RESEARCH ARTICLE

Surface runoff and nitrogen (N) loss in a bamboo (*Phyllostachys pubescens*) forest under different fertilization regimes

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Abstract Nitrogen (N) losses from agricultural fields have been extensively studied. In contrast, surface runoff and N losses have rarely been considered for bamboo forests that are widespread in regions such as southern China. The thriving of bamboo industries has led to increasing fertilizer use in bamboo forests. In this study, we evaluated surface runoff and N losses in runoff following different fertilization treatments under field conditions in a bamboo (*Phyllostachys pubescens*)

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forest in the catchment of Lake Taihu in Jiangsu, China. Under three different fertilization regimes, i.e., control, site-specific nutrient management (SSNM), and farmer's fertilization practice (FFP), the water runoff rate amounted to 356, 361, and 342 $m^3 ha^{-1}$ and accounted for 1.91, 1.98, and 1.85 % of the water input, respectively, from June 2009 to May 2010. The total N losses via surface runoff ranged from 1.2 to 1.8 kg ha^{-1}. Compared with FFP, the SSNM treatment reduced total nitrogen (TN) and dissolved nitrogen (DN) losses by 31 and 34 %, respectively. The results also showed that variations in N losses depended mainly on runoff fluxes, not N concentrations. Runoff samples collected from all treatments throughout the year showed TN concentrations greater than 0.35 mgL^{-1}, with the mean TN concentration in the runoff from the FFP treatment reaching 8.97 mgL^{-1}. The loss of $NO_3^- $–N was greater than the loss of NH_4^+–N. The total loss of dissolved organic nitrogen (DON) reached 23–41 % of the corresponding DN. Therefore, DON is likely the main N species in runoff from bamboo forests and should be emphasized in the assessment and management of N losses in bamboo forest.

Keywords Bamboo forest · *Phyllostachys pubescens* · Surface runoff · Nitrogen loss · Fertilization

Introduction, aim, and scope

With population growth and rapid economic development in China, surface water in China is heavily polluted in many regions due to point source pollution (e.g., municipal sewage and industrial wastewater effluents) and nonpoint source pollution. An extreme example is Lake Tai that has experienced

dramatic toxic algal blooms in recent years (Qin et al. 2007). Lake Tai, with an area of 2,250 km^2, is the third largest freshwater lake in China and provides water to 30 million residents. Surrounding the lake are thousands of factories and vast farm lands, mingled with large areas of bamboo forests. Although many efforts have been made by the government to curtail the pollution, the lake's water quality has not shown any significant improvement (Zhang and Chen 2011; Jin et al. 2010).

The continued deterioration is likely due to nonpoint source pollution that is challenging to mitigate (Zhang et al. 2010). Nitrogen (N) losses from arable land in dissolved and particulate forms tend not only to cause eutrophication in water bodies, but also impoverish soil nutrient stocks and lower soil productivity (Teixeira and Misra 2005; Matlou and Haynes 2006) where N is limiting. Although N loss through runoff and leaching from croplands is suspected to contribute to the deterioration of surrounding water systems, there is no conclusive evidence to assess the contribution from forest soils. Control of runoff N is critical for sustainable agriculture as well as water quality protection.

Nitrogen in runoff can be separated into particulate (PN) and dissolved N (DN). DN includes dissolved inorganic N (NH_4^+–N and NO_3^-–N, collectively known as dissolved inorganic nitrogen (DIN)) and dissolved organic N (DON). Research on soil N pools and cycling has traditionally focused on inorganic forms (Fang et al. 2009). However, recent studies in some forested watersheds have shown that soil DON is the dominant form of N in adjacent water bodies. These findings suggest that DON from terrestrial sources may be an important contributor to the pollution of waterways (Zhong and Makeshin 2003). Information on N loss, especially the dynamic characteristics of N loss by runoff and suspended materials from rainfall, is currently limited for forest soils, especially bamboo forests.

China has the world's richest bamboo resource with about 500 species (Di and Wang 1996), which accounts for one third of the world's total bamboo species. Bamboo (*Phyllostachys pubescens*) forests are widely distributed in the catchments of Lake Taihu. These forests are about 30 % of the total hilly and mountainous area of the watershed and support a billion dollar industry that is vital to the local economy (Zhang et al. 2001). The estimated coverage of bamboos around Lake Taihu is 728,000 ha^{-1}. Like elsewhere in southern China, more and more primary bamboo forests have been cultivated in recent decades (Zhou 1998). To promote growth and productivity, many bamboo forests are routinely fertilized with inorganic and organic fertilizers. For example, a survey of the study area indicated the monthly N input as fertilizers is 70 kgha^{-1}month^{-1} in bamboo forest. Accompanying this shift in practice, some environmental problems, such as degradation of bamboo forests, deterioration of soil quality, and water pollution, have begun

to occur (Shen et al. 2000). However, N losses from bamboo forests under different practices have yet to be determined, and little information is available on the ecosystem response to different fertilization regimes. Site-specific nutrient management (SSNM) was suggested by International Rice Research Institute scientists, in which fertilizer application is based on time and quantity plant need. Base on this technique, rice yield and fertilizer efficiency can be improved significantly (Witt and Dobermann 2002). Thus, we applied the SSNM to bamboo forest. Field-specific fertilizer N, P, and K recommendations are calculated in five key steps according to Witt and Dobermann (2002) and Wang et al. (2003) reported: step 1, estimation bamboo target yield; step 2, estimating nutrient requirements to get the target yield; step 3, estimating indigenous nutrient supply from soils; step 4, calculating fertilizer requirement; and step 5, dynamic adjustment of fertilizer N application. The primary objective of this study was to evaluate N losses via surface runoff from bamboo forests over the course of a year under different management conditions and to provide a basis for estimating the overall N loss potential in a bamboo ecosystem.

Materials and methods

Study site

The study was carried out from 2009 to 2010 in the Siling watershed, Yuhang County, Zhejiang Province (Fig. 1). The Siling watershed drains into a tributary of the Tiaoxi River and ultimately into Lake Taihu. Bamboo forest covers about 70 % of the entire hilly and mountainous area of the watershed. The study site is characterized with a typical subtropical monsoon climate and has a mean temperature of 15.7 °C. Average rainfall is 1,550 mm, about 70 % of which occurs between March and August. The soil is mainly Red Soil series (Ultisol) according to the soil classification system of China. The basic soil properties and bamboo growth status in the study areas are shown in Table 1. Experimental plots were established on slightly sloping bamboo land in the watershed.

Field experiment design

In May 2009, three typical primary bamboo forests within 1,000 m of each other in the watershed were chosen for the experiment. These bamboos belong to *Phyllostachys* (Gramineae: Bambusoideae), uniaxial scattered type. Three runoff plots as three fertilizer treatments were established in each typical primary bamboo. There were nine runoff plots for three fertilizer treatments with three replicates in the three typical primary bamboo forest. The plot size was 300 m^2 (20×15 m) and each plot was surrounded by low cemented walls. The 6-cm wide cemented wall was 50 cm tall, with
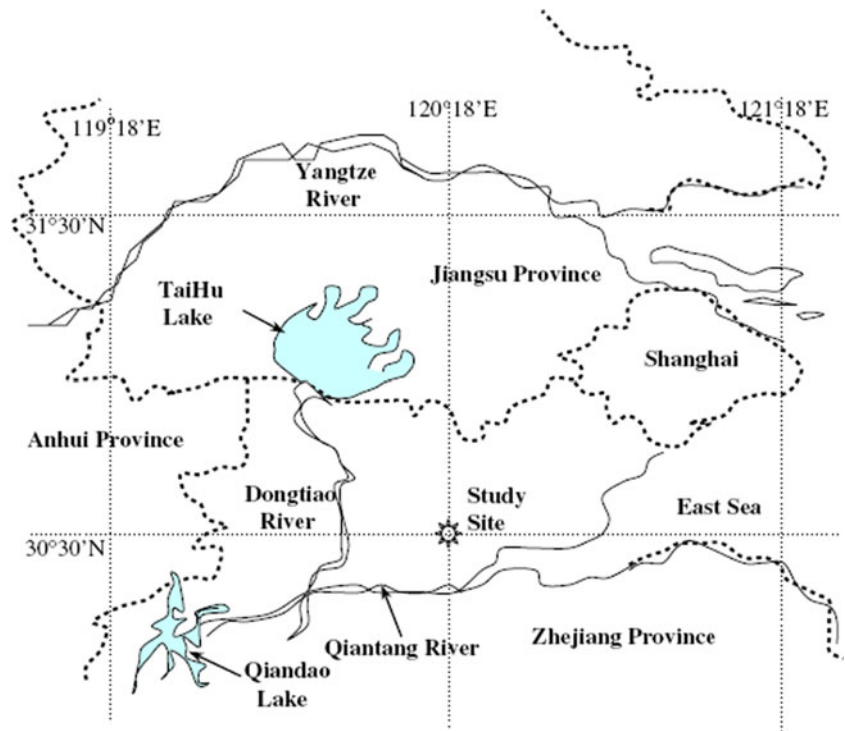
30 cm buried into the soil, leaving 20 cm above the soil surface for separation. Devices made of cement with 1 m tall, 1 m wide, and 1 m long for runoff collection were installed at the lower end of the plot. WatchDog 2700 Weather Stations were also installed near the experimental area to record the daily meteorological data during study period.

The experiment was designed using a randomized block design with three replicates. The fertilizer treatments were no inorganic fertilizer and organic manure application (CK), farmers' fertilizer practices (FFP), and SSNM. The sources of N, P, and K were urea, superphosphate, and potassium chloride, respectively. For FFP, according to local farmer practices, the fertilizer rates for N, P, and K were 465, 50, and 94 kgha^{-1}, respectively. Fertilizers were applied by broadcasting in February (25 %), May (25 %), and September (50 %). Taking into account the indigenous nutrient supply of the soil, reasonable bamboo yield targets and their corresponding nutrient demands as well as nutrient balance, nutrient use efficiency, and socioeconomic factors, the

fertilizer requirement was calculated for the SSNM treatment (Wang et al. 2003). The fertilizer rates for SSNM were 207, 46, and 79 kgha^{-1} for N, P, and K, respectively. The fertilizers were applied in February (50 %) and September (50 %) according to bamboo growth stage. The fertilizers were applied in 20-cm wide and 30-cm deep trenches that were horizontally and parallel to each other and spaced at 2.5 m intervals.

Water sampling and chemical analysis

Following each rainfall event, depth of water in devices was measured to calculate the runoff volume and water samples were immediately collected. Aliquots of runoff samples were filtered within 24–48 h of collection through 0.45-μm filters for DN determination. The unfiltered runoff samples were used for total nitrogen (TN) determination following perchloric acid digestion (Olsen and Sommers 1982) and soil losses using weight after filter and dry. All samples

Table 1 Physical characteristics, mean stem diameter at breast height (*D*) and stem density, and soil chemical properties of the three bamboo experimental area (P1, P2, and P3)

Site[a]	Slope (°)	Aspect	D^{a}, cm	Stand density bamboo ha^{-1}	pH	OM, gkg^{-1}	Total N, gkg^{-1}	Avail. N, mgkg^{-1}	Olsen P, mgkg^{-1}	Avail. K, mgkg^{-1}
P1	31	22° E by S	9.9	3,435	4.9	42.5	1.76	102	2.5	50.6
P2	31	13° N by E	10.0	3,301	4.9	55.5	3.29	112	2.7	51.6
P3	31	13° N by W	10.1	3,268	5.0	38.9	2.9	109	2.5	38.4

OM organic matter, *Avail.* available

[a] Average diameter at breast height between the bamboo stems

were stored at 4 °C for further chemical analysis. PN was calculated as the difference between TN and DN. The NH_4^+–N concentration in filtered samples was determined using the indophenol blue method followed by colorimetry (APHA 1998). The NO_3^-–N concentration was determined after cadmium reduction to NO_2^-–N followed by a sulfanil-amide–nicotinamide adenine dinucleotide (NAD) reaction (Liu et al. 1996). DON was calculated by subtracting DIN ($DN–NH_4^+–NO_3^-$) from DN.

Measurement of bamboo yield

We measured the number of bamboo shoots (S) and the number of new bamboos (N) in every plot in 2011. Diameter from 1.3 m above soil surface was measured for diameter at breast height to calculate the average diameter at breast height between the bamboo stems (D). Then, bamboo emerging rate (R) was calculated as $R=S/N$, and yield of new bamboo (W) was calculated as $W=0.1527 D^{1756}$.

Statistical analysis

N loads in surface runoff from 39 individual runoff events were calculated for the individual plots by multiplying N concentrations in the runoff sample by the runoff volume, and the values were then summed to generate 1-year loads from June 2009 to May 2010 (Table 3). Data preparation, calculation, and statistical analyses were performed using Microsoft Office Excel and SPSS 11.0 for Windows. Analysis of variance (ANOVA) was used to determine treatment effects. Comparisons of means were performed using Duncan's studentized range test at $P<0.05$.

Results

Water runoff, soil loss, and nitrogen concentration

From June 2009 to May 2010, there were 39 runoff events. The cumulative precipitation was 1,855 mm (Fig. 2), which was higher than the long-term average precipitation of 1,550 mm in the area (Zhang et al. 2002). The rainfall occurred mostly in the rainy season (July to September; 58 % of the total precipitation). In the CK, SSNM, and FFP treatment, the surface runoff volume amounted to 355, 367, and 344 $m^3 ha^{-1}$, equivalent to 1.91, 1.98, and 1.85 % of the total water input, respectively. The cumulative soil losses for these treatments were more than 300 $kg ha^{-1}$, and FFP even amounted to 437 $kg ha^{-1}$ (Table 2). The runoff and soil losses were highly correlated with precipitation from June 2009 to May 2010 (r^2 from 0.86 to 0.92; P values from <0.001 to 0.039). ANOVA analysis showed that there was no significant difference in the amount of runoff among
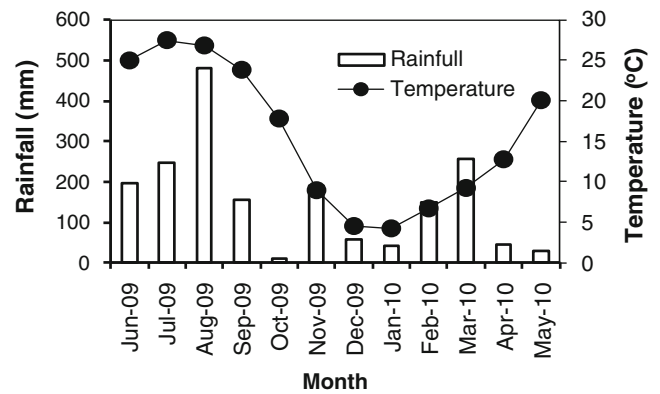

Fig. 2 Monthly rainfall and monthly mean air temperature at the study site during the study period

fertilization treatments during the experimental period. Unlike runoff, soil loss was significantly higher ($P<0.05$) under FFP (417 $kg ha^{-1}$) than under CK or SSNM. Compared to SSNM, soil loss in FFP increased 5.7 %.

The NO_3^-–N concentration was lower in the runoff from the SSNM treatment than that from the FFP treatment from March to May (Fig. 3b). However the one-way ANOVA indicated that there were no differences in NO_3^-–N concentrations between any of the treatments during the study period as indicated by the one-way ANOVA. The NH_4^+–N concentration in the surface runoff was generally lower than the NO_3^-–N concentration in all fertilizer treatment. Statistically significant effects of different fertilization treatments on NH_4^+–N ($F=3.7$, $P=0.03$) and DON ($F=3.9$, $P=0.02$) concentrations were observed, especially in the last 4 months of the study period (Fig. 3a, c), indicating that concentration of NH_4^+–N and DON in runoff was decreased in SSNM treatment compared to FFP treatment. The average NO_3^-–N concentrations in runoff from the CK, FFP, and SSNM treatments were 1.49, 2.0, and 1.63 $mg L^{-1}$, respectively. The corresponding average NH_4^+–N concentrations were 0.73, 1.29, and 0.87 $mg L^{-1}$, respectively (Fig. 3a, b). The TN concentrations in runoff ranged from 1.10 to 60.22 $mg L^{-1}$, with an average value of 6.90 $mg L^{-1}$, whereas DON concentrations in the runoff ranged from 0.36 to 20.52 $mg L^{-1}$, with an average value of 1.45 $mg L^{-1}$ across all treatments (Fig. 3c, d).

Table 2 Mean soil loss and water runoff from the beginning of June 2009 to the end of May 2010 in bamboo plots given three fertilizer treatments

Treatment	Runoff ($m^3 ha^{-1}$)	Soil loss ($kg ha^{-1}$)
CK	355±32 a	393±6.8 b
SSNM	367±24 a	397±94.5 b
FFP	344±2 a	737±7.2 a

Values with different letters indicate significant differences at $P<0.05$, $n=3$

Fig. 3 Effect of fertilizer treatment on the mean monthly concentrations of NH_4^+–N, NO_3^-–N, DON, and TN in runoff water over the study period. *Bars* show standard error, $n=3$
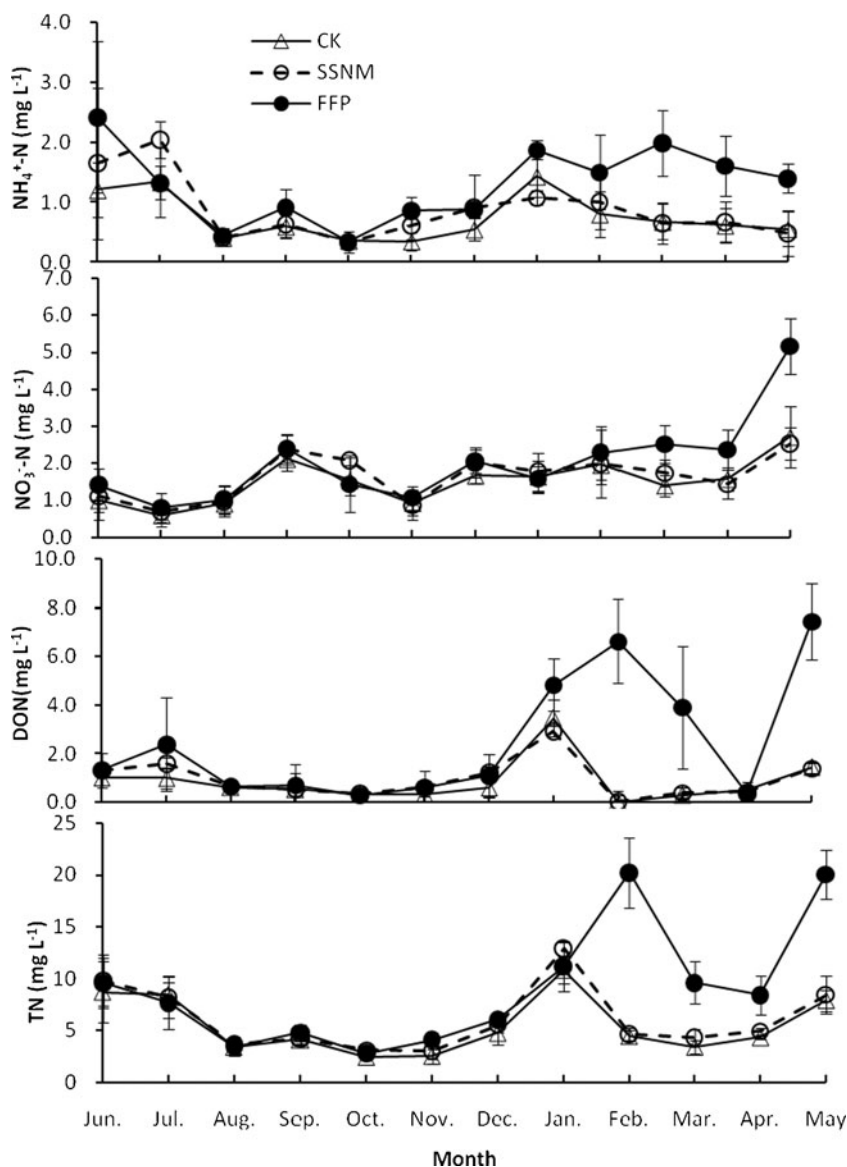
All of the runoff samples had total N concentrations higher than 0.35 $mg L^{-1}$, which is the critical TN concentration recommended to keep algal biomass below the nuisance level of 100 $mg m^{-2}$ in freshwater (Smith et al. 1999). Runoff water from bamboo forest soils should be regarded as an important nonpoint source of pollution for surface water eutrophication in this region. There was a marginally significant difference in TN concentrations under the SSNM and FFP treatments ($F=3.3$, $P=0.048$). Both DIN (that is, NH_4^+–N and NO_3^-–N) and DON concentrations in the surface runoff displayed a strong seasonality with low values in the summer months (Fig. 3).

Nitrogen losses in surface runoff

Compared with the FFP treatment, the SSNM treatment decreased N losses significantly except PN. With the

exception of total N, losses of all N forms in the FFP treatment exceeded those in the SSNM treatment, which in turn exceeded those in the unfertilized plots ($P<0.05$, Table 3). For PN, losses in the FFP treatment exceeded those in the control ($P<0.05$), but losses in these treatments did not differ significantly from the SSNM treatment. DIN (NH_4^+–N and NO_3^-–N) represented 28–41 % of TN export in the surface runoff and constituted smaller percentages in the CK treatment than in the FFP or SSNM treatment (Table 4). The total loss of DON reached 126–355 gha^{-1} during the study period (Table 3). This loss accounted for 23–41 % of the corresponding DN, and this percentage was smaller for the SSNM and CK treatments than for the FFP treatment (Table 4). The loss of PN ranged from 503 to 1,348 gha^{-1} with an average of 577 gha^{-1}. This amount accounted for 47 % of the TN, which indicates that PN was also the main form of N loss in the surface runoff.

Table 3 Amounts of nitrogen (in gram per hectare) in runoff from the beginning of June 2009 to the end of May 2010 in bamboo plots given three fertilizer treatments

Treatment	NH_4^+–N	NO_3^-–N	DON	DN	PN	TN
			gha^{-1}			
CK	164±21 c	252±37 c	126±30 c	542±61 c	617±98 a	1,158±79 c
SSNM	217±56 b	302±36 b	171±48 b	683±104 b	586±61 a, b	1,269±165 b
FFP	274±34 a	333±78 a	355±230 a	1,035+412 a	529±129 b	1,837±185 a

Values with different letters indicate significant differences at $P<0.05$, $n=3$

In all treatments, monthly variations in total N loss depended more on the fluxes of runoff (Fig. 4) than on the N concentration. The correlation between monthly TN loss and monthly runoff fluxes was significant for the CK, SSNM, and FFP treatments ($r^2=0.74$, 0.93, and 0.63, respectively; $P<0.01$ to 0.05). However, relationships between total N loss and concentrations were not significant (data not shown). Although strong relationships between N losses and rainfall were observed, other meteorological factors (e.g., solar radiation, humidity, and air temperature) were not consistently correlated with N loss in runoff (data not shown). Nitrogen losses increased concurrently with rainfall intensity; this finding indicates that the main factor influencing N losses was precipitation.

Yield of bamboo

Number of bamboo shoots was 1,612, 2,501, and 2,968 ha^{-1} in CK, SSNM, and FFP, respectively (Table 5). Compared with CK and FFP, average diameter at breast height between the bamboo stem (D) in SSNM increased by 1.07 and 1.00 %, respectively. Bamboo emerging rate in SSNM increased by 12.7 and 17.1 %, respectively, compared to CK and FFP. Yield

Table 4 The percentage (%) of DN to TN, PN to TN, and DON to DN under different fertilizer treatments in a bamboo forest in southern China

Site	Treatment	DIN to TN	PN to TN	DON to DN
P1	CK	38	46	28
P2	CK	31	59	23
P3	CK	16	54	19
P1	SSNM	44	47	20
P2	SSNM	36	46	32
P3	SSNM	42	45	23
P1	FFP	31	47	69
P2	FFP	44	40	26
P3	FFP	42	40	29
Average	CK	28 b	53 a	23 b
Average	SSNM	41 a	46 a	25 b
Average	FFP	39 a, b	42 a	41 a

Values with different letters indicate significant differences at $P<0.05$, $n=3$

of new bamboo in SSNM increased by 4 % as compared to FFP and by 83 % as compared to CK.

Discussion

Agricultural sources of N have long been considered to be the largest of nonpoint pollution leading to downstream water quality degradation. Elevated N leaching from forests is a critical signal of N saturation as defined by Aber et al. (1998). Nitrogen loss in surface runoff under rainfall events from farmlands has been extensively studied during the last decades. However, bamboo plantation, although a traditionally low input practice, has become increasingly managed with frequent fertilization. In this study, we found that the mean total N concentration in runoff following the FFP and SSNM treatments was 8.97 and 7.50 mgL^{-1} (Fig. 3d), respectively. All runoff water samples had a total N concentration greater than 0.35 mgL^{-1}, which is the critical total N concentration for water eutrophication (Smith et al. 1999).

In our study, total loss of DON reached 217 gha^{-1} during the study period and accounted for 37 % of the corresponding total dissolved N (Table 4). This finding suggests that
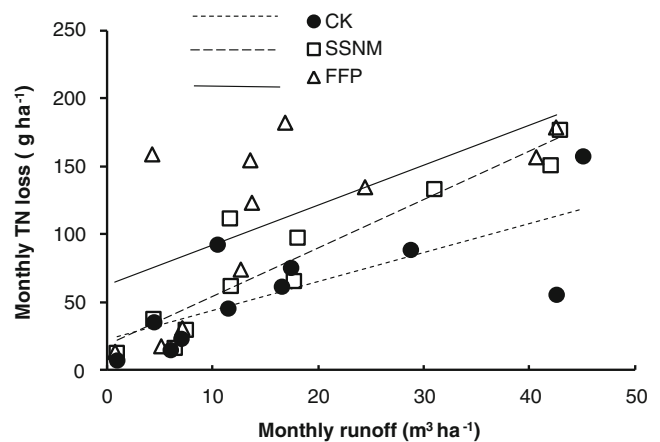

Fig. 4 The relationships between monthly fluxes of runoff and TN with different fertilizer treatments. Each datum point is the mean of three replicated plots. $N=11$ in each of the treatments. The data for August were not shown due to high values. $P<0.01$, 0.01, and 0.05 for CK, SSNM, and FFP treatments, respectively

Table 5 The bamboo yield of different fertilization treatments

	Treatment	S^a, ha^{-1}	D^b, cm	R^c, %	W^d, kg/ha^{-1}
P1	CK	1,634	9.50	67	22,529
P2	CK	1,634	8.46	53	13,793
P3	CK	1,567	9.05	64	18,400
Average	CK	1,612	9.00	61	18,241
P1	SSNM	2,601	9.63	69	37,915
P2	SSNM	2,468	8.65	68	27,819
P3	SSNM	2,435	9.21	74	34,413
Average	SSNM	2,501	9.16	70	33,383
P1	FFP	3,735	9.53	54	41,244
P2	FFP	2,568	8.64	64	27,228
P3	FFP	2,601	9.03	58	27,501
Average	FFP	2,968	9.07	58	31,991

[a] Number of bamboo shoots

[b] Average diameter at breast height between the bamboo stems

[c] Bamboo emerging rate

[d] Yield of new bamboo

dissolved organic N is an important component of the overall runoff N flux from bamboo forests. Dissolved organic nitrogen also represents an important component of biogeochemical cycles in terrestrial ecosystems (Perakis and Hedin 2002). However, compared to DIN, DON has received relatively little attention. Our study showed that in addition to inorganic N losses via surface runoff from bamboo forests, a significant fraction of TN was lost via organic N. Studies on DON pools in agricultural soils have found that DON constituted 57±8 % of the total dissolved N pool (Christou et al. 2005). The origin of DON in bamboo forests was not determined in this study, but was apparently from the accumulation and decomposition of dead leaves on the forest floor over time. The percentage of PN to DN ranged from 0.09 to 2.08 and decreased gradually during the study period (data not shown). This decrease in PN to DN ratio suggested that soil loss significantly increased PN loss in the earlier period of rainfall events, whereas DN was the main form of N loss during later rainfall events.

A survey of N output from 65 forested plots and catchments throughout Europe showed that sites receiving N inputs above 25 kgha^{-1}year^{-1} all leached significant quantities of N (Dise and Wright 1995). Though the leached N is not the same as runoff N, there is some similarity between leached N and runoff N. In the present study, the total N losses via surface runoff were 1.2, 1.3, and 1.8 kgha^{-1} for the CK, SSNM, and FFP treatments (Table 3), respectively, which are within the ranges reported for forest ecosystems in Europe and North America (0.7 to 20 kgha^{-1}) (Andersson et al. 2001; Bergholm et al. 2003; Moldan et al. 2006). Total N loss from the bamboo forests, however, was much lower than the values reported by Fang et al. (2009) for disturbed pine forests in China (14.6 kgha^{-1}). Moreover, the N losses from our study were

at the lower end of the range reported for N-saturated forests in North America (0.04–38.9 kgha^{-1}) (Dise and Wright 1995). Under the experimental conditions, the rates of N losses via surface runoff, when expressed as the fraction of the applied N amount, were quite low for both under FFP (0.2 %) and SSNM (0.5 %) treatments. There are a few possible reasons for the low rates of N loss found in this study. First, the experiments were carried out in primary bamboo forests, which had soil with low levels of available nutrients (Table 1). As a result, the soil had the potential to retain added N from the first year of study. Second, bamboo is known to have high C and N tissue concentrations (Wang et al. 2006), and thus, the bamboo plants had the potential to retain added N with high production of biomass. And third, N may also be lost via subsoil leaching in the bamboo forests, although the amount lost research this pathway needs to be quantified. Last, the major reason for low N loss in runoff is low runoff water flux. A number of N addition experiments carried out in both European and North American forests have demonstrated that N saturation could be induced by chronic N additions in previously N-limited systems (Magill et al. 2004). Therefore, it is likely that more N losses via surface runoff may occur for mature bamboo forests or high rainfall year.

Conclusions

In this study, the mean total N concentration in runoff following the FFP and SSNM treatments was 8.97 and 7.50 mgL^{-1} (Fig. 3d), respectively. At this level of total N, all runoff water from the bamboo forests would contribute to eutrophication in downstream aquatic ecosystems. Our results showed the loss of DON accounted for 37 % of the corresponding total dissolved N, indicating DON is an important component of runoff N from bamboo forests. Here, we should note that DON figure is calculated by subtracting DIN (DN–NH_4^+–NO_3^-) from DN, instead of direct measurement. The results also indicated that N losses were not quite as high in the unfertilized bamboo forest as in the fertilized bamboo forest plots. Compared with the FFP treatment, the SSNM treatment decreased TN and DN loss by 31 and 34 %, respectively (Table 3) and increased yield of new bamboo by 4 % (Table 5), which indicated that the reduction of N losses responded rapidly to N management under SSNM. Site-specific nutrition management is thus suitable for forest nutrient management in bamboo forests. This investigation was conducted from June 2009 to May 2010 and the rainfall is 1,420 mm, which is lower than average rainfall (1,550 mm) at the study site. Therefore, it is expected that N losses in these bamboo forests would increase over time as fertilizers are applied as farmer's fertilizer practice during normal precipitation years. Our results demonstrated that SSNM should be recommended and practiced more to reduce N losses, although long-term effects of different fertilization rates or practices on

the fate and transport of N in bamboo forest ecosystems need to be further investigated.

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