-N\) removal efficiency of RBSs with different vegetation types was significantly higher than that of the
Figure 5 | The removal efficiency of N by the RBSSs with different stand densities.
Figure 6 | The effect of RBSs with various vegetation types on runoff N removal.
wasteland (control) (45.99%) in the widths of 5, 15 and 30 m (p < 0.05). The average removal efficiency of the poplar forest (61.71%) was higher by 3.6%, 9.2% and 34.2% than that of the T. hybrid ‘Zhongshanshan’ forests (59.57%), mixed forests (56.52%) and the wasteland (control) (45.99%), respectively. The removal efficiencies occurred from the highest to lowest as follows: poplar forests > T. hybrid ‘Zhongshanshan’ forests > mixed forests. In the 5 m-wide part of the RBSs, the NO3–N removal efficiency of the poplar RBS and the mixed RBS clearly differed (p < 0.05), while at other widths, the removal efficiencies were not different. The average efficiency of the poplar forest and T. hybrid ‘Zhongshanshan’ forest differed little at all widths of the RBSs. The mixed forests at the 30 m (70.05%) and 40 m (69.92%) widths showed higher removal efficiencies than those of the other two vegetation forest types, among which the efficiency of the T. hybrid ‘Zhongshanshan’ forest (65.47%) at 30 m width clearly differed (p < 0.05).

The effect of the RBSs with various vegetation types on runoff TN removal

In the case of TN, it showed clear differences with various vegetation types in TN removal efficiencies (Figure 6(c)). The TN removal efficiency of mixed forests (65.57%) and poplar forest (62.67%) were higher than that of T. hybrid ‘Zhongshanshan’ forests (60.63%) and the wasteland (control) (53%). The TN removal efficiency of the RBSs with three different vegetation types occurred from highest to lowest as follows: mixed forests > poplar forest > T. hybrid ‘Zhongshanshan’ forest. In the 50 m-wide RBSs, the TN removal efficiencies of the poplar forest and the mixed forests clearly differed (p < 0.05), while at other widths, the removal efficiencies did not differ. The efficiencies of the mixed forest and T. hybrid ‘Zhongshanshan’ forest RBSs did not substantially differ at any width of the RBSs, and the mixed forests at a width of 5 m showed lower removal efficiencies (60.67%) than the efficiencies of the two other forest types. At the 15, 30 and 40 m-wide RBSs, the efficiencies of the poplar forest and T. hybrid ‘Zhongshanshan’ forest were lower than that of the mixed forest possibly because most of the roots were concentrated in the deeper soil layer, and after reaching a certain width, the TN in the runoff water seeped out of the runoff.

RBS vegetation served its function of preventing and controlling nonpoint source pollution by the mechanism of transporting and absorbing dissolved oxygen, providing habitats for microorganisms, reducing the speed of runoff, loosening the soil and regulating the microclimate (Schoonover et al. 2010). This mechanism may differ in each reaction depending on RBS condition, and a certain mechanism could be especially effective for a certain nitrogen pollutant. Different types of vegetation cause differences in plant tissue compositions, root types and activity intensities, resulting in differences in the absorption and transformation of nitrogen and other pollutants in RBSs containing different vegetation types (Schultz et al. 1995).

The results showed that the concentrations of NH4+-N, NO3–N and TN in the runoff decreased significantly in RBSs with different types of vegetation with increasing widths. The NH4+-N and NO3–N removal rates in RBS with poplars were higher than those with other vegetation types. The TN removal rate in the mixed forest RBS was higher than the RBSs with other vegetation types, but there was no significant difference from that with poplars (p > 0.05, except 30 m). In general, broad-leaved forests can improve nitrogen accumulation in soil, while coniferous forests are not conducive to improving nitrogen accumulation (Gutknecht et al. 2006).

CONCLUSIONS

The RBSs had a better removal capacity for N pollutants than strips without any tree cover (wasteland) and the removal capacity could be improved in the aspects of the width, vegetation type and density. In summary, the 15 m-wide RBS attained the desired goal in terms of nitrogen removal. The poplar forest RBSs were more suitable for nitrogen removal. The RBS with 1,000 stem-hm−2 was the optimal density in terms of nitrogen removal.

This study for optimizing RBS patterns not only suggests that the widths, vegetation types and stand densities are very important in influencing N removal, but also provides essential scientific and technological support for the prevention
and control of nonpoint source pollution in the lake basin and the steady improvement of the lake water quality.

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AUTHOR CONTRIBUTIONS

W.Y.B. conceived and designed the experiments; L.J. made contributions to the design, data processing; L.J. wrote the paper; both authors read and approved the manuscript.

ADDITIONAL INFORMATION

The authors declare there is no conflict of interest regarding the publication of this paper.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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