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Nitrogen export by runoff from agricultural plots in two basins in China

Weijin Yan*, Shen Zhang, Xibao Chen and Yijian Tang
*Department of Environmental Biogeochemistry and Health, Institute of Geographic Science and Natural Resources Research, Chinese Academy of Sciences, 971 Building, Datun Road, Beijing 100101, P.R. China; *Author for correspondence (phone: +86-10-64863998; e-mail: yanwj@igsnrr.ac.cn)*

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Abstract

Runoff and sediment yields from agricultural fields are major sources of nitrogen (N) entering lakes in China. Export of sediment and N can be impacted by soil and cropping management practices, but there is relatively little information on N leaving agricultural fields in lake basins in China. Sediment and surface runoff N from a series of field plots in two experimental lake basins were evaluated *in situ* under simulated rainfall conditions. Objectives of the study were to evaluate the effects of crop cover, slope, and fertilizer application on N in surface runoff and eroded soils. Sediment yields varied from 4.3 to 299.0 g m^{-2}, depending on management practice. Mean dissolved nitrogen (DN) and total nitrogen (TN) concentrations are 1.35 and 5.4 mg L^{-1}, respectively, in Lake Taihu basin, while mean DN and TN concentrations are 2.66 and 4.3 mg L^{-1}, respectively, in Lake Baiyangdian basin. For all experimental plots in two basins, weighted average concentrations of N for total-N, dissolved N and sediment N are 1.0–5.0 mg L^{-1}, much higher than 0.2 mg L^{-1}, indicating a problem in lake eutrophication due to high N concentration from agricultural surface runoff. The estimated mean annual export of total N was 6.0 and 14.7 kg ha^{-1} yr^{-1} for Baiyangdian and Taihu lake basins, respectively. The study showed that significantly more N (approximately ranging from 10% to 90% of total N) exported was associated with sediment, constituting a long-term source of potentially bioavailable N in lakes.

Introduction

Nitrogen (N) is a limiting element for terrestrial production, particularly in intensive agricultural systems relying on high inputs of N fertilizer to achieve sufficient yields to maintain an increasing population. However, long-term agricultural application of N fertilizer and lower fertilizer use efficiencies have resulted in substantial surplus in N balance; the surpluses in the N balance amount varied from approximately 30 kg N ha^{-1} (Høyås et al. 1997; Yan et al. 1999a) to more than 150 kg N ha^{-1} in intensive agricultural systems on the Loess Plateau (Emteryd et al. 1998), and 217–335 kg N ha^{-1} in the (rice-wheat double cropping) Taihu region in eastern China (Richter and Roelcke 2000), which is an indication of significant overfertilization. This surplus is a potential source of diffuse pollution to adjacent aquatic environments, causing eutrophication (Vollenweider 1968). Global N overload is an emerging environmental issue for the 21^{st} century (Munn et al. 1999). The worldwide use of N fertilizers is causing regional and global N overload problems (Moffatt 1998). N loss from agricultural fields to aquatic ecosystems is one of the important processes in N regional cycles, and is receiving increased attention (Harris et al. 1995; Kronvang et al. 1996; Van der Molen et al. 1998; Novotny 1999; Galloway and Cowling 2002; Van Breemen et al. 2002).

N is one of the major fertilizer nutrients used in China. The total amount of N fertilizer was about 2.2 $\times 10^{10}$ kg in 1997, approximately 190 kg ha^{-1} fertilizer N for agricultural fields in China (China State Statistical Bureau 1998). This is compared to 10 kg ha^{-1} in the 1950s and 70 kg ha^{-1} in the late 1970s (China State Statistical Bureau 1985). The increase in N fertilizer use should significantly increase N concentration in lakes and rivers of China (Yan et al. 1999a, 2001). Recently, China's National EPA launched a national water pollution control project to improve water quality in 'three lakes and three rivers' to target long-term planning on lake eutrophication control through to 2010. Some studies indicated that agriculture is the major source of N in lakes, accounting for more than half of the total load (Tu et al. 1990; Jin et al. 1995). One way in which N is transported to neighboring water bodies from agricultural fields is by surface runoff and sediment. Many studies have reported N loss from agricultural fields in heavily-agricultural regions of China. For example, in Chaohu Lake basin of Eastern China, annual total N load by runoff varied from 2.0 to 30.0 kg ha^{-1} from crop lands and rice fields (Peng and Chen 1988; Yan et al. 1998, 1999b); while in Donghu Lake basin of Central China, the N load was 28.3 kg ha^{-1} by surface runoff (Zhang et al. 1984), and 11.2 kg ha^{-1} in the Three-Gorge Reservoir region of the upper Yangtze River (Chen 1992). In addition to surface runoff and erosion, leaching is the third way in which N is transported to receiving water bodies. For example, N load by leaching varied from 3.0 to 10.0 kg ha^{-1} a^{-1} in the intensive agricultural (rice-wheat double cropping) systems at Taihu region in eastern China (Zhu and Wen 1992; Ma et al. 1997; Lian et al. 2003). The export of N from fields through runoff and erosion is influenced by various factors including rainfall, hydrology, geology, cropping and management, and integrated biogeochemical cycles; however, there is little information on processes, mechanisms and influencing factors of N export from agricultural fields through runoff and erosion in China. The objective of this study was to determine the effect of cropping and management on N export in two lake basins in China, Baiyangdian and Taihu.

Experimental sites

Lake Baiyangdian, the largest natural freshwater body in North China Plain (360 km^2 in surface area), is located 130 km south of Beijing (48°43′–39°02′ N and 115°38′–116°07′ E). The lake has a reduced surface area and it is in a eutrophic state. The lake depth varies according to the hydrologic conditions, but is usually less than 2.0 m. In some dry years, the lake retains only a very small amount of water and typically becomes a marsh. The water quality in the lake is degraded, mainly caused by agricultural runoff and wastewater discharge from Boading City, while the reduction of the surface area and depth of the lake worsen the eutrophic situation (Zhang and Tang 1995). The common cropping practice is winter wheat-peanut (or soybean, maize) rotation in the basin with topdressed fertilization by 350 kg ha^{-1} of $CO(NH_2)_2$ (46.7% of N) for winter wheat production. In addition, there are 300 kg ha^{-1} of $CO(NH_2)_2$ for peanuts, soybean, maize, and other crops. The 30-yr mean long-term precipitation is 560 mm yr^{-1}, with an average rainfall intensity of 50 mm h^{-1}. Most of the rainfall occurs during the summer season.

Lake Taihu, one of the five largest freshwater lakes (2340 km^2 in surface area) in China, is located in Eastern China (30°55′–31°33′ N and 119°53′–120°36′ E) on a tributary of the Yangtze River. Lake Taihu basin serves both agriculture and industry. In recent decades, with rapid industrial development and heavy application of fertilizers, increasing amounts of nutrient-rich pollutants have drained into the lake, resulting in lake eutrophication. For most fields, the cropping system is early rice, late rice, and rape. Other cropland is normally cultivated with wheat (*Triticum aestivum* L.), cotton (*Gossypium hirsutum* L.), peanut (*Arachis hypogaea* L.), and soybean (*Glycine max* L. *Merr.*), etc. Similar to most areas in Eastern and Central China, N fertilizer use is increasing. Common fertilizer applications are 1200 kg ha^{-1} of NH_4HCO_3 (17.7% N), 300 kg ha^{-1} of $CO(NH_2)_2$ (46.7% N) for rice production. In addition, there are 600 kg ha^{-1} of NH_4HCO_3 and 200 kg ha^{-1} of $CO(NH_2)_2$ for wheat, oilseed, and other crops. Normally, all fertilizers are surface-applied by hand. The 30-yr mean long-term precipitation is 1100 mm yr^{-1}, with an average intensity of about 70 mm h^{-1}. Most of the heavy rainfall occurs from April through September.

Methods of procedures

Field experiments under simulated rainfall conditions were conducted from September 1 to 10, 1993 at Anxin County, upstream of Lake Baiyangdian, and from July 16 to 28, 1998 at Jurong County in the Lake Taihu basin. Generally, the rain season is from July

Table 1. Plot information.

Watershed	Crop	Crop height (cm)	Crop cover (%)	Slope (%)	Moisture content of soil (%)
Lake Taihu basin	Rice	40	90	< 2	Submerged
	Fallow	10	10	< 2	23.4
	Cotton (I)	90	80	7	21.0
	Cotton (II)	70	80	< 2	19.1
	Maize (I)	100	35	< 2	18.2
Lake Baiyangdian basin	Maize (II)	150	65	≤ 2	7.3
	Plowed (I)	0	0	≤ 2	10.9
	Plowed (II)	0	0	≤ 2	31.8

Table 2. Characteristics of soils in selected plots.

Watershed	Plot crop	Soil type	Texture class	Density (g cm^{-3})	OM (%)	TN (mg kg^{-1})	TP (mg kg^{-1})	Particle-size distribution		
								Clay†	Silt	Sand
Lake Taihu basin	Rice	Paddy soil	Clay	1.54	1.52	956.1	197.7	54.1	39.2	6.7
	Fallow	Yellow brown soil	Clay loam	1.67	1.29	701.5	336.1	47.0	45.8	7.2
	Cotton (I)	Yellow brown soil	Clay loam	1.67	1.29	701.5	336.1	47.0	45.8	7.2
	Cotton (II)	Yellow brown soil	Clay loam	1.67	1.29	701.5	336.1	47.0	45.8	7.2
	Maize (I)	Yellow brown soil	Clay loam	1.45	1.21	706.4	458.6	48.2	44.5	7.3
Lake Baiyang-dian basin	Maize (II)	Meadow drab soil	Loam	1.56	0.87	260.0	630.0	17.0	53.0	30.0
	Plowed (I)	Meadow drab soil	Loam	1.03	1.63	520.0	550.0	17.8	51.2	31.0
	Plowed (II)	Meadow drab soil	Loam	1.03	1.63	520.0	550.0	17.8	51.2	31.0

†Clay: < 2 μm, silt: 2–53 μm, sand: > 53 μm.

to September each year in the two basins. Especially in Lake Taihu basin, middle-rice is often planted in July, during which fertilization also takes place. Eight rectangular 2 × 5 m plots (much larger than the 1 × 2 m plots chosen by other studies, Schlesinger et al. 1999) were established in two drainage basins (Table 1), 5 in the Taihu basin and 3 in the Baiyangdian basin. Before each rainfall, the soil was sampled to 50 mm depth and analyzed for physical-chemical properties by standard methods (Table 2) (Page 1982). A detachable protective extension 50 cm in height was placed on three sides of the plots to prevent rain and runoff water from splashing and moving between the outside and inside of the plots. A sprinkling device for simulated rainfall (Luk et al. 1986) was used to simulate natural rainfall. This simulator delivers rainfall with 90% of the kinetic energy of natural rainfall and a comparable drop-size distribution. Rainfall time is designed to be 30 min. Rainfall density is designed to represent heavy rainfall (about 1.2–1.6 mm per minute) and general rainfall (about 0.6 mm per minute) (Table 3). Surface runoff rates were determined by taking timed volumetric samples of the water discharge with V-type flumes, equipped with plastic containers at the lowest side of the plot. Total water and sediment in runoff were collected at 3-min

Table 3. The simulated rainfall-runoff information for all plots.

Watershed	Plot crop	Rainfall volume (mm)	Time when runoff occurs (min/sec)	Runoff volume (mm)	Runoff coefficient (%)	Sediment load (g m^{-2})
Lake Taihu basin	Rice	49.1	17′5″	9.6	19.6	4.3
	Fallow	52.5	1′50″	34.4	65.4	43.4
	Cotton(I)	38.4	2′10″	18.0	46.9	299.0
	Cotton (II)	37.5	5′40″	12.1	32.3	16.9
	Maize (I)	18.0	7′40″	5.5	30.6	5.6
Lake Baiyangdian	Maize (II)	33.3	14′6″	4.2	12.6	4.8
basin	Plowed (I)	35.1	8′5″	13.8	39.3	41.6
	Plowed (II)	17.1	2′0″	9.5	55.6	12.5

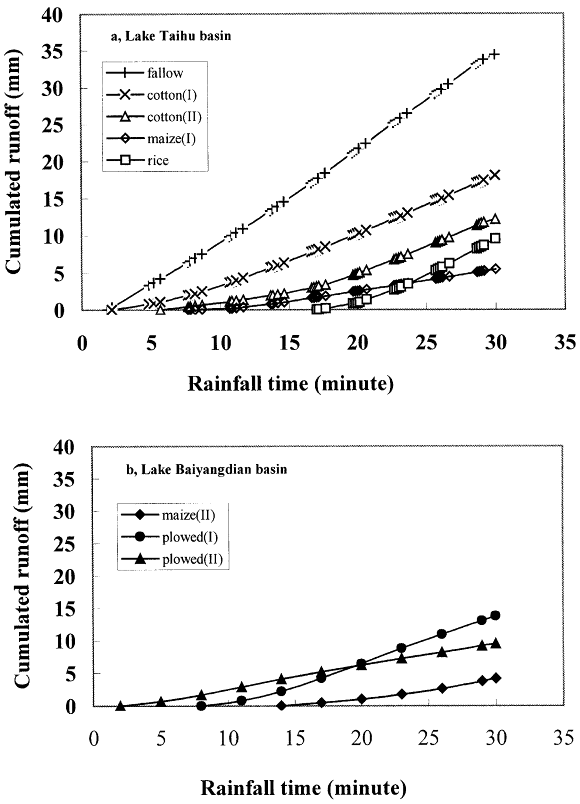

Figure 1. Cumulated surface runoff over three-min intervals during rainfall simulation experiments.

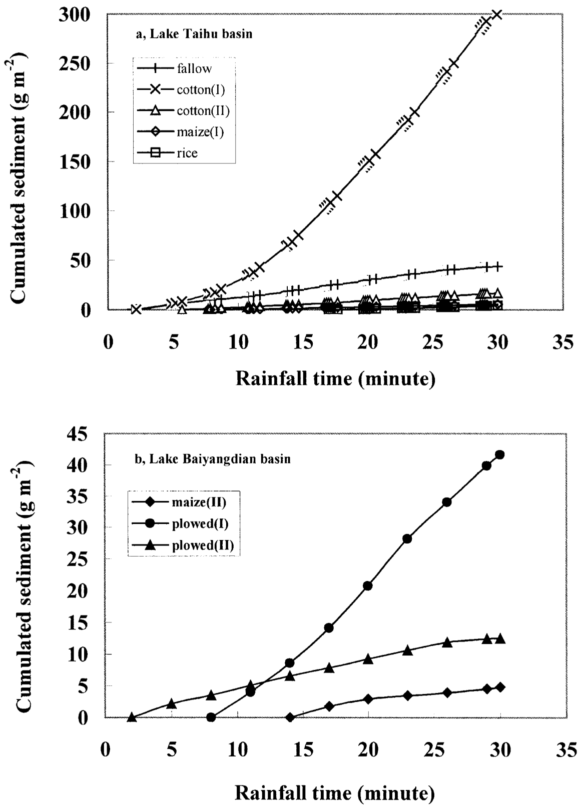

Figure 2. Cumulated sediment production over three-min intervals during rainfall simulation experiments.

intervals. Water and sediment were vigorously stirred, duplicate samples of 200-mL aliquots from each sample were collected, and concentrated H_2SO_4 was immediately added to the samples. Samples were refrigerated at 4 °C until being analyzed. All sediments from each sample of 3-min runoff were totally collected through 0.45 μm filters and air-dried to determine sediment weight. Sediment concentration was calculated using the sediment weight. The collected 200-mL aliquots from each sample were vacuum filtered through 0.45 μm glass fiber filters, and the filtrate was analyzed for dissolved nitrogen (DN) and dissolved inorganic nitrogen (DIN) on an organic nitrogen analyzer (DN-1902) produced by Dohrmann in 1996. Dissolved organic nitrogen (DON) was calculated as the difference between DN and DIN. Sediment N (Sedi-N) and soil N were determined by the Kjeldahl method (Page 1982). The concentration of total N (TN) in runoff was calculated as the sum between DN and Sedi-N. Contents of N in the applied water were subtracted from the contents in runoff to estimate net loss in runoff. The yields of TN from the plots were calculated by multiplying mean TN concentration by total runoff during the designed rainfall time. Enrichment ratios (Ghadiri and Rose 1991) were calculated by dividing N contents of sediment by N contents of the top 50 mm of source soil. All the data were examined by statistical analysis (ANOVA; SSPS software).

Results and discussion

Runoff and sediment yield

Rainfall-runoff relationships for 8 field plots are given in Table 3. The time that runoff started may differ significantly between plots ($p = 0.01$), but in part this can be contributed to different rainfall intensities. Rainfall intensity at the fallow plot is significantly higher than in the other plots. Runoff started significantly sooner in the fallow plot (1 min 50 sec) and cotton plot (I) (2 min 10 sec) than in the other plots. In contrast with these two plots, runoff started significantly later in the plot with maize (II) cover (14 min 16 sec) and the rice plot (17 min 5 sec) (runoff occurs when water overflows from the mouth of the rice plot). The processes of cumulated runoff and sediment yields with rainfall time are shown in Figures 1 and 2, respectively. As shown in Figure 1, there was a significant difference ($p = 0.05$) in runoff production for each plot. The curve for the fallow plot has the largest slope (Figure 1), showing that runoff from the fallow plot was significantly greater than that from other plots, likely because this plot had less soil cover ($<$ 10%) and higher soil moisture content (23.4%) (Table 1). The curves for the plots with rice, cotton (I, II) and one of the plowed (I) plots have similarly higher slopes than those for the plots with maize (I, II) and the other plowed plot. This reflects that runoff was significantly higher in the plots with rice, cotton (I, II), and one of the plowed (I) plots; while runoff was significantly lower in the plots with maize (I, II), and the other plowed (II) plot. The result indicates that soil cover, slope and rainfall intensity could be main factors influencing runoff. Sediment production has a different pattern than runoff (Figure 2). The cotton (I) plot produced the greatest sediment yield among the plots, reaching 299.0 g m^{-2}. The fallow and plowed (I) plots also had higher sediment yield, reaching about 43.4 g m^{-2}; while the rice plot had the smallest sediment yield, about 4.3 g m^{-2}.

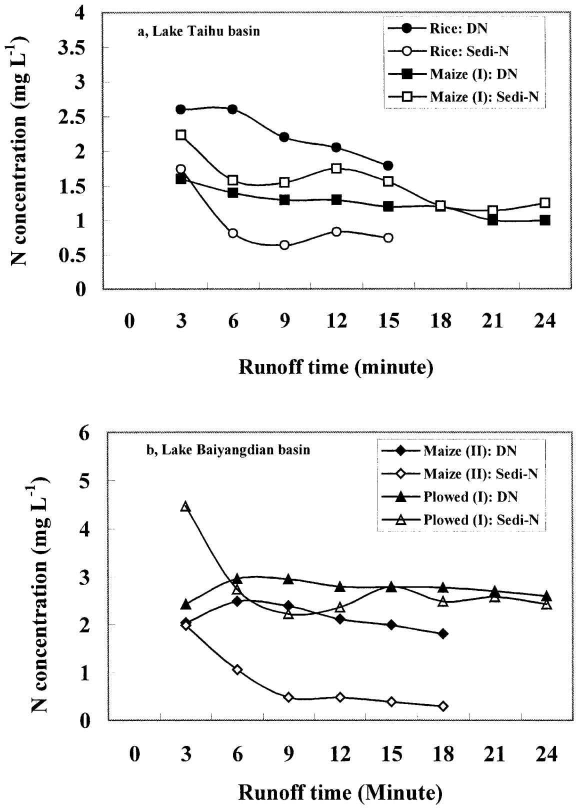

Figure 3. Changes in concentration of nitrogen during rainfall simulation experiments.

Nitrogen concentration and export

For most plots, concentrations of both DN and Sedi-N declined with time during the rainfall simulation experiments (Figure 3). Volume-weighted mean concentrations of N for different forms (TN, DN, Sedi-N, DIN and DON) in surface runoff of each plot are presented in Table 4. N concentrations in surface runoff varied significantly in different plots in two basins. No straight-linear relationship was found between runoff rate and concentration of TN in surface runoff in two basins (Figure 4). This observation is consistent with the results that Yan et al. (1998) obtained from a 732 ha agricultural watershed planted with rice, wheat, cotton and other crops; and with the results McDowell et al. (1989) obtained from the study of a watershed planted with cotton. However, a curvilinear relationship was observed between runoff

Table 4. Mean concentration of nitrogen in surface runoff.

Watershed	Plot crop	DN mg L^{-1}	Sedi-N	TN	DIN	DON	DN/TN %	DIN/DN
Lake Taihu basin	Rice	2.59	1.0	3.6	0.47	1.43	72.5	24.7
	Fallow	0.69	1.3	2.0	0.16	0.65	35.0	19.7
	Cotton (I)	1.10	15.0	16.1	0.40	0.73	6.8	35.4
	Cotton (II)	1.05	1.1	2.2	0.20	0.86	48.4	18.9
	Maize (I)	1.31	1.6	2.9	0.17	0.96	45.5	15.0
Lake Baiyangdian basin	Maize (II)	2.65	0.8	3.4	nd[†]	nd	77.7	nd
	Plowed (I)	3.01	2.8	5.9	nd	nd	51.4	nd
	Plowed (II)	2.31	1.4	3.7	nd	nd	62.9	nd

[†]nd: not determined.

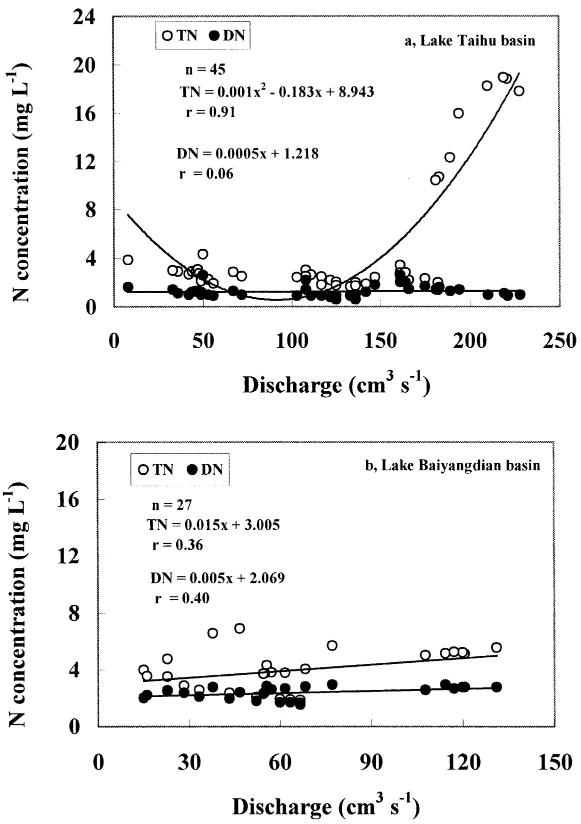

Figure 4. Relationship between concentration of N and discharge in plot runoff.

rate and concentration of TN in Lake Taihu basin, and the dataset also indicates there may be a threshold after 180 cm^3 per second discharge (Figure 4a). Likewise, no relationship was observed between runoff rate and concentration of DN ($r = 0.06$ in Lake Taihu basin and 0.40 in Lake Baiyangdian basin) in plot runoff (Figure 4b). N concentrations were highest in the runoff from the cotton (I) plot, with average concentrations of 16.1 mg TN and 15.0 mg Sedi-N L^{-1} (Table 4). This plot also had the highest sediment yield in runoff. The plowed (I) plot had highest concentration of DN and higher concentration of Sedi-N in runoff, both plowed (I) and (II) plots had higher concentration of TN in runoff (Table 4), likely because of the long-term irrigation with urban waste water in these two fields. Portions of N forms in runoff also varied with different plots. DN was about 72% of TN from the rice plot, and DIN about 25% of DN. DN accounted for about 78% of TN from the maize (II) plot. In contrast with this plot, DN accounted for less than 7% of TN from the cotton (I) plot. For cropped plots, DN was about 30–60% of TN. The TN and Sedi-N concentrations had good relationships with sediment concentration (for both TN and Sedi-N, $r = 0.99$ in Lake Taihu basin, and $r \geq 0.99$ in Lake Taihu basin, and $r \geq 0.91$ in Lake Baiyangdian basin) (Figure 5). The strong correlation between sediment and Sedi-N suggests that N loss in particulate form (more than 40–70% TN) is the most critical pathway of transportation in agricultural runoff for most cropland soils in these basins (Figure 6). In addition, for most plots, N concentrations for TN, DN and Sedi-N were in the range from 1.0 to 5.0 mg L^{-1}, which is consistent with N concentrations of most lake waters in China (Jin et al. 1995). These N concentrations are much higher than 0.2 mg L^{-1}, which is the critical concentration limit for eutrophication in lake waters (Vollenweider 1968; Jin et al. 1995), indicating a great potential problem that can result in lake eutrophication from agricultural surface runoff in China.

The yield of TN was calculated by multiplying mean TN concentration (Table 4) by total runoff (Table 3) during the designed rainfall time for each plot. The highest yield of TN is from the cotton (I)

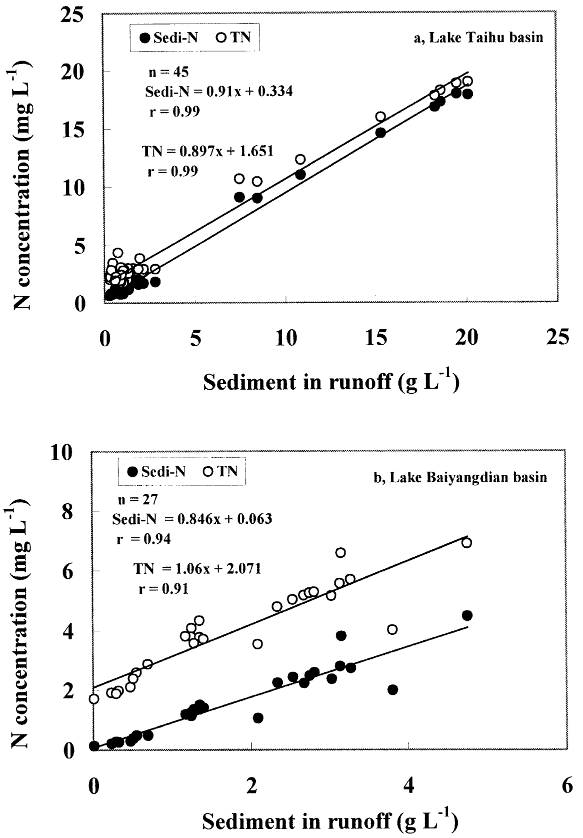

Figure 5. Relationship between concentration of N and sediment in plot runoff.

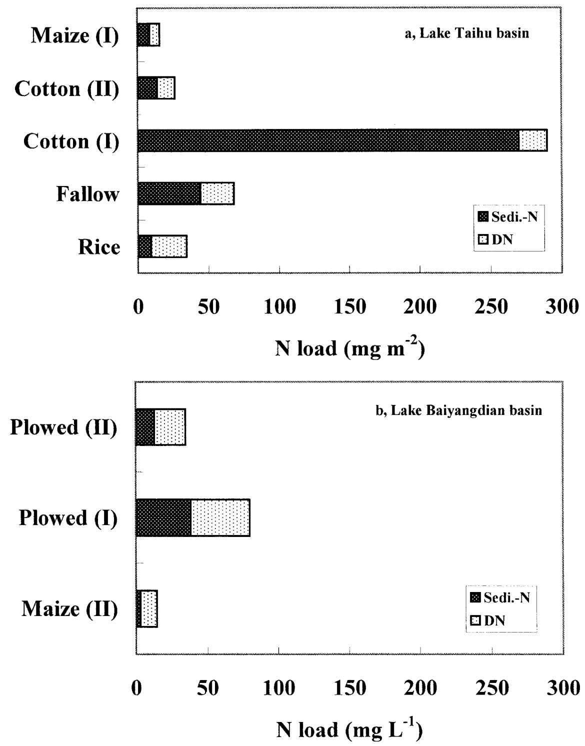

Figure 6. Mean load (mg m^{-2}) of sediment nitrogen (Sedi-N) and dissolved nitrogen (DN).

plot in Lake Taihu basin (Figure 6), reflecting the greatest sediment yields (299.0 g m^{-2}) in runoff and higher runoff coefficients (46.9%) (Table 3). The total TN export of 290.0 mg m^{-2} is about 2.5% of the pool of soil-N in the surface 10 mm of soil planted with cotton. The higher yield of TN from the plowed (I) plot in Lake Baiyangdian basin reflects higher N concentrations in runoff and higher runoff coefficients (39.3%). The total TN export of 80.9 mg m^{-2} is approximately 1.5% of the pool of soil-N in the surface 10 mm of the soil, suggesting that soil and N are easily exported by runoff from plowed fields. The lowest TN export from the maize (I, II) plots (15.8 and 14.3 mg m^{-2}, respectively) reflects the least runoff and lowest sediment yields (5.6 and 4.8 g m^{-2}), despite the higher DN concentration in runoff (Table 4).

For each of the two basins, considering the standard problem of up-scaling, we only provide rough estimates of annual N exports from different kinds of agricultural fields on the basis of the annual precipitation of 550 and 1100 mm in Baiyangdian and Taihu basins, respectively. These estimates are referred to as minimum, average, and maximum estimates at 12.5, 25, and 50% of runoff coefficients, respectively, based on the long-term rainfall-runoff conditions. Annual N export is calculated by multiplying N concentration by annual runoff for each plot. The estimated values are listed in Table 5. The average DN exports from agricultural fields varied from 3.2 to 4.2 kg ha^{-1} yr^{-1}, and TN exports varied from 4.7 to 8.1 kg ha^{-1} yr^{-1} in Lake Baiyangdian basin; while the average DN exports varied from 1.9 to 7.1 kg ha^{-1} yr^{-1}, and TN exports varied from 5.5 to 44.3 kg ha^{-1} yr^{-1} in Lake Taihu basin. Our data are consistent with the results of others obtained from lake basins in Southern and Eastern China (Peng and Chen 1988; Yan et al. 1998; Jin et al. 1995). The range of TN exports from agricultural fields in Taihu basin is higher than that in Baiyangdian basin (Table 5). This could be the difference of rainfall intensity and rainfall volume in the two basins. The strong rainfall intensity and high rainfall volume could cause more soil loss to increase the Sedi-N export due to the sediment enrichment effect. Sediment enrichment ratios (ER) of N are shown in Figure 7. The values of N ER were variable (rang-

Table 5. Estimates of annual N export from each plot in two basins.

Watershed	Plot crop	N conc. ($mg\ L^{-1}$) DN	N conc. ($mg\ L^{-1}$) TN	Annual runoff (mm) Min.	Annual runoff (mm) Ave.	Annual runoff (mm) Max.	N export† ($kg\ ha^{-1}\ yr^{-1}$) DN Min.	DN Ave.	DN Max.	TN Min.	TN Ave.	TN Max.
Lake Taihu basin	Rice	2.59	3.6	138	275	550	3.6	7.1	14.2	5.5	9.9	19.8
	Fallow	0.69	2.0	138	275	550	1.0	1.9	3.8	2.8	5.5	11.0
	Cotton(I)	1.10	16.1	138	275	550	1.5	3.0	6.0	22.2	44.3	88.6
	Cotton(II)	1.05	2.2	138	275	550	1.5	2.9	5.8	3.1	6.1	12.2
	Maize(I)	1.31	2.9	138	275	550	1.8	3.6	7.2	4.0	8.0	16.0
Lake Baiyangdian basin	Maize(II)	2.65	3.4	69	138	275	1.9	3.7	7.4	2.4	4.7	9.4
	Plowed(I)	3.01	5.9	69	138	275	2.1	4.2	8.4	4.1	8.1	16.2
	Plowed(II)	2.31	3.7	69	138	275	1.6	3.2	6.4	2.6	5.1	10.2

†N export is calculated by multiplying N concentration by annual runoff.

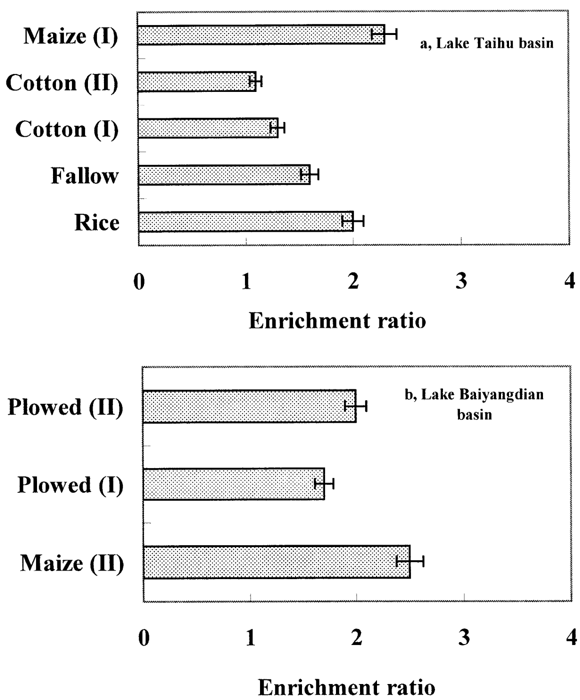

Figure 7. Sediment enrichment ratios of nitrogen during the rainfall simulation experiments.

ing from 1 to 3) and significantly different among the plots. The values of N ER were larger than 1, indicating that N enrichment occurred in sediments from all plots resulting in high N content in sediments. These N ratios are similar to N ER ratios found by Douglas, Jr. et al. (1988) from a 5-yr (1980–1984) study of wheat-pea rotation in Northeast Oregon. Normally, all fertilizers are topdressed and liable to be lost from agricultural fields by surface runoff and erosion in China. Therefore, we arrive at a critical question: How to control or prevent agricultural nutrient losses? Since only less than 50% of N fertilizer applied in agriculture is absorbed by crop (Galloway and Cowling 2002), the most important step is how N fertilizer is effectively applied in agricultural fields. Other steps include improving cultivation ways (such as taking immuning-tillage measurement in rice production) and cropping systems (such as cultivating grass instead of other crops in the fields with larger slopes).

Conclusions

Sediment yields varied from 4.3 to 299.0 g m^{-2} for all plots in Lake Taihu basin, and from 4.8 to 41.6 g m^{-2} in Lake Baiyangdian basin. For all plots in Lake Taihu basin, DN concentrations varied from 0.69 to 2.59 mg L^{-1}, while TN concentrations varied from 2.0 to 16.1 mg L^{-1}. For all plots in Lake Baiyangdian basin, DN concentrations varied from 2.31 to 3.01 mg L^{-1}, while TN concentrations varied from 3.4 to 5.9 mg L^{-1}. The estimated mean annual export of TN from agricultural fields varied from 4.7 to 8.1 and from 5.5 to 44.3 kg ha^{-1} yr^{-1}, respectively, for Baiyangdian and Taihu basins under normal hydrological conditions. For all the experimental plots, the weighted average concentrations of N for TN, DN and Sedi-N in runoff were much higher than the limiting concentration of 0.2 mg L^{-1} in lake waters, showing the great potential for lake eutrophication from agricultural surface runoff. Significantly more N (ranging from 10 to 90% of TN) lost was associated with sediment, which had a larger N ER than 1 for all sites. This large amount of Sedi-N constitutes a long-term source of potentially bioavailable N in lake waters.

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