



Mechanism of nitrogen loss driven by soil and water erosion in water source areas

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Abstract Nitrogen (N) present in drinking water as dissolved nitrates can directly affect people's health, making it important to control N pollution in water source areas. N pollution caused by agricultural fertilizers can be controlled by reducing the amount of fertilizer applied, but pollution caused by soil and water erosion in hilly areas can only be controlled by conservation forests. The catchment area around Fushi Reservoir was selected as a test site and mechanisms of N loss from a vertical spatial perspective through field observations were determined. The main N losses occurred from June to September, accounting for 85.9–95.9% of the annual loss, with the losses in June and July accounting for 46.0% of the total, and in August and September for 41.9%. The N leakage from the water source

area was effectively reduced by 38.2% through the optimization of the stand structure of the conservation forests. Establishing well-structured forests for water conservation is crucial to ensure the security of drinking water. This preliminary research lays the foundation for revealing then loss mechanisms in water source areas and improving the control of non-point source pollution in these areas.

Keywords Water source areas · Nitrogen loss · Non-point source pollution · Water quality · Surface runoff

Introduction

With the population growth and the modernization of agricultural practices, human activities are having an increasing effect on aqueous environments (Hobbie et al. 2017; Tasdighi et al. 2017). For instance, the impact of agricultural production in the USA during the 1960s and 1970s led to a deterioration of the water quality in the Great Lakes, where the proliferation of cyanobacteria seriously affected the survival of fish and other aquatic organisms. Lake Erie, one of these lakes, is now referred to as a “dead sea” in North America (Rudra et al. 2020). A similar situation is also found in China, where roughly 60% of lakes have varying degrees of pollution, 50% of which is caused by non-point source pollution (NPSP) (Zhang et al. 2018). Nitrogen

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(N) pollution contributes 81% of water pollution in China (Ongley et al. 2010; Yang et al. 2011). High levels of N in a water body can lead to eutrophication (Shen et al. 2014), and this in turn triggers the proliferation of harmful and toxic algae, exhausts the oxygen content of the water body, affects aquatic biodiversity, and damages the balance of the surrounding ecosystem and the development of the social economy (Zhang et al. 2018).

Nitrogen in drinking water can directly affect the health of residents around the water body (Li et al. 2021), with studies showing that a high intake of nitrates increases the incidence of cancer, blood diseases and other illnesses (Knobeloch et al. 2000; Liu et al. 2014a). Currently, the World Health Organization and many countries (including the USA and China) require that the nitrate-N content of drinking water should not exceed 10 mg L^{-1} (Li et al. 2021; Wang et al. 2022b). Thus, reducing the N content of water bodies, especially in source areas for drinking water, is important in the sustainable development of regional ecosystems and in protecting the health of residents around the water source.

Taihu Lake Basin is located in the most economically developed region in China and is also the most important water source area. According to the China Statistical Yearbook 2020, the areas surrounding the basin (Jiangsu, Shanghai, and Zhejiang) account for 20.2% of China's total gross domestic product. NPSP in Taihu Lake Basin is a hindrance to further economic and social progress in this area and a threat to the health of residents (Li et al. 2017; Wang et al. 2017; Xu et al. 2017). Lian et al. (2018) and Yan et al. (2019) both found that a large amount of N enters Taihu Lake every year, posing a threat to its aquatic ecosystems. In view of this, controlling N pollution is the priority for water resource management in Taihu Lake Basin.

Research on controlling losses of N have mainly focused on managing losses from farmland, especially paddy fields (Ding et al. 2020). Zhao et al. (2020) found that fertilization in the Taihu Lake area was the main factor leading to local N pollution in paddy fields. They also found that decreasing the amount of fertilizer applied to paddy fields from 300 to 240 kg N ha^{-1} could reduce the loss of total-N by 31.6% while maintaining crop yields. Reducing the application of fertilizer during agricultural production is therefore an effective approach to limiting N pollution.

Fushi Reservoir is located southwest of Taihu Lake Basin and is the largest reservoir in northern Zhejiang province and one of the most important drinking water sources in the district (Wang et al. 2022a). To prevent agricultural non-point source pollution, the local government currently prohibits large-scale agricultural production around the reservoir (Sun et al. 2020), and therefore fertilization is not a major contributor to NPSP. However, the region is hilly, with abundant rainfall between June and September, making it prone to soil erosion during this period. N and phosphorus (P) in the soil

are transported into the reservoir by surface runoff, leading to eutrophication.

Our research group has carried out a series of studies on the prevention and control of NPSP in this area for more than 10 years (Sun et al. 2020; Wang et al. 2022a), and the results have demonstrated that the loss of N through soil erosion is the main risk to local water bodies and the loss of total-N from bamboo stands in the catchment area exceeds the drinking water threshold. The form of nitrogen lost is dominated by nitrate-N, which shows there is a specific problem with N pollution that needs to be resolved urgently. However, the mechanism of N loss is still unclear. Are the characteristics consistent over time? Does it differ vertically (from rainfall to throughfall and surface runoff)? What factors influence N loss? These questions are worthy of in-depth study.

Accordingly, a systematic study on the mechanism of N loss was carried out. An area covered by moso bamboo stands was selected as the test plots and in situ field observations were used to explore N loss from both temporal and spatial perspectives. We hypothesized that: (1) N loss would differ over time because of atmospheric variations in different seasons; (2) N loss would show different characteristics in vertical spatial terms as a result of the different influences of various bamboo stand structures and surface vegetation cover; and, (3) N loss may be effectively reduced by optimizing the stand structure in water source areas. The overarching aim of this study was to clarify the mechanisms of N loss and provide a scientific basis for the treatment of NPSP.

Materials and methods

Description of test area

Fushi Reservoir is the largest reservoir in Anji County ($119^{\circ}14' - 119^{\circ}53' \text{ E}$, $30^{\circ}23' - 30^{\circ}53' \text{ N}$), with a storage capacity of $217 \times 10^6 \text{ m}^3$ and a depth of 28 m. When its flood waters are discharged, the reservoir is connected to the Xitiaoxi River through a canal and eventually flows into Taihu Lake. Fushi Reservoir is one of the most important water sources in the Taihu Lake watershed.

The terrain of Anji County is steep in the southwest and low in the northeast. It has a mild subtropical maritime monsoon climate with abundant sunlight and rainfall, four distinct seasons and an average annual temperatures of $12.2 - 15.6 \text{ }^{\circ}\text{C}$. The main forest type in the area is evergreen broadleaved forest. There are three main soil types: cambisols, anthrosols (hydragric) and leptosols (lithic). The average annual rainfall is 1450 mm, mostly concentrated in the June–September rainy season (Wang et al. 2022a).

Since the reform of the economic system in China in the 1980s, local residents have planted moso bamboo

(*Phyllostachys edulis*) as an important commercial species, plantations of which formed the main vegetation cover in our test plots. Three runoff plots with different bamboo stand structure were established in the catchment area of the reservoir (Fig. S1). The plots were the T1 runoff plot, consisting of pure *P. edulis* (local species) as the control without interplanting; the T2 runoff plot of *P. edulis* with interplanted *Taxus chinensis* (Rehd. & Wilson) Rehd. and *Illicium lanceolatum* L. (introduced species) at a row spacing of 4 m × 3 m; and the T3 runoff plot of *P. edulis* with interplanted *Amorpha fruticosa* L. (local species) in a strip pattern at a row spacing of 3–4 m. *P. edulis* and *I. lanceolatum* are evergreen species; *A. fruticosa* is deciduous.

Each runoff plot was 5 m wide and 20 m long (100 m²). Runoff buckets were set up inside the runoff plots to collect the throughfall and a runoff pond was set at the bottom of each to collect surface runoff generated by rainfall. In addition, a runoff bucket was set up in the surrounding open space to collect atmospheric rainfall (Fig. S1). The basic conditions of the runoff plots are shown in Table S1.

In recent years, due to a decline in the value of bamboo, the local residents have adopted an extensive management model to control costs and no longer fertilize the bamboo plantations.

Sample collection

After rain falls on forested areas, it first interacts with the forest canopy. Part is intercepted by the canopy and part passes through the canopy to create rainfall inside the forest called throughfall (Wang et al. 2022a). Thus, the vertical variation of precipitation in forests, from high to low, is composed of atmospheric rainfall, throughfall, and surface runoff (Fig. S2). To probe the vertical variation of N runoff in bamboo stands, different types of rainfall and runoff were measured, including atmospheric rainfall; rainfall at the crown measured at the top of the bamboo stand; throughfall measured at a bamboo-stand height of approximately 30–40 cm; and surface runoff measured at ground level.

The sampling period was from July 2020 to July 2021. Eight effective rainfall events (in which runoff was produced) were observed and samples collected (Table S2). The main aim of our study was to observe rainfall events that produced surface runoff which, in turn, affected water bodies. Not all rainfall events produce surface runoff as this depends on soil water content, the volume of rainfall and other factors. After each rainfall event, a 250-mL polyethylene bottle was used to collect surface runoff and throughfall in the three runoff plots. Water samples were also taken from the atmospheric rainfall in the runoff buckets in the surrounding open space. Each sample was taken in triplicate.

Water sample analysis

Total-N, dissolved-N, particulate-N, nitrate-N, and ammonia-N as the main indicators were measured to determine N migration in runoff. Dissolved-N is easily soluble in water and migrates with surface runoff. However, the main form of N loss has been reported to be nitrate-N, followed by ammonia-N (White et al. 2018). An incubator and ice bag were used to keep the water samples at low temperatures during the sampling process.

Total-N in the water samples was determined by potassium persulfate oxidation and ultraviolet spectrophotometry (Wang et al. 2020). For the determination of dissolved-N, the water samples were filtered through a 45- μ m filter membrane and measured by potassium persulfate oxidation and ultraviolet spectrophotometry (Tang et al. 2018; Wang et al. 2020). The concentration of particulate-N was evaluated by subtraction (total-N minus dissolved-N) (Uusitalo et al. 2001). Ammonia-N was calculated by the indophenol blue spectrophotometric method (Lu 1999) and nitrate-N by ultraviolet spectrophotometry (Lu 1999).

Data analysis

Data analysis was performed using Excel 2016 (Microsoft USA 2015), SPSS 19.0 (IBM Armonk USA 2010) and the R Programming Language 3.6.2. Excel 2016 plotted the changes in N concentration over time. SPSS 19.0 performed least significance difference and Duncan significance analysis on the N concentrations among atmospheric rainfall, throughfall and surface runoff. Pearson correlation analyses between the atmospheric rainfall N concentration and throughfall N concentration, as well as the soil N content and surface runoff N concentration, were performed using R 3.6.2.

Results

Characteristics of nitrogen loss over time

Changes in N concentrations in throughfall

The trends of variation in the throughfall total-N concentration over time were basically the same for the three different stand structures (Fig. 1a). Concentrations of total-N in the three stands peaked on 21 April 2021, and concentrations of total-N in plots T1, T2 and T3 were 5.4, 4.0 and 4.3 mg L⁻¹, respectively. The total-N concentrations in the throughfall then gradually decreased and remained relatively stable during rainfall events from 21 June to 30 August 2021 and was generally < 1.50 mg L⁻¹. However, it showed a second peak during a rainfall event on 7 September 2021, with

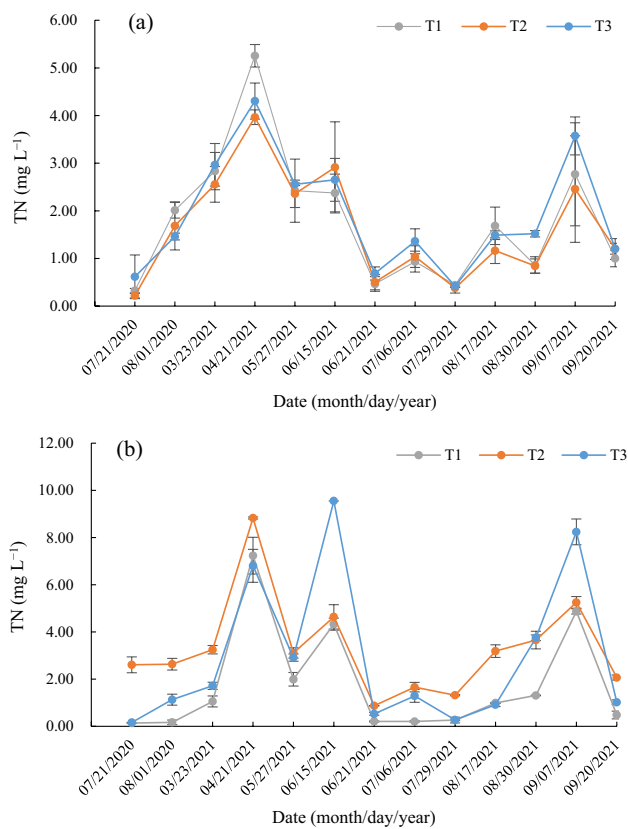


Fig. 1 Changes in the total-N concentration in **a** throughfall and **b** surface runoff over time in the three experimental plots

concentrations of 2.8, 2.5 and 3.6 mg L⁻¹ in plots T1, T2 and T3, respectively.

Changes in N concentrations in surface runoff

There were differences in total-N levels in the surface runoff from the three plots, but the overall trend over time was

consistent (Fig. 1b). From April to early June and on 7 September 2021, total-N concentrations in surface runoff were relatively high. The highest concentration in surface runoff (9.5 mg L⁻¹) occurred in plot T3 on 15 June 2021, followed by plot T2 (8.8 mg L⁻¹) 21 April 2021. Total-N levels in surface runoff were relatively low in March 2021 and from late June to September 2021. During this period, it was < 2.0 mg L⁻¹.

Changes in N loss in surface runoff

It is important to determine the N loss in surface runoff. Plot T2 was explored the distribution of N loss during 2021 (Table 1) and it was found that it was highest during the rainy season (June–September). Within this period, the loss of total-N, dissolved-N, particulate-N, nitrate-N, and ammonia-N accounted for 87.9%, 88.4%, 85.9%, 87.3%, and 95.9%, of the annual loss, respectively. Losses of total-N, dissolved-N and nitrate-N were mainly concentrated in June and July, accounting for 46.0%, 50.6% and 57.8%, of the total losses, respectively. Particulate-N and ammonia-N losses were mainly in August–September, accounting for 56.9% and 71.6%, respectively, of the total losses.

Vertical variation in N loss

There were also differences in N loss vertically. Total-N, dissolved-N and nitrate-N increased significantly from atmospheric rainfall to throughfall and then to surface runoff ($P < 0.05$). The total-N concentrations in atmospheric rainfall, throughfall and surface runoff were 1.5, 1.8, and 2.7 mg L⁻¹, respectively, representing an increase of 79.5% from the highest to lowest position (Fig. S3). Growth is greatest from March to October, when the structure of the bamboo crown is complete with both branches and leaves. This allows the bamboo to intercept the maximum amount of rainfall, and

Table 1 Nitrogen loss in surface runoff from plot T2

Sample No.	Runoff volume (L)	Total-N loss (mg ha ⁻¹)	Dissolved-N loss (mg ha ⁻¹)	Particulate-N loss (mg ha ⁻¹)	Nitrate-N loss (mg ha ⁻¹)	Ammonia-N loss (mg ha ⁻¹)
210,323	50	16,227.36	12,456.67	3770.69	14,077.24	1079.79
210,421	10	8828.98	7890.91	938.07	7625.29	168.84
210,527	130	40,398.49	28,717.49	11,681.00	23,382.68	2763.21
210,615	130	60,311.33	52,199.40	8111.93	50,530.81	1510.92
210,621	470	40,968.33	33,451.72	7516.61	35,365.27	5610.18
210,706	390	64,739.20	55,716.93	9022.27	37,227.74	16,191.32
210,729	620	81,860.66	72,656.37	9204.29	81,406.48	454.43
210,817	460	146,640.71	88,287.05	58,353.66	36,893.17	69,550.36
210,830	35	12,799.56	11,522.66	1276.90	11,335.53	86.12
210,907	40	21,008.43	20,388.13	620.30	19,462.93	48.17
210,920	220	45,522.84	39,416.67	6106.17	36,352.61	287.94

therefore, total-N levels in rainfall are reduced. Vegetation, therefore, has an important role in reducing runoff and nitrogen loss.

The dissolved-N levels in atmospheric rainfall, throughfall and surface runoff were 1.1, 1.3 and 2.2 mg L⁻¹, respectively. The concentrations therefore, increased by 100.9% from the highest to lowest position. Nitrate-N concentrations in atmospheric rainfall, throughfall and surface runoff were 0.7, 1.1 and 2.0 mg L⁻¹, respectively.

Although particulate-N concentrations increased from high to low vertically, there was no significant difference between each position ($P > 0.05$), with concentrations of 0.4 mg L⁻¹ particulate-N in rainfall and 0.5 mg L⁻¹ in throughfall and surface runoff. There was also no significant difference in the ammonia-N concentrations among the different vertical positions ($P > 0.05$).

Analysis of the different forms of nitrogen in different vertical spaces (Fig. 2) showed that, moving from high to low, the proportion of nitrate-N increased from 46.2% in rainfall to 72.3% in surface runoff. In contrast, the proportion of ammonia-N gradually decreased from 17.4 to 9.4%, respectively. An analyzes of the solubility of nitrogen variations in vertical space showed that it was mainly present as dissolved-N (Fig. 2). Among the different levels, the largest

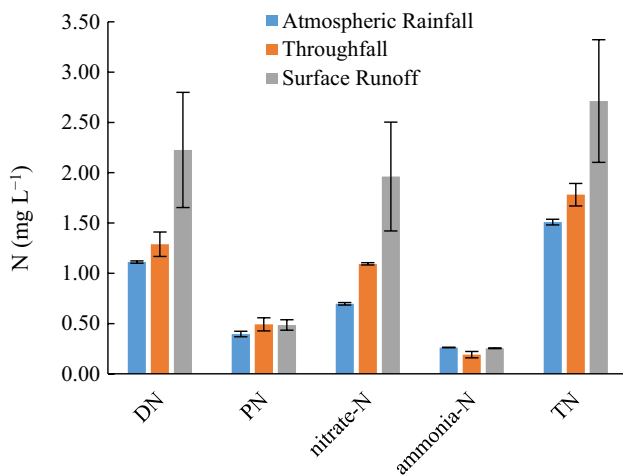


Fig. 2 Loss of N in different vertical spaces. The different letters represent significant differences. DN, dissolved-N; PN, particulate-N; NN, nitrate-N; AN, ammonia-N; TN, total-N

Table 2 Nitrogen loss from surface runoff in plots T1–T3

Plot No.	Total-N loss (mg ha ⁻¹)	Dissolved-N loss (mg ha ⁻¹)	Particulate-N loss (mg ha ⁻¹)	Nitrate-N loss (mg ha ⁻¹)	Ammonia-N loss (mg ha ⁻¹)
T1	25,853.09	12,465.34	13,387.75	19,537.92	3326.40
T2	15,986.69	14,336.05	1650.64	14,838.15	351.34
T3	23,703.32	18,371.28	5332.04	15,305.70	1644.95

proportion of dissolved-N was in surface runoff, accounting for 82.1% of the total, followed by rainfall at 73.7%.

Five rainfall events without runoff overflow were selected (sample numbers 200801, 210,323, 210,421, 210,830 and 210,907) to further explore the amount of nitrogen loss in the three plots (Table 2). Results show that the average N loss in a single rainfall event was largest from plot T1 (pure moso bamboo stand) and lower from plots T2 (*P. edulis* with interplanted *T. chinensis* and *I. lanceolatum*) and T3 (*P. edulis* with interplanted *A. fruticosa*), with the lowest from the former. Specifically, the losses of total-N, particulate-N, nitrate-N, and ammonia-N in T2 were 38.2%, 87.7%, 24.0% and 89.4% lower, respectively, compared with plot T1. This suggests that nitrogen losses can be effectively reduced by optimizing the stand structure of conservation forests. The loss of N from each plot was mainly in the form of nitrate-N, accounting for 64.6–92.8% of the total loss.

Impact of rainfall on N loss in vertical space

Figure 3 shows that the concentrations of total-N, dissolved-N, and nitrate-N in throughfall were positively correlated with the concentrations in rainfall ($P < 0.01$ or $P < 0.001$). Likewise, concentrations of total-N and dissolved-N in surface runoff were positively correlated with the concentrations in rainfall ($P < 0.05$) and with the nitrate-N concentration in rainfall ($P < 0.01$ or $P < 0.001$). Specifically, the nitrate-N concentration in surface runoff was positively correlated with total-N in rainfall ($P < 0.05$), and with the dissolved-N and nitrate-N levels in rainfall ($P < 0.01$).

The correlation between N loss in surface runoff and rainfall was assessed and showed that rainfall intensity was an important factor affecting N loss in surface runoff (Table 3). The average rainfall intensity was positively correlated with the loss of total-N, dissolved-N, particulate-N, and nitrate-N in plot T3 ($P < 0.05$), with correlation coefficients of 0.966, 0.953, 0.980 and 0.967, respectively. Although there was no significant correlation between maximum rainfall intensity and nitrogen loss from plot T2, the correlation coefficient was large. The correlation coefficients for the loss of total-N, dissolved-N particulate-N, nitrate-N, and ammonia-N for plot T2 during the maximum rainfall intensity were 0.873, 0.867, 0.869, 0.871, and 0.824, respectively.

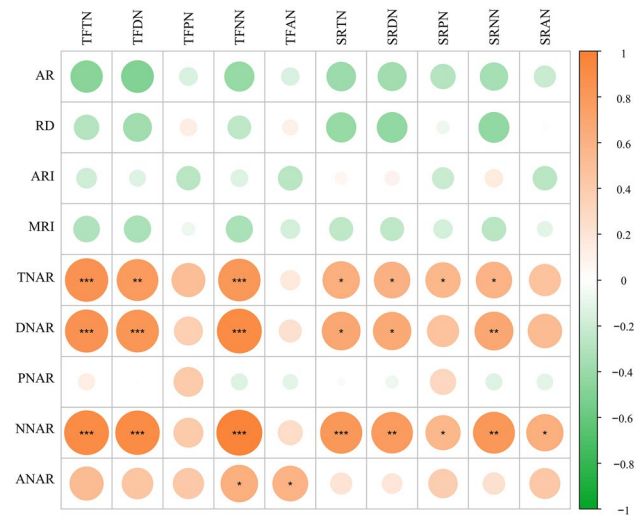


Fig. 3 Influence of atmospheric rainfall on N concentrations. AR, accumulated rainfall; RD, rainfall duration; ARI, average rainfall intensity; MRI, maximum accumulated rainfall per unit time; TNAR, total-N in atmospheric rainfall; DNAR, dissolved-N in atmospheric rainfall; PNAR, particulate-N in atmospheric rainfall; NNAR, nitrate-N in atmospheric rainfall; ANAR, ammonia-N in atmospheric rainfall; TFTN, throughfall total-N concentration; TFDN, throughfall dissolved-N concentration; TFPN, throughfall particulate-N concentration; TFNN, throughfall nitrate-N concentration; TFAN, throughfall ammonia-N concentration; SRTN, surface runoff total-N concentration; SRDN, surface runoff dissolved-N concentration; SRPN, surface runoff particulate-N concentration; SRNN, surface runoff nitrate-N concentration; SRAN, surface runoff ammonia-N concentration; *, correlation significantly different at the 0.05 level; **, correlation significantly different at the 0.01 level; ***, correlation significantly different at the 0.01 level

In addition to rainfall intensity, accumulated rainfall and duration also influence the loss of nitrogen. There was a positive correlation between accumulated rainfall and surface runoff for the loss of particulate-N from plot T3 ($P < 0.05$), with a correlation coefficient of 0.984. Rainfall duration was positively correlated with the loss of ammonia-N from plot T1 ($P < 0.01$) and plot T3 ($P < 0.05$), with correlation coefficients of 0.998 and 0.962, respectively.

Discussion

Temporal variations in nitrogen loss

The results show that N concentrations in surface runoff were relatively high from April to early June but lower from late June to September. Soil moisture is an important factor affecting the loss of soil N (Ouyang et al. 2017): the higher the soil moisture, the easier to produce runoff during low-intensity rainfall events (Liu et al. 2014b). Rainfall is an important factor affecting the soil moisture. The test area was in the Taihu Lake Basin of the Yangtze River Delta

Table 3 Correlation between rainfall factors and N loss in surface runoff

	T1TN	T1DN	T1PN	T1NN	T1AN	T2TN	T2DN	T2PN	T2NN	T2AN	T3TN	T3DN	T3PN	T3NN	T3AN
AR	0.604	0.377	0.938	0.828	-0.297	-0.239	-0.259	-0.118	-0.251	-0.194	0.878	0.853	0.984*	0.881	0.021
RD	0.540	0.726	0.096	0.304	0.998**	0.179	0.142	0.380	0.145	0.430	-0.661	-0.688	-0.391	-0.656	0.962
ARI	0.294	0.034	0.758	0.580	-0.601	-0.343	-0.346	-0.307	-0.341	-0.387	0.966*	0.953*	0.980*	0.967*	-0.325
MRI	0.502	0.467	0.302	0.398	-0.099	0.873	0.867	0.869	0.871	0.824	0.358	0.380	0.148	0.360	0.061

AR accumulated rainfall, RD Rainfall duration, ARI Average rainfall intensity, MRI Maximum accumulated rainfall per unit time, T1TN Surface runoff total-N loss in plot T1, T1DN Surface runoff dissolved-N loss in plot T1, T1PN Surface runoff particulate-N loss in plot T1, T1NN Surface runoff nitrate-N loss in plot T1, T1AN Surface runoff ammonia-N loss in plot T1, T2TN Surface runoff total-N loss in plot T2, T2DN Surface runoff dissolved-N loss in plot T2, T2PN Surface runoff particulate-N loss in plot T2, T2NN Surface runoff nitrate-N loss in plot T2, T2AN Surface runoff ammonia-N loss in plot T2, T3TN Surface runoff total-N loss in plot T3, T3DN Surface runoff dissolved-N loss in plot T3, T3PN Surface runoff particulate-N loss in plot T3, T3NN Surface runoff nitrate-N loss in plot T3, T3AN Surface runoff ammonia-N loss in plot T3

*Correlation significantly different at the 0.05 level, **Correlation significantly different at the 0.01 level

where the rainy season is from June to September. There is more rainfall in this period than at other times as a result of typhoons and other factors, so soil moisture is relatively high. More surface runoff is therefore generated (Table 1), which dilutes nitrogen concentrations in surface runoff. The maximum volume of surface runoff was recorded during the rainfall event of 29 July 2021, followed by those on 21 June and 17 August 2021 in the rainy season, which had the lowest N concentrations (Fig. 1).

An increase in vegetation cover is an effective measure to reduce nitrogen loss (García-Díaz et al. 2017). The moso bamboo growth is vigorous during the July to September rainy season (Tong et al. 2020). In this period, branches and leaves of moso bamboo reach their maximum growth and vegetation cover can reach 0.68–0.75. However, our field observations showed that bamboo cover was only 0.50–0.55 in the non-rainy season. Vegetation, therefore, has a protective effect on the surface soils of water source forests during the rainy season, reducing nitrogen losses (Zhang et al. 2020). Research by Suescún et al. (2017) and Zhao et al. (2019) also showed that an increase in vegetation can prevent the loss of nitrogen.

The results clearly show that N losses can be effectively reduced through the optimization of stand structure. For plots T2 and T3, stand structure was modified and vegetation cover increased. Plot T2 had the highest vegetation cover (Table S1), and therefore the lowest nitrogen losses (Table 2). Losses of total-N, particulate-N, nitrate-N, and ammonia-N from plot T2 decreased by 38.2, 87.7, 24.0, and 89.4%, respectively, compared with plot T1 (without optimization). This may have been due to the varied stand structure. Plot T2 was intercropped with *I. lanceolatum* with an average height of 3.5–4.0 m and wide crowns (2.5–3.5 m), whereas the height of *A. fruticosa* in plot T3 was only 0.5–1.5 m with crowns of 0.8–1.5 m. *I. lanceolatum* therefore captured rainfall over a larger area and reduce throughfall in plot T2, further reducing surface runoff (Dietz et al. 2006; Liu and Zhao 2020), resulting in a reduction in the migration of nitrogen in surface runoff (Table 3). Plot T2 had the lowest surface runoff (Table 2), which verified this conjecture.

Similar results have been reported by Chu et al. (2019), who modified the stand structure by planting local tree species in a eucalyptus plantation in Dongguan, China. After three years (2010–2012), the total-N loss in plots TEP (planted with native hardwood species and the eucalyptus thinned by 60%) and NEP (planted with local hardwood species but no thinning of the eucalyptus) was reduced by 42–60% and 25–28%, respectively, compared with pure eucalyptus plantations. This may be due to the change of soil nitrogen cycle through the optimization of stand structure (Asadiyan et al. 2013; Sharma and Kumar 2021), thus, reducing nitrogen loss.

Nitrogen from our plots (total-N, dissolved-N, particulate-N, nitrate-N and ammonia-N) was mainly lost during the June–September rainy season (85.9–95.9%), similar to other studies. Song et al. (2017) in southwest China found that 90% of the local nitrogen loss was concentrated in the rainy season. Wang et al. (2019) also confirmed that the rainy season was a high-risk period for N loss in the Yingtan area. These results confirm that, although N concentrations in surface runoff are relatively low in the rainy season, the annual loss in surface runoff is mainly composed of that which occurs in this season.

The study area is affected by typhoons, and the rainy season therefore has a higher rainfall intensity and greater volume (Table 1) than in other regions. Soil erosion is more likely to occur, resulting in the loss of soil nitrogen. Although the N concentration in surface runoff was diluted as a result of the large volume of surface runoff, nitrogen loss over this period was still large. Simulation experiments by Xing et al. (2016) showed that, as rainfall intensity increased from 25 to 75 mm h⁻¹ at a site with a slope of 15°, the rate of loss of total-N increased from 0.126 to 0.342 mg m⁻² min⁻¹. The loss of total-N increased significantly ($P < 0.05$) as rainfall intensity increased. Zheng et al. (2021) conducted a K-means clustering analysis of 253 rainfall events from 2012 to 2018 in De'an County, China and found that intense rainfall was an important factor in local soil erosion, whereas long-duration rainfall had less effect. They also reported that rainfall intensity had a greater effect on soil nitrogen loss than rainfall duration. These studies concur with our results—i.e., rainfall intensity and volume were the main factors affecting nitrogen loss.

Vertical changes in nitrogen loss

The results show that N loss was primarily dissolved-N and nitrate-N in all three vertical spaces, i.e., from rainfall to throughfall to surface runoff, accounting for 72.4–82.1% and 46.2–72.3%, respectively. Accordingly, the proportion of nitrate-N increased gradually on moving from high to low positions vertically. This may be because soil colloids are generally negatively charged and produce more anions (Vandervoort et al. 2013; Bennett et al. 2019). Because the nitrate in nitrate-N is an anion, the repulsion between the two species (soil colloids and nitrate-N) causes the nitrate-N in the soil to be readily soluble in water, as confirmed by Latifah et al. (2017) and Rajta et al. (2020). When rain washes the leaves and surface soil, nitrate-N in the soil dissolves in the water, increasing the proportion of nitrate-N. White et al. (2018) in Australia and Wang et al. (2022b) in the Three Gorges area of China found that the loss of nitrogen in surface runoff was dominated by nitrate-N. An 11-year observational study from 2008 to 2018 by Du et al. (2021) in the purple lands area of southwest China showed

that dissolved-N loss accounted for 58.0–70.34% of the total-N loss in runoff, consistent with our findings.

This study has clarified that the concentrations of total-N, dissolved-N, and nitrate-N increased significantly from atmospheric rainfall to throughfall, to surface runoff. In this respect, the increase in the nitrogen concentration in throughfall may have been caused by rainfall scouring and leaching the leaves of plants. Su et al. (2019) showed that the nitrate content in throughfall increased compared with that in atmospheric rainfall. Bessaad and Korboulewsky (2020) showed that leaching by rainfall may lead to the loss of nitrogen from leaves. This is similar to the results of this study.

The results also show that the concentration of N in atmospheric rainfall was positively correlated with N in throughfall (Fig. 3). However, nitrogen in surface runoff was less affected by the N in atmospheric rainfall than by the concentration in throughfall. Because surface runoff interacts directly with the soil, it was concluded that nitrogen concentrations in surface runoff was affected by soil N levels and that surface runoff from rainfall caused soil erosion which in turn, caused the loss of soil N.

A correlation analysis of the soil N content and surface runoff N concentration indicated that there was a significant positive correlation between the total-N content of soil and the total-N, dissolved-N, and nitrate-N concentrations in surface runoff ($P < 0.01$), with correlation coefficients of 0.881, 0.855 and 0.875, respectively (Table 4). The available N in soil and the total-N, dissolved-N and nitrate-N concentrations in surface runoff were positively correlated ($P < 0.01$), with correlation coefficients of 0.895, 0.873 and 0.893, respectively. Surface runoff removes N from the soil because it continuously washes the ground surface. Shen et al. (2010) found that surface runoff in plantations was affected by the chemical properties of the soil. Geng and Sharpley (2019) showed that concentrations of N and P in surface runoff were affected by soil properties. These studies reflect our conclusion that nitrogen concentration in surface runoff is affected by soil N levels and that soil and water erosion are important factors causing its loss. Plot T2 had the highest soil nitrogen (Table S1) and N levels in surface

runoff were higher than from the other two plots (Fig. 1). This may be due to good management of the bamboo forest in plot T2, which includes maintaining a specific bamboo density by felling stems > 4 years old. Intercropping with *I. lanceolatum* gave the T2 plots a better stand structure. It is unlawful to dig up bamboo shoots and other measures that disturb the soil surface, thus protecting surface vegetation. A lower surface runoff volume resulted in the least amount of N loss from plot T2 (Table 2). This suggests that soil nutrient contents could be increased, and soil quality improved by optimizing the stand structure and establishing well-structured water source conservation forests. This would also reduce the risk of water pollution by nitrogen in the watershed (Fig. 4).

The mechanism of N loss driven by soil and water erosion in water source areas was established through in situ observations based on analyses in the two dimensions of time and space (Fig. 5). From the temporal perspective, the highest N loss (85.9–95.9%) was mainly concentrated in the June–September rainy season, followed by March–May (12.1%). From the spatial perspective (in the vertical direction), N loss gradually increased from atmospheric rainfall (1.5 mg L^{-1}) to throughfall and to surface runoff (2.7 mg L^{-1}). High-intensity rainfall was the main driving force of soil erosion in water source areas.

Conclusions

Based on our findings, the *A. angustifolia* population structure differed significantly between protected and unprotected areas. The population structure influenced aboveground biomass and species diversity which were conditioned by protection status. The old-growth populations supported overstocked stands but with lower species diversity. However, lower biomass stock in old-growth populations was also affected by the human disturbance in unprotected forests. The results also highlight the importance of protected areas and sustainable forest management techniques to ensure population renewal and maintenance. Finally, our results

Table 4 Effects of soil N content on N loss in surface runoff

	SC	STN	SAN	STP	SAP	SpH
SRTN	0.891**	0.881**	0.895**	0.737*	0.790*	−0.545
SRDN	0.866**	0.855**	0.873**	0.714*	0.820**	−0.584
SRPN	0.588	0.580	0.574	0.592	0.165	−0.006
SRNN	0.879**	0.875**	0.893**	0.711*	0.878**	−0.579
SRAN	0.200	0.196	0.208	0.313	−0.089	0.341

SC Soil carbon, STN Soil total-N content, SAN Soil available N content, STP Soil total P content, SAP Soil available P content, SpH Soil pH, SRTN Surface runoff total-N concentration, SRDN Surface runoff dissolved-N concentration, SRPN Surface runoff particulate-N concentration, SRNN surface runoff nitrate-N concentration, SRAN Surface runoff ammonia-N concentration

*Correlation significantly different at the 0.05 level, **Correlation significantly different at the 0.01 level

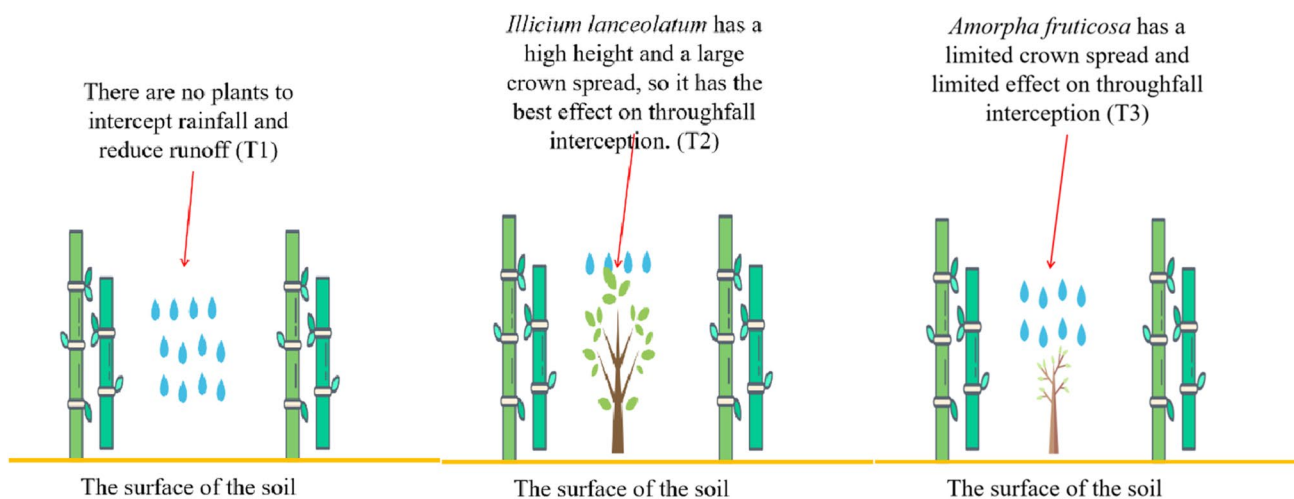


Fig. 4 Effects of different stand structures on throughfall

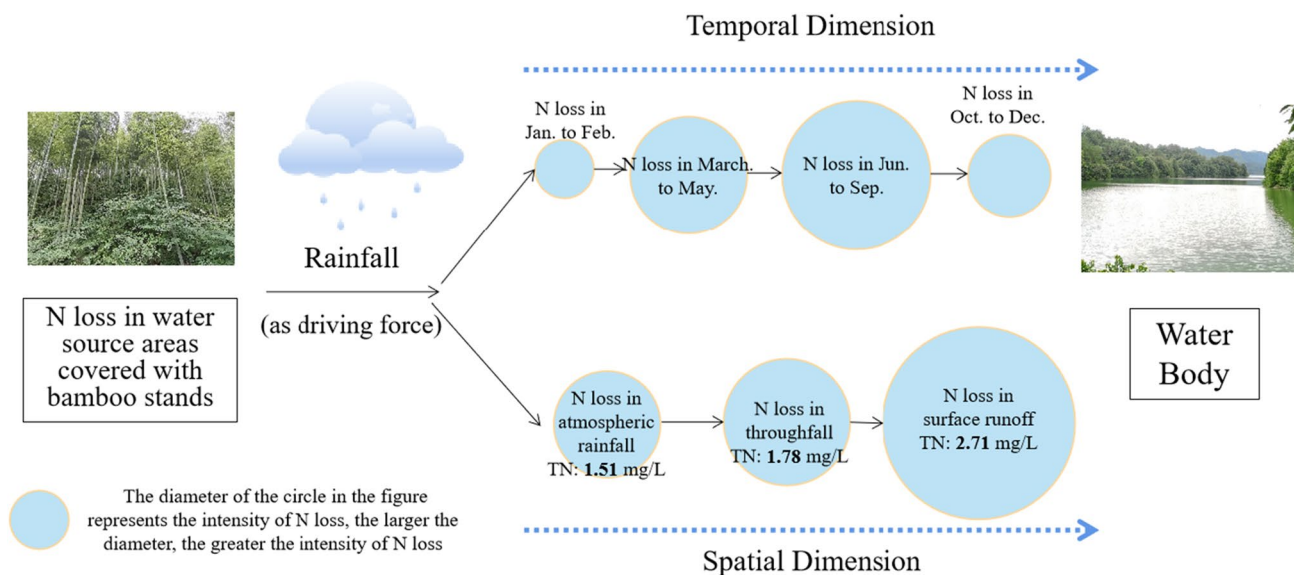


Fig. 5 Mechanisms for the loss of N in water source areas. The size of the circle represents the amount of N loss. TN, total-N

indicate that diameter distribution can be a useful guide for sustainable management and for effective protection at the species level.

- (1) Rainfall intensity and rainfall volume were the key factors affecting nitrogen loss which was mainly in the June–September rainy season, which accounted for 85.9–95.9% of the annual loss.
- (2) From high to low vertical levels (i.e., from atmospheric rainfall to throughfall and surface runoff), nitrogen concentrations (total-N, dissolved-N, and nitrate-N) gradually increased from 1.5 mg L⁻¹ in atmospheric rainfall

to 2.7 mg L⁻¹ in surface runoff. The main forms of loss were nitrate-N and dissolved-N.

- (3) Optimizing the stand structure of water conservation forests is an effective measure to reduce nitrogen loss in water source areas. For T2, species such as *T. chinensis* and *I. lanceolatum* were interplanted and herbaceous plants grew well. Thus, the vertical structure of the stand changed from a mono- to a poly-structure. Tree species with wide crowns captured more throughfall, reducing surface runoff and the migration of nitrogen in this runoff and reduced the total-N loss by 38.2% compared with the pure bamboo stand (T1).

Based on these results, the mechanism of nitrogen loss driven by soil and erosion water is: (1) high-intensity rainfall is the main driving force; (2) nitrogen loss is mainly concentrated in the rainy season (June–September), followed by March–May and October–December, with the lowest loss between January and February; and, (3) the intensity of nitrogen loss increases from high to low vertical positions. A proper stand structure can affect the amount of throughfall, reducing the volume of surface runoff and N losses. This preliminary study provides insights into the mechanism of nitrogen loss in water source areas and contributes to knowledge on reducing losses from forests, thereby helping to ensure the quality of drinking water and the health of residents is maintained.

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