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Spatial-seasonal variation of soil denitrification under three riparian vegetation types around the Dianchi Lake in Yunnan, China

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Outbreaks of nuisance cyanobacterial bloom are predicted to occur frequently under the effect of severe eutrophication in the water body of Lake Dianchi since the 1990s. Riparian buffers are now well recognized for their roles in the removal of inorganic nitrogen mainly *via* denitrification. Little is known, however, about the mechanisms of nitrate removal in the riparian buffers of Lake Dianchi. We investigated the wet and dry seasonal dynamics of denitrification rate (DNR) in the soil profiles along the topographic gradient in three riparian buffers with different vegetation types (*i.e.* forest, open forest, and grass). A strong vertical pattern was observed in soil organic C and N concentrations (*i.e.* total N, DON, NO_3–N, and NH_4–N) along the soil layers. We also found significantly higher *in situ* denitrification activity in the upper horizon along each topohydrosequence while the activities of soil denitrification could be detected down to deeper soil horizons (0.1 to 0.8 mg N per kg dry soil per day), which may contribute significantly to the reduction of the ground water nitrate. Meanwhile, the DNR in the zones near the lake was significantly higher than that in zones near the border with the upland terrace, and also in the wet seasons than in dry seasons. Denitrification rates in the forest, open forest and grass sites were significantly different only in wet seasons. Especially, we found soil organic C had a strong correlation with denitrification in all sites, despite the large intersite variability of soil and vegetation. Our data suggested spatial heterogeneity of substrate availability along a hydrologic and topographic gradient can be the primary control on spatial-seasonal patterns of denitrification in riparian buffers.

Environmental impact

Riparian buffer is a good technique for inorganic nitrogen removal as it can effectively reduce and retain the nutrient source. This study aimed to explore the mechanisms of nitrate removal *via* denitrification in the riparian buffers of Lake Dianchi. We presented some significant scientific data of N removal in different riparian buffers (*i.e.*, forest, open forest, and grass) of Lake Dianchi, which are useful as a reference for the practice of eutrophication control of the water body.

Introduction

Riparian buffers, zones adjacent to streams, rivers, or wetlands,[1] are now well recognized for their roles in the removal of nitrogen (N) from upland sources, effectively and substantially improving the water quality of aquatic ecosystems.[2,3] Mechanisms for the removal of dissolved N in aquatic systems include plant uptake, soil storage, microbial immobilization and denitrification.[4,5] Among these factors of influencing N removal, plant assimilation produces organic N that may later be mineralized, and the litter decomposition reintroduces stored N to the soils, which may later create a hot-spot of terrestrial and aquatic N availability.[6] Microbial N transformations, such as assimilative uptake and assimilatory nitrate reduction, can also participate in N removal. Denitrification, however, is considered as a real sink of NO_3^- in riparian areas since NO_3^- is transformed to gaseous products (N_2, NO, N_2O) which are emitted to the atmosphere,[7] and plant uptake and microbiological immobilization only represent a temporary storage system.

Denitrification in riparian buffers can be controlled by the environment variability such as soil moisture and temperature, soil nutrient, soluble organic matter, vegetation, and soil texture.[8–10] Spatial and temporal variations of these parameters and their interactions under biogeochemical conditions are often linked to the high variability of soil denitrification rates in riparian ecosystems.[11–14] At a landscape scale, the interaction between floodplain topography, seasonal change of hydrology, land use ways, nitrogen concentration, and diffusion pattern

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may have a large influence on denitrification in riparian ecosystems.[15,16] The upland–wetland interface was demonstrated as an important area in controlling diffuse nitrate fluxes from up slope.[10,17] Clement *et al.* (2002)[18] reported that the factors limiting denitrification capacity shift from anaerobiosis in the upland position to a lake of NO_3^- in the lower end of the topohydrosequence. There were some conflicting results about the roles of upland ecosystem types in N attenuation in riparian zones.[19] Some studies have demonstrated high efficiency in nitrate removal of forest riparian zones compared with riparian grass,[20] while others observed substantial removal capacity of riparian grass.[21,22] At the riparian ecosystem scale, these apparently divergent results might have arisen from the interaction of geology and hydrology to control the residence time of water and thus the processing time of N. Land use change, such as converting cropland to grassland, was reported to reduce the rates of denitrification.[23] At the soil scale, this denitrification variability was under the control of C and N substrate availability in soils and soil texture.[24,25] Denitrifying denitrifiers require organic carbon (OC) as an energy source and are typically most active near the "hot-spot" interface with the oxic zone where nitrification occurs.[11,24] Soil N or organic C may be concentrated near vegetation[26] or organic debris,[27] forming patches that may foster denitrification. Soil texture may determine the capacity of soils to retain C and N[8], and spatial variation in texture of riparian soils often occurs along topographic gradients,[28,29] which would then produce gradual spatial variation in denitrification. Denitrification is also dependent upon redox conditions, which vary spatially in riparian ecosystems[30] and are related to soil texture, organic matter, or moisture. There were some comparative studies on denitrification in the different riparian ecosystems (*i.e.* forest, pasture and cropped soils). Some conflicting results, however, have been yielded.[18,31] Some of these differences could be explained by the fact that these studies did not take into account the influence of substrate availability and soil parameters on *in situ* denitrification rates.

At present, the vast majority of riparian denitrification research is in agricultural and forested watersheds, while there are a few studies on soil denitrification in urban riparian areas despite the fact that urban watersheds commonly deliver high loads of NO_3^- to coastal waters. Lake Dianchi, a typical large, shallow, plateau lake located in Kunming city, is reported to have undergone serious eutrophication processes.[32] A nuisance cyanobacterial bloom has frequently appeared in this lake since the 1990s.[33] The different vegetation types in the riparian buffers of Dianchi are explained by the fact that the change of land use of the sites has occurred at different periods. Little is known, however, about the roles and the mechanisms of nutrient removal in the riparian buffers of Lake Dianchi. The objectives of this study were: (i) to explore the seasonal pattern of soil nitrogen and denitrification under soil profiles along the topohydrosequences formed at the upland–wetland interface, (ii) to evaluate the importance of different vegetation types (*i.e.*, forest, open forest, and grass) on the denitrification activity in riparian buffers, and (iii) to probe the effects of some soil characteristics on denitrification rates in three riparian soils.

Materials and methods

Site description

The study was conducted in a northeastern lakeshore of Dianchi Lake. Lake Dianchi (24°40′–25°03′ N, 102°37′–102°48′ E), the largest plateau lake in Yunnan Province, is a tectonic lake located in the central part of the Yunnan-Guizhou Plateau. Kunming City is located at its northern end and is upstream within its catchment region. The lake covering an area of 370 km^2, 150 km long and 40 km wide, is the sixth largest freshwater lake in China. Its maximum depth is 10.3 m, and the average depth is 4.4 m. The area around the Lake Dianchi drainage basin has a northern subtropical wet monsoon climate. The annual mean temperature is about 15 °C. The annual rainfall varies from 797 mm to 1007 mm, with annual evaporation of 1870–2120 mm. Precipitation shows a strong seasonal variation with a rainy season (about 85% rainfall of annual precipitation) from May to October and a dry season (only about 15% rainfall of all year) from November to April of next year.

The landscape was a typical mixed agriculture area of residential and cropland at the outskirt of Kunming. The upland was an arable field with Chinese chive planted.

Experimental design

Three study sites (approximately 35 m in length along the bank and 30 m in width into the riparian area) were selected with different vegetation types: (i) a forested site with typical wetland trees (*i.e.*, *Populus yunnanensis* and *Salix babylonica*); (ii) an open forest site characterized by understory shrubs (*Celtis kunmingensis*, *Taxodium ascendens*, and *Ficus microcarpa cv. Golden Leaves*, *etc.*) without mature trees; and (iii) a grass site characterized by herbaceous species (*Bidens pilosa* L., *Artemisia annua*, *Lolium perenne* L., *Holcus lanatus* L., *Juncus effusus* L., *etc.*). Trees in the forested site were approximately 35 years old. The mean diameters of the trees were 55 cm. The mean height of the tree canopy was approximately 15.5 m high and its percentage of coverage about 85%. The vegetation of the open forest site was mainly characterized by low standing plants with about 45% of vegetation coverage, and was coppiced. The soils of three sites belong to a type of red soil with fine clay. Three study sites presented a similar soil profile.Each site has been divided into three zones parallel to the lake. The zones were positioned across an elevation gradient from near the lake edge towards the non-flooded upland bordering the agricultural field. Zone I, closest to the lake, was 8 m wide as measured at the river boundary. Zone II and Zone III were 4 m wide, respectively (Fig. 1).

Sampling and analysis

Soils were sampled in the three sites in the wet seasons in Jul and Oct 2010, respectively, and the dry seasons in Dec 2010 and Mar 2011 respectively, using a manual soil corer. Three soil replicates were sampled in each of the three zones from hillslope to Dianchi Lake and at the three depths (0–10 cm, 10–20 cm, 20–50 cm). Soil inorganic N content (NO_3–N and NH_4–N) was extracted from approximately 30 g field-moist, 8 mm seived soil sub-samples with 2 M KCl solution and determined with a

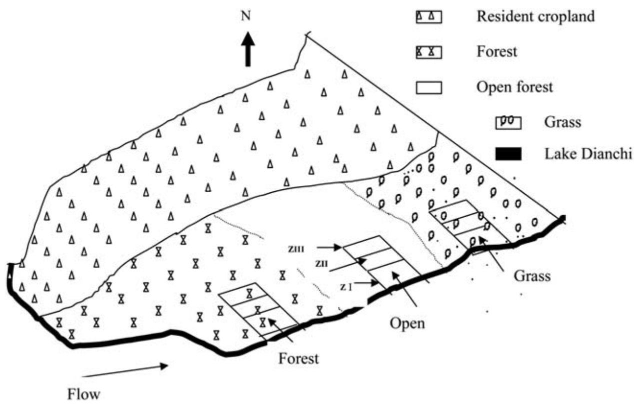

Fig. 1 Sites location and experimental design in the Kunming, Yunnan province of China.

UV-VIS spectrophotometer (UV mini 1240, Shimadzu, Japan).[34] Total organic C (OC) was analyzed by the dichromate oxidation with an external heating procedure, and total N by the Kjeldahl digestion method.[35] Dissolved organic N (DON) was measured with the K_2SO_4 extract by oxidation to NO_3^- with potassium persulfate at 120 °C, and analyzed by the above-mentioned procedure. Soil moisture was determined gravimetrically after drying approximately 20 g of fresh soil at 105 °C for 48 h. Soil temperatures were measured with a soil thermometer. *In situ* denitrification rates (DNRs) were measured using an intact core incubation method with acetylene inhibition and immediately assayed after sampling.[36,37] The intact soil cores were inserted in gas-tight jars. At the start of the incubation, jars were filled with acetone-free acetylene to bring soil atmosphere concentration to 10 kPa (10%, v/v) acetylene and 90 kPa air. Samples were incubated at field temperature, and denitrification rates were calculated as the rate of nitrous oxide (N_2O) accumulation in the head space between 1 and 4 h.

Statistical analyses

Differences between sites, zones, depths, and seasons for water content (%H_2O), ammonium content (NH_4–N), nitrate content (NO_3–N), dissolved organic nitrogen content (DON), and *in situ* denitrification rate (DNR) were tested using the Kruskal–Wallis nonparametric analysis of variance (ANOVA). Differences were considered statistically significant if $p < 0.05$. Pearson's correlation coefficients were used to express the relationships between soil parameter values and denitrification rates. All statistical analyses were performed using SPSS software.[38]

Results

Spatial patterns

The nitrogen-related parameters were found to be in strong gradient and significant differences between depths for all sites. There was a significant decreasing trend of soil parameters measured in the three layers at the three sites ($p < 0.003$). This strong vertical pattern was observed in soil organic C and dissolved organic N (DON) in the three zones (Table 1). Moreover, soil NO_3–N concentrations (Table 1) in the 0 to 10 cm soil layer (between 6.7 and 9.4 mg N per kg of dry soil) were always significantly higher than in the deeper soil layers (between 2.0 and 6.6 mg N per kg of dry soil). Similarly, soil NH_4–N concentrations (Table 1) presented the same pattern with higher values in the 0 to 10 cm upper organic horizon (between 2.7 and 6.7 mg N per kg of dry soil) than in the deeper soil layers (between 1.5 and 5.3 mg N per kg of dry soil). This vertical pattern was also observed for *in situ* denitrification (DNR) with the maximum in the 0 to 10 cm layers (between 0.4 and 2.5 mg N per kg of dry soil) (Fig. 2). Although there was a sharp gradient of DNR measured along the soil profiles, some significant activities (from 0.1 to 0.8 mg N per kg dry soil per day) of soil microbes could be detected down to 50 cm soil layers (Fig. 2).

Temporal patterns

In the study, temporal dynamics of soil denitrification along the topohydrosequences gradient were explored among sites (Fig. 2). Although no consistent pattern could be found from the season or the zone perspective, there were some significant differences ($p < 0.05$) for the denitrification rate (DNR)

Table 1 The soil nutrient concentrations at different depths (mean ± SE) across seasons in three riparian sites

		Forest			Open forest			Grass		
Index	Depth (cm)	ZI	ZII	ZIII	ZI	ZII	ZIII	ZI	ZII	ZIII
OC ($g\ kg^{-1}$)	0–10	77.5 ± 7.4	65.2 ± 4.4	43.2 ± 2.2	48.3 ± 3.6	47.8 ± 3.3	39.3 ± 3.6	49.1 ± 3.7	51.6 ± 3.7	36.9 ± 3.7
	10–20	47.3 ± 4.5	44.4 ± 2.8	30.2 ± 1.5	32.5 ± 1.9	31.5 ± 1.6	26.9 ± 1.6	33.4 ± 1.5	42.3 ± 2.2	25.7 ± 0.5
	20–50	22.9 ± 1.6	23.6 ± 1.8	14.6 ± 0.3	14.7 ± 1.6	15.8 ± 0.7	16.3 ± 0.8	15.6 ± 0.7	18.1 ± 0.5	11.2 ± 0.3
TN ($g\ kg^{-1}$)	0–10	3.3 ± 0.3	2.2 ± 0.2	1.8 ± 0.1	2.6 ± 0.2	3.2 ± 0.3	1.6 ± 0.1	4.4 ± 0.4	4.7 ± 0.4	1.5 ± 0.1
	10–20	1.1 ± 0.1	2.4 ± 0.2	1.1 ± 0.1	1.2 ± 0.1	1.3 ± 0.1	1.3 ± 0.1	4.1 ± 0.2	1.1 ± 0.1	0.9 ± 0.1
	20–50	0.8 ± 0.1	1.8 ± 0.1	1.5 ± 0.1	0.7 ± 0.1	0.8 ± 0.1	0.8 ± 0.1	0.3 ± 0.1	0.5 ± 0.1	0.4 ± 0.1
DON ($mg\ kg^{-1}$)	0–10	7.8 ± 1.5	8.8 ± 1.6	7.4 ± 1.7	6.6 ± 1.7	6.9 ± 2.2	7.3 ± 2.3	5.7 ± 1.4	6.5 ± 1.3	7.4 ± 1.7
	10–20	5.2 ± 1.0	5.4 ± 1.1	5.2 ± 1.3	4.5 ± 0.8	4.3 ± 0.9	6.2 ± 1.1	2.6 ± 1.0	3.4 ± 1.1	5.5 ± 1.2
	20–50	2.1 ± 0.5	1.8 ± 0.4	2.2 ± 0.6	1.7 ± 0.5	2.7 ± 0.7	2.2 ± 0.7	2.3 ± 0.6	2.1 ± 0.8	3.1 ± 0.9
NO_3 ($mg\ kg^{-1}$)	0–10	7.2 ± 1.7	8.4 ± 1.8	7.7 ± 2.1	6.7 ± 1.9	8.6 ± 2.5	9.4 ± 2.7	7.8 ± 1.4	8.3 ± 1.3	8.9 ± 1.7
	10–20	5.6 ± 1.2	5.7 ± 1.2	6.5 ± 1.2	5.3 ± 1.1	5.0 ± 0.9	6.6 ± 1.2	3.4 ± 1.0	4.6 ± 1.1	5.5 ± 1.2
	20–50	2.4 ± 0.6	2.1 ± 0.6	2.0 ± 0.7	2.0 ± 0.5	3.4 ± 0.7	3.6 ± 0.8	2.2 ± 0.6	3.2 ± 0.8	3.4 ± 0.9
NH_4 ($mg\ kg^{-1}$)	0–10	6.5 ± 1.3	6.2 ± 1.5	6.6 ± 0.9	5.1 ± 2.3	4.2 ± 0.6	2.7 ± 0.6	6.7 ± 1.7	4.5 ± 1.7	3.8 ± 0.9
	10–20	4.2 ± 0.7	4.7 ± 0.8	5.3 ± 1.1	4.6 ± 1.2	3.2 ± 0.5	2.2 ± 0.6	2.3 ± 0.6	3.6 ± 0.7	2.5 ± 0.7
	20–50	4.0 ± 0.6	4.5 ± 0.4	4.2 ± 0.5	2.6 ± 0.6	2.1 ± 0.3	1.7 ± 0.5	1.5 ± 0.4	2.7 ± 0.5	1.8 ± 0.4

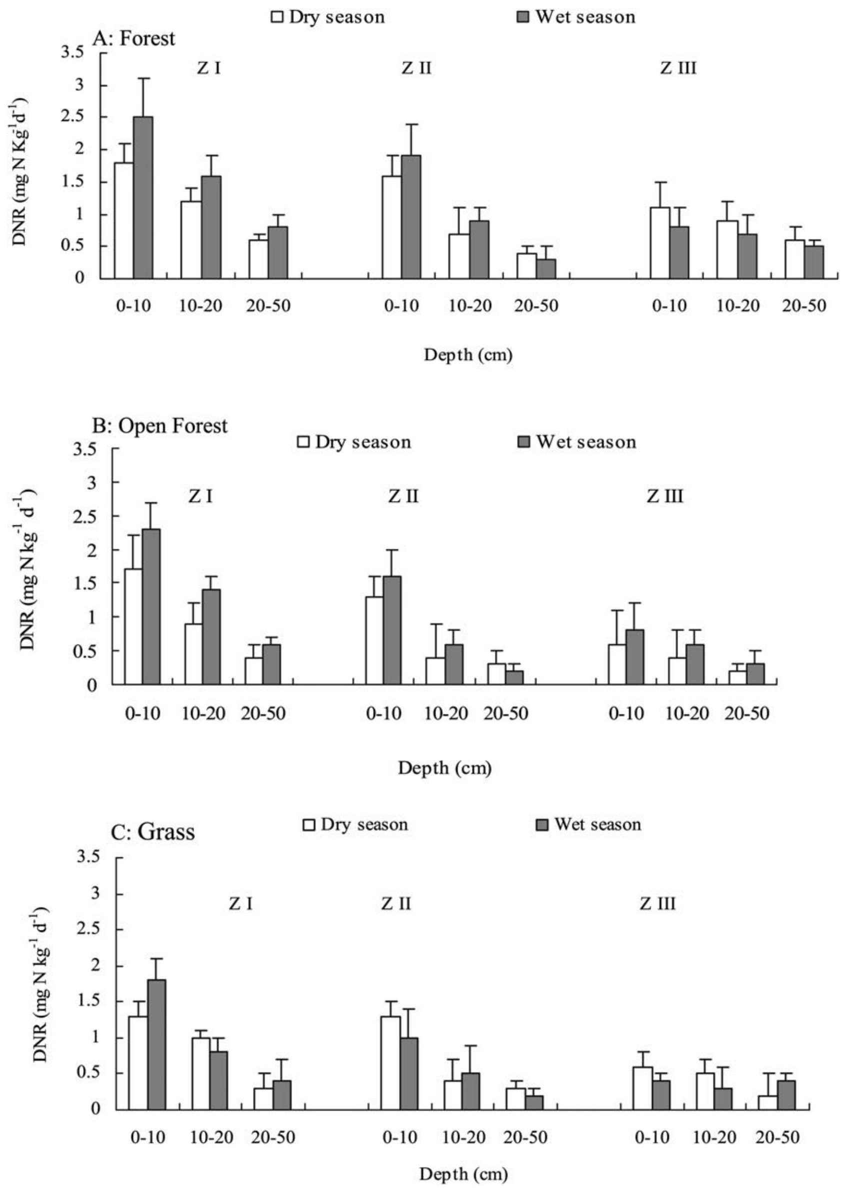

Fig. 2 Seasonal patterns of denitrification rate (DNR) (mean and standard errors) in soil profiles along the three topohydrosequences: ZI (proximity to the lake) and Zones III, II (upland) in different riparian sites ((A) forest; (B) open forest; (C) grass).

between sites (Table 2). In the forested site, the denitrification rate (DNR) was observed to be significantly higher in the wet seasons than in the dry seasons in Zones I and II ($p < 0.05$) but not in Zone III, whereas the DNR in the open forest site was higher in the wet seasons than in the dry seasons in all of the zones (Zones III, II and ZI) ($p < 0.05$), and such seasonal pattern of soil denitrification only appeared in Zone I for the grass site (Fig. 2). The denitrification rate (DNR) of Zone I (from 0.3 to 2.5 mg N per kg dry soil per day) was significantly higher than that of Zones II and III (between 0.1 and 1.6 mg N per kg dry soil per day) ($p < 0.05$), no matter what the seasons or sites were, while there were no significant differences of denitrification rate between Zone III of sites in dry or wet season. Soil denitrification in the upper soil layer (0–10 cm) was maximum when compared with the deeper soil layer in the different zones and seasons.

We also compared the intersite differences of some relevant soil characteristics in the upper soil layer of the three different sites for zones in the dry and wet seasons (Table 2). Soil denitrification (DNR) and soil moisture in Zone I, and soil dissolved organic nitrogen (DON) in dry seasons were significantly different between sites ($p < 0.05$), while in the wet seasons, NO_3–N, soil dissolved organic nitrogen (DON), denitrification rate, and soil moisture in the sites were significantly different ($p < 0.05$). Despite the large intersite variability (Table 1), significant differences were also found in the denitrification rates (DNR) of 0 to 10 cm soil layer in the wet seasons (not in dry seasons) between zones when sites were pooled by zone (Table 3).

Table 2 Nonparametric variance (ANOVA; Kruskal–Wallis test) of intersite differences for the 0 to 10 cm soil layer in the three zones in dry seasons and wet seasons. *H* is the value of the Kruskal–Wallis test. *$p < 0.05$. ns: $p > 0.05$

	Dry season						Wet season					
	ZI		ZII		ZIII		ZI		ZII		ZIII	
Soil variables	*H*	*P*	*H*	*P*	*H*	*P*	*H*	*P*	*H*	*P*	*H*	*P*
Soil temperature (°C)	4.2	ns	3.6	ns	3.2	ns	3.4	ns	2.7	ns	3.5	ns
Soil moisture (%)	6.5	*	5.5	ns	4.3	ns	7.8	*	7.5	*	7.2	*
OC (g kg^{-1})	5.3	ns	4.3	ns	3.8	ns	5.3	ns	4.3	ns	4.3	ns
N (g kg^{-1})	5.4	ns	5.1	ns	4.7	ns	5.6	ns	5.2	ns	5.2	ns
DON (mg kg^{-1})	6.5	*	6.3	*	6.1	*	8.7	*	8.4	*	8.1	*
NO_3 (mg kg^{-1})	5.9	ns	3.9	ns	3.9	ns	7.8	*	7.8	*	7.3	*
NH_4 (mg kg^{-1})	3.4	ns	5.5	ns	4.8	ns	5.5	ns	4.7	ns	4.8	ns
DNR (mg kg^{-1} d^{-1})	7.7	*	5.6	ns	5.0	ns	8.8	*	8.0	*	7.5	*

Table 3 Interzone differences for the 0 to 10 cm layer in the dry seasons and wet seasons. The data for the three sites were pooled by zones. Nonparametric variance (ANOVA; Kruskal–Wallis test) equivalent to a one-way ANOVA based on median of ranks. *H* is the value of the Kruskal–Wallis test. *$p < 0.05$, **$p < 0.001$. ns: $p > 0.05$

	Dry season		Wet season	
Soil variables	*H*	*P*	*H*	*P*
Soil temperature (°C)	5.3	ns	5.4	ns
Soil moisture (%)	4.5	ns	9.6	**
C (g kg^{-1})	4.3	ns	5.0	ns
N (g kg^{-1})	4.8	ns	5.0	ns
DON (mg kg^{-1})	5.2	ns	5.8	ns
NO_3 (mg kg^{-1})	5.9	ns	6.9	*
NH_4 (mg kg^{-1})	3.4	ns	9.4	**
DNR (mg kg^{-1} d^{-1})	4.5	ns	7.8	*

Factors correlated with denitrification

Significant correlations were observed between DNR and soil moisture for the soils of forest and open forest sites, and the correlation was lower for the grass soils, while soil temperature had low negative correlation with DNR in three riparian sites (Table 4). There was significantly positive correlation between DON and DNR for the forest and open forest soils. In contrast, the correlation between DNR and DON was not significant in the grass soil. The relationship between DNR and either total N or NO_3–N was not significant in the forest soil. In contrast, there were positive correlations between DNR, and both total N and NO_3–N in the open forest and grass soils (Table 4). The soil denitrification rate showed a low correlation with soil NH_4–N in the forest soil, and a strong relationship with NH_4–N for the open forest and grass soils. Soil organic C, however, was found to have a significant correlation with DNR in all sites (Table 4 and Fig. 3).

Table 4 Correlations between denitrification rates and soil characteristics in riparian soils. Values are Pearson correlation coefficients; *$P < 0.05$, **$P < 0.001$

	Denitrification rate		
	Forest	Open forest	Grass
Soil temperature	−0.36	−0.15	−0.27
Soil moisture	0.67*	0.62*	0.54
C (g kg^{-1})	0.90**	0.84**	0.68*
N (g kg^{-1})	0.58	0.88**	0.63*
DON (mg kg^{-1})	0.73*	0.61*	0.45
NO_3 (mg kg^{-1})	0.64*	0.49	0.47
NH_4 (mg kg^{-1})	0.53	0.94**	0.82**

Discussion

Spatial and temporal structure of denitrification

Spatial heterogeneity in denitrification may be a function of the distribution of available organic C and NO_3^- substrates in soils. Soil N or organic C, which are often concentrated near vegetation[26] or organic debris,[27] may foster denitrification. In our study, we found a significantly higher *in situ* denitrification activity in the upper horizon whatever the site or the zone (Fig. 3), which corresponds to the rich organic layer. Meanwhile, a significant decreasing trend of soil parameters was explored along the three layers. These strong vertical patterns were observed in soil organic C and TN, and also the concentrations of DON, NO_3–N, and NH_4–N in the three zone soils of three sites (Table 1). Therefore, spatial heterogeneity in substrate availability was the primary controlling factor on spatial patterns in denitrification.

Although there was a sharp gradient of DNR measured along the soil profiles, some significant activities of soil denitrification could be detected down to 50 cm soil layers (Fig. 2). The results may reveal that there existed enough organic carbon to sustain some significant denitrification in deeper soil profiles, which contributed to the reduction of the ground water nitrate load. On the other hand, the denitrification activity can be sustained in deeper soil profiles where the NO_3–N concentration of 20–50 cm soil layer (between 2.0 and 3.4 mg N per kg of dry soil) was not low even though the denitrifying bacteria density may be low for some incommodity conditions. At the upland–wetland interface scale, even though there were strong vertical gradients, the denitrification activity should be considered as a function of the entire soil profile and/or volume rather than as a surface-related process.[25] When considering the volume of soil, one can negotiate on a proper riparian width basis that can get a longer surface of contact between soil matrix

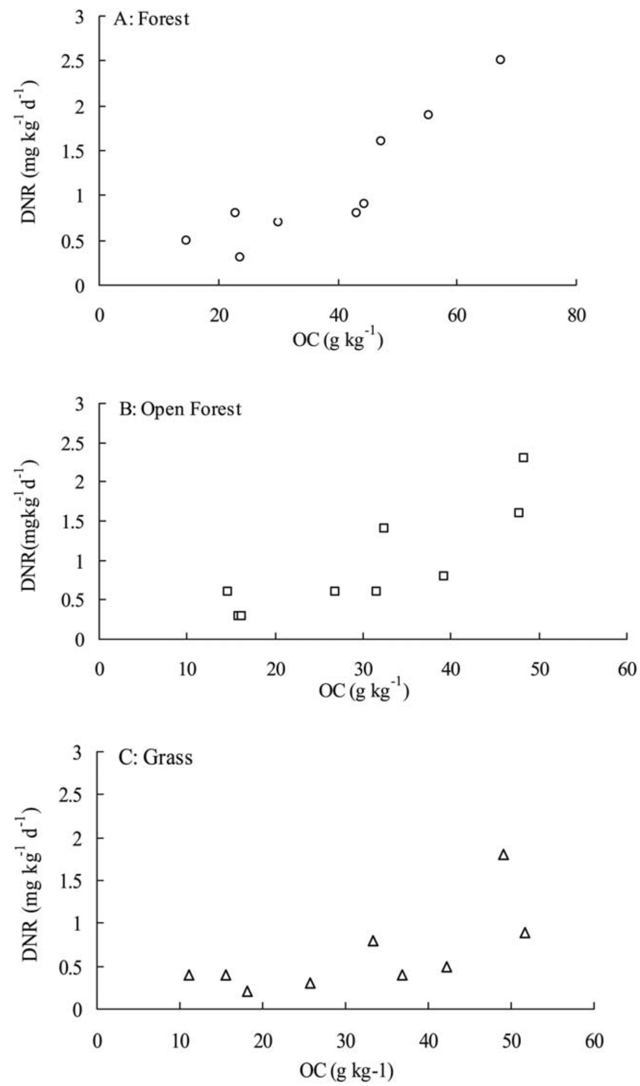

Fig. 3 Relationships between denitrification rate (DNR) and organic carbon (OC) in different riparian sites ((A) forest; (B) open Forest; (C) grass).

and water to remove nitrate. This aspect clearly had some management implications for ground water quality control.

Soil characteristics can determine the spatial locations of denitrification through the influence of accessible resources, while hydrologic vectors may determine where and when soils are biologically active by influencing the water conditions or by importing substrates required for denitrification.[39,40] The declines of soil resources and denitrification may occur away from the stream where water tables are deep and floods infrequent, indicating a positive influence of water availability. In contrast, the homogenization of soil resources fostering denitrification should be larger where floodplain inundation is more frequent and spatially extensive, or where shallow groundwater is available. In our study, the effect of hydrologic vectors on the denitrification rate was evidenced by seasonal changes within the sites, and by contrast between zones and sites along a topohydrosequence gradient although there were no significant differences of DNR between wet season and dry season in some of the zones and sites, which might be due to soil moisture being too low to restrain DNR or other soil characteristics having significant contributions to denitrification. Although no consistent pattern of denitrification rate could be explored from the season perspective, there were some significant differences for the denitrification rate between sites (Table 2). Moreover, no matter what the seasons or sites were, the denitrification rate that was significantly higher in Zone I (near the lake) than zones near the border with the upland areas exhibited spatial patterns with respect to distance from the lake. In the wet seasons, we also found that NO_3–N, soil dissolved organic nitrogen (DON), and soil moisture in the sites were significantly different (p < 0.05). Therefore, spatial heterogeneity in substrate availability and hydrologic gradient can be the primary influence on spatial-temporal patterns in denitrification.

Implication of riparian vegetation type for denitrification

Significant differences in the denitrification rate were measured among different riparian sites of forest, open forest, and grass along a topohydrosequence gradient (from Zone III to ZI). Yet there was no consistent difference between these regions. For instance, in the wet seasons, there were significant differences of denitrification rates among the sites, while soil denitrification was significantly different only in Zone I during dry season (Table 2). These results only add to the conflicting results already described in the literature concerning the respective efficiency of different riparian zones.[41]

It has been suggested that the absence of significant differences among vegetation covers could be due to that they all provide enough organic C and N for the heterotrophic denitrifying bacteria. However, this does not mean that there could never be any shortage of available organic C under a higher carbon demand, which could be generated by either a seasonal or a chronic increase of nitrate from the upland catchment.[42] On the other hand, the variation of denitrification rate for different riparian buffers is fundamentally related to the differences of substrate matter quality and microbial activity among the sites.[10] Our study suggested that, in the wet seasons, 85% rainfall of annual precipitation may be an important regulating factor of soil moisture, because soil moisture could affect many other edaphic parameters that relate to microbial activity required by denitrification. Soil moisture related to organic carbon, NO_3–N and soil dissolved organic nitrogen in the wet seasons might support this hypothesis in the study.

Influence of soil parameters on denitrification

Regulating factors of denitrification are readily decomposable organic carbon and nitrogen, anaerobic conditions, NO_3–N source, and environmental conditions favorable to microbial activity.[43,44] However, most of the above mentioned conditions are not simultaneously present in the buffers, making it difficult to predict denitrification patterns. Soil parameters are spatially and temporally variable, leading to high variability in denitrification rates and formation of hot spots and hot moments.[11,45]

We found that soil organic C had a strong correlation with denitrification in all sites (Table 4 and Fig. 3). At the microbial scale, the most important factor affecting denitrification in riparian buffers may be the labile carbon source for electron donor, microbial energy and biomass production.[46–48] NO_3–N is another limiting factor for denitrification because nitrate often acts as an electron acceptor instead of oxygen, so denitrifiers are active in C-rich and water saturated soils.[49] In wet seasons, there was significantly higher denitrification in the riparian forest site (Table 3 and Fig. 2) where dissolved organic nitrogen and NO_3–N were rich (Table 2). However, no significant differences in the NO_3^- content among some zones in the site may be arisen from the homogeneity of plant cover and nutrient return. Moreover, NH_4–N can be important to denitrification because the dissolved NH_4–N can be taken up by plants and also nitrified to NO_3–N. DON in riparian ecosystems has been considered to be a major component of the N cycle which has important contribution to denitrification.[50] The soil denitrification rate showed low or high correlation with soil NH_4–N and DON in sites (Table 4). This might support the above hypothesis.

Soil moisture and temperature are proved to be important influential factors for denitrification.[51] Very low soil temperature can limit microbial activity required by denitrification. However, our results suggested that soil temperature had little influence on the denitrification rate in the riparian site because air temperature was not low and had little fluctuation (Table 4) in the sites. Another important control variable predicting denitrification was soil moisture, which is determined by hydrological events, flood or rainfall. Denitrification is strictly anaerobic, requiring saturated soils to operate. Therefore the end products of nitrogen cycling in riparian soils are directly controlled by the ground water table with important implications for floodplain productivity. Alternate aerobic and anaerobic conditions triggered by short-term periodicity of flood–drainage cycles or short rainfall events will enhance the process of denitrification. The denitrification rate in our study was significantly higher in the wet seasons than in dry seasons and soil moisture had a significant correlation with the denitrification rate because precipitation in Kunming showed a strong seasonal variation with rainy seasons (about 85% rainfall of annual precipitation) from May to October and dry seasons (about 15% rainfall of all year) from November to April of next year.

Conclusion

Studies on soil denitrification in the Dianchi Lake and its possible controlling mechanisms are of great interests to ecologists and environment agencies in China. In order to better understand the control of nutrient removal in vegetative buffer strips along the seasonally eutrophic Lake Dianchi (Yunnan, China), the study measured denitrification rate as a function of depth, vegetation type and season. We collected the data for the soil profiles, which were along topographic gradients from three riparian buffers, including soil temperature, soil moisture, C, N, CON, nitrate and ammonia. We observed the significant differences in denitrification rate with depth in both wet and dry seasons, and significant differences in denitrification rate with distance from lake and with vegetation type in the wet season. The results suggest that the availability of organic C plays a major role in the control of the denitrification rate (and buffer capacity) that varies with zonation and vegetation.

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