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Responses of N$_2$O flux to water level fluctuation and other environmental factors at littoral zone of Miyun Reservoir: a comparison with CH$_4$ fluxes

M. Yang[1], X. M. Geng[1], J. Grace[2], Y. F. Jia[1,*], Y. Z. Liu[1], S. W. Jiao[1], L. L. Shi[1], C. Lu[1], Y. Zhou[1], and G. C. Lei[1]

[1]School of Nature Conservation, Beijing Forestry University, Beijing, China
[2]School of Geosciences, The University of Edinburgh EH9 3FF, Edinburgh, UK
[*]now at: Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing, China

Correspondence to: G. C. Lei (guangchun.lei@foxmail.com)

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Abstract

There have been only a few studies that allow us to estimate the contribution of newly-created reservoirs to greenhouse gas budgets. In particular, information is limited for understanding the spatiotemporal variation of N_2O flux and the underlying mechanisms in the littoral zone where complex biochemical processes are induced by water level fluctuations. A study was carried out at five different water levels (deep water area, shallow water area, seasonally flooded area, control site for seasonally flooded area and non-flooded area) at the littoral zone of a temperate reservoir using the static chamber technique. Seasonal and spatial variations of N_2O flux and environmental factors were monitored throughout the growing season including a flood event during summer rains. The N_2O flux ranged from -2.29 to $182.47\,\mu g\,m^{-2}\,h^{-1}$. Non-flooded dry land emitted more N_2O than flooded land, no matter whether it was permanently or seasonally flooded. However, no significant difference was observed between seasonally flooded sites and their control sites. Wind speed, air temperature, soil water content, dissolved oxygen in water and soil nitrate influenced N_2O flux significantly. In order to know the contrasting characteristics of N_2O and CH_4 fluxes in the littoral zone of the reservoir, results were compared with a previous study on CH_4 emission carried out at the same sites and time with comparable methods. It showed that N_2O flux and CH_4 flux was influenced by distinct factors and in differing ways. This work highlights the complexity of N_2O flux at the littoral zone. The different response ways of N_2O and CH_4 to environments implies the big challenge of greenhouse gas emission control through ecosystem management.

1 Introduction

Nitrous oxide is an important greenhouse gas, with a Global Warming Potential 298 times that of carbon dioxide. It accounts for $0.17\,W\,m^{-2}$ of the current radiative forcing according to recent reports (Stocker et al., 2013). Moreover, N_2O also plays an im-

portant role in ozone depletion in the stratosphere (Revell et al., 2012; Kroeze, 1994). Concentrations of N$_2$O have increased by 20 % compared to the pre-industrial level, reaching 324 ppb and exceeding the highest concentration recorded in ice cores during the past 0.8 million years. Man-made sources of N$_2$O are estimated to be 11 Tg N yr^{-1},

5 accounting for nearly 40 % of the total amount of natural and anthropogenic sources of this gas (Stocker et al., 2013). N$_2$O emissions have often been measured in terrestrial systems including farmlands, forests and grasslands (e.g. van Kessel et al., 2013; Wu et al., 2013; Cheng et al., 2014), but much less often in aquatic systems. Great spatial and temporal variations of N$_2$O flux have been noted, although the data are in

10 some cases quite limited, especially for wetlands (Nicolini et al., 2013), and there have been very few studies dealing with the special case of reserviors, where conditions are often quite different from those of natural lakes, especially in regard to the extent of inundation of the littoral vegetation.

Currently the greenhouse gas emissions from reservoirs are attracting the attention

15 of researchers because these water bodies are increasing rapidly in number and area, growing with the continuing demand for water and hydropower. In rapidly developing countries like China, India and Brazil this growth is likely to continue for many years (Yang and Lu, 2014; Kumar et al., 2011). Of all the greenhouse gases, methane has received the most attention, but nitrous oxide may also be important. It is speculated

20 that the construction of impoundments causes sediment accumulation and vegetation change, and when agricultural lands are inundated during creation of reservoirs, and for many years afterwards, there may be a strong enhancement of greenhouse gas emissions (Tranvik et al., 2009). It is noteworthy that this speculation is usually based on the expectation of an altered carbon cycle whilst data on aspects of the nitrogen

25 cycle are lacking (L. Yang et al., 2014).

The littoral zone of reservoirs plays an important role for both nature and humans, including providing habitats for many kinds of creatures, acting as a filter between the terrestrial ecosystems and the aquatic body, and providing possibilities of recreational activities (Capon et al., 2013; Likens, 2010). Comprehensive and accurate understand-

ing of the littoral zone of reservoirs is the basis for ecosystem evaluation, management and wise use. As an active material exchange area, the littoral zone is reported to be a hotspot of N_2O emissions (Wang et al., 2006). This zone is usually smaller than the pelagic zone, but in the few cases where it has been studied, its N_2O emissions (in natural lakes), have been observed to be higher (Huttunen et al., 2003).

Soil water status is a critical factor for the N cycle and for N_2O emissions (Peng et al., 2011). It influences soil oxygen concentration, input of nutrients, vegetation distribution and activity of microbes (Ahn et al., 2014; Trost et al., 2013), which in turn influence N_2O production (Lu and Xu, 2014). Periodic wet/dry changes in the soil could provide both aerobic and anaerobic environments for nitrification and denitrification which are the most important two processes producing N_2O as a middle or end product (Mander et al., 2005). Laboratory-assessed denitrification activity is reported to be approximately 4 times higher in flood-affected than in flood-protected areas (Jacinthe et al., 2012a). The direct control of groundwater table over the rates of soil N cycle is assumed to override other key factors such as climatic condition, vegetation cover and soil type (Hefting et al., 2004). However, counter observations have been published in which flooding did not always change the N_2O flux (Hernandez and Mitsch, 2006), suggesting large uncertainly in our level of understanding.

Although the influence of water levels on fluctuations of N_2O emissions have been reported at periodically flooded environments, e.g. marshes, estuaries or rice paddies (Sun et al., 2014; Hou et al., 2012; Kudo et al., 2014), there is no direct information about emissions, following flooding, from the littoral zone of reservoirs or even the analogous natural ecosystem, i.e. lake. Considering the differences in ecological characteristics, including vegetation species and distribution, hydrological regime and sediment deposition (Kumar et al., 2011) there is an urgent need to characterize the emissions from the littoral zone of reservoirs. To address this information gap, the present study was carried out with objectives of (i) capturing the spatial and temporal variation of the N_2O flux at littoral zone of the Miyun Reservoir and (ii) finding the relationship between the observed flux and environmental factors. It is hoped also to be able to evaluate the

importance of the N_2O flux by comparing it to our earlier report on the CH_4 fluxes of the same site (M. Yang et al., 2014).

2   Methods

2.1   Study area

The research was carried out at Miyun Reservoir ($40°29'$ N, $116°50'$ E), which is located in the northern mountainous area of Beijing, China. It was built in 1960 with a maximum water area of 188 km^2. Its catchment is characterized by warm temperate semi-humid monsoonal climate with an annual average air temperature of 10.5 °C, maximum air temperature of 38 °C, and a minimum of -18 °C. The reservoir is normally covered by ice from the middle of November to the end of March. The growing season is from April to November. The annual average precipitation is close to 600 mm, of which 80 % is concentrated from July to August (Gao, 1989). Over 93 % of the soils around the reservoir are classed as cinnamon soils (*korichnezems*) with typical soil pH from 7.0 to 8.2 (Anonymous, 2008). Alongside the reservoir, higher land is always reclaimed as farmland for growing maize, typically from May to September. Nitrogenous fertilizer is applied during sowing, and sometimes with further application in the middle of the growing season. This reservoir is mainly used as the domestic water supply for Beijing. The water quality is controlled to level II according to Environmental Quality Standards for Surface Water of People's Republic of China (levels are rated on a scale I to V, where level I is the cleanest). The annual change in the water level is 1–5 m, reflecting the balance between rainfall, evaporation and usage. The area between the highest and lowest water level from 1984 to 2005 was 84 km^2 (Cao et al., 2008). In the summer of 2012, when the work was carried out, unusual and continuous heavy rain in July caused a sudden water level increase of one meter, and part of the littoral vegetation was inundated. Such severe inundation does not occur in every year.

We divided the littoral zone into five areas based on water level (Fig. 1). Sites were selected ranging from locations in open water to the dry area on higher ground, to provide five contrasting environments: (i) deep water area (DW); (ii) shallow water area (SW); (iii) seasonal (August and September) flooded area (SF); (iv) "seasonally flooded control" (SFC) area, which was 500 m away from SF, had the same plant species and similar soil carbon/nitrogen content as SF, but escaped the flood in August and September because of its 1-m-higher elevation; and (v) permanent non-flooded area (NF). Details of the water levels in each of these areas are shown in Fig. 2d. For more details on biomass and soil, see Figs. 2f and 3.

2.2 N$_2$O flux measurements

Nitrous oxide flux was measured in November 2011, then May, July, August, September and October 2012. The experiment with three plots at site SFC was carried out just after the flooding and during the time when the water level dropped from August to October 2012. In order to reduce uncertainty in the average daily flux, a sampling protocol designed to capture any diurnal variation was performed at three-hourly intervals (local time: 6, 9, 12, 15, 18, 21 and 24 h). Each plot had four replicates located within three meters from each other. To eliminate disturbance to the soil during sampling wooden access platforms were built.

The static opaque chamber technique was used to determine the N$_2$O flux. The chambers were made of stainless steel (volume: 125 litres; surface area: $0.25\,\text{m}^2$) and covered with polyethylene foam to minimize any warming effect inside the chamber. An extension chamber (volume: 200 litres; surface area: $0.25\,\text{m}^2$) was added if plants were tall. Two fans were built into the chamber for air mixing. Four gas samples (200 mL each) were taken using 100 mL polypropylene syringes at 15 min intervals over a 45 min period after enclosure, and stored in 500 mL plastic and aluminum membrane gas sampling bags. The concentration of N$_2$O was analyzed within one week by gas chromatography (7890A, Agilent, USA) equipped with a micro-electron capture detector (μ-ECD). Gases were separated with a column (3 m, 3.2 mm) packed with Porpak Q

(80/100 mesh). The temperatures of the oven, injector, and detector were 70, 20, and 330 °C, respectively. The flow rate of the carrier gas (N_2) was 25 mL min^{-1}. Standard N_2O gas (310 ppb in air, China National Research Center for Certified Reference Materials, China) was used for precision verification for N_2O concentrations. The coefficient of variation was below 1.5 %. The flux of N_2O was calculated following Li et al. (2014). Chambers were reset into new positions near the old positions each sampling month. All positions at each site were within an area of 20 m^2, but not so close to each other to cause artifacts in the data through (for example) changes in the local hydrology.

2.3 Environmental factors

Weekly precipitation was accessed through the China Meteorological Data Sharing Service System (http://www.escience.gov.cn/metdata/page/index.html). Average wind speed was recorded during the sampling period with a hand-held vane anemometer (4101, Testo, Germany). Diurnal air temperature was measured by a digital thermometer (JM624, Jinming, China) at the start and end of each gas sampling at every plot. Dissolved Oxygen (DO) in water was measured during the gas sampling by a handheld multi-parameter meter (Professional Plus, YSI, USA), after flooding. The aboveground biomass of every replicate in the chamber was weighed after drying at 80 °C to constant mass.

Water level was measured after gas sampling at DW, SW and SF (when SF had standing water in August and September 2012). At site SF (when there was no standing water in November 2011, May, July and October 2012) and SFC, a 1 m PVC tube was inserted vertically into the soil under the chamber after all monthly gas sampling was complete, allowing two hours for the water level to equilibrate before measuring the level. The water table of site NF was calculated according to the elevation measured by a Global Navigation Satellite System receiver (BLH-L90, Daheng International, China).

Soil water content (SWC) was measured every month after all gas sampling with a Soil Water Sensor (UNI1000, Shunlong, China). Soil samples at site DW, SW, SF and NF were collected from three different layers (0–10, 10–20, and 20–30 cm below

ground) at each replicate location in November 2011, except site SFC in October 2012. Fresh soil samples were used for NH_4^+ and NO_3^- analysing using a discrete analyser (Smartchem 300, AMS, Italy). After air-drying and grinding (passing through a 100 mesh sieve), pH of soil extractions were measured using a pH meter (IQ160, Hach, USA) while soil total carbon (TC) and nitrogen (TN) were analyzed using an elemental analyzer (vario MACRO cube, Elementar, Germany). Soil bulk density was measured following Chinese national standards NY/T 1121.4-2006 (MAPRC, 2007).

2.4 Statistical analysis

Flux differences were analyzed with one-way ANOVA, and then using LSD for multiple comparisons. A log10 transformation was used to show the correlation between positive N_2O flux and wind speed, air temperature, water DO and soil NO_3^-. Where appropriate, a piecewise function (two segment liner) was calculated using SigmaPlot (version 11.0, SYSTAT, USA). Spearman's Rank Correlation was used to test for correlations between flux and environmental factors. All the analyses above were performed using IBM SPSS Statistics (version 19.0, IBM, USA). Charts were made using SigmaPlot (version 11.0, SYSTAT, USA).

3 Results

3.1 Environmental characteristics

Precipitation occurred from March to November. The highest rainfall was in July which accounted for one fourth of the total (Fig. 2a). Water levels rose rapidly after the summer monsoon rainfall, and then declined after August (Fig. 2d). Temperature peaked at summer time (Fig. 2c). The non-flooded site was very dry before the rains began (Fig. 2e), increasing from a dry condition (10 % water content) to a moist condition after rain (but never exceeding 35 %).

3.2 N₂O fluxes

The mean flux from the littoral zone of Miyun Reservoir was $6.61\,\mu g\,m^{-2}\,h^{-1}$. Significant differences were observed between the 5 sample areas ($p < 0.05$; Fig. 4). N₂O emission from the non-flooded area (NF) was $16.96 \pm 5.45\,\mu g\,m^{-2}\,h^{-1}$, which was significantly higher than the other 4 areas. There was no statistical difference between emissions from the seasonal flooded area (SF) and its control site (SFC), which was 4.39 ± 1.10 and $4.17 \pm 0.89\,\mu g\,m^{-2}\,h^{-1}$ respectively. Highest emissions were observed in the warm season, July and August in particular (Fig. 5). The highest emission was $182.47 \pm 45.11\,\mu g\,m^{-2}\,h^{-1}$ occurring in July at site NF-C.

3.3 Relationships between flux and environmental parameters

Significant positive correlations ($p < 0.05$) were obtained between flux and wind speed, air temperature, water DO and soil NO_3^-, while negative correlation was observed between flux and SWC (Table 1). There was no significant correlation between flux and water depth, biomass, soil density, pH, TN, TC and NH_4^+. Linear correlations can hide important non-linear features and so scatterplots are also shown, where log10 flux was plotted against wind speed, air temperature, water DO and soil NO_3^- (Fig. 6). Piecewise correlations were found between log10 flux and air temperature, also log10 flux and soil NO_3^- ($p < 0.05$). There was a negative correlation when the air temperature was from 5 to 18.7 °C and a positive correlation when air temperature was from 18.7 to 31 °C. The soil NO_3^- seemed to accelerate N₂O emission when its concentration was higher than $7.1\,mg\,kg^{-1}$, but it did not influence emission rate when lower than this knot point.

4   Discussions

4.1 N_2O flux

The mean flux from the littoral zone of the Miyun Reservoir was $6.61\,\mu g\,m^{-2}\,h^{-1}$. Besides one observation which was as high as $182.47\pm45.11\,\mu g\,m^{-2}\,h^{-1}$, the mean fluxes ranged from -2.29 ± 1.81 to $31.61\pm8.87\,\mu g\,m^{-2}\,h^{-1}$ (Fig. 5), which is comparable to those from the littoral zone of a shallow lake in Eastern Austria, also in the temperate region (Soja et al., 2014). We did not examine fluxes from the pelagic zone, but we can compare our fluxes with pelagic data from elsewhere, as follows. The N_2O emission in this study is slightly higher than those from five perialpine and alpine reservoirs ($1.56\,\mu g\,m^{-2}\,h^{-1}$) in Switzerland (Diem et al., 2012), while it is much lower than a same-latitude fluvial reservoir ($84\,\mu g\,m^{-2}\,h^{-1}$) located in an agricultural landscape (Jacinthe et al., 2012b).

Nutrient loading is considered to be an efficient accelerator for N_2O production (Trost et al., 2013; Pilegaard, 2013). Indeed, hyper-eutrophic lakes in China do show very high fluxes: the same-latitude lake Baiyangdian averaged $58\,\mu g\,m^{-2}\,h^{-1}$ (Yang et al., 2012) and the seriously eutrophic Taihu Lake ranged from -278 to $2101\,\mu g\,m^{-2}\,h^{-1}$ in the littoral zone (Wang et al., 2007).

Greenhouse gas emissions from low latitude ecosystems are found to be higher than the corresponding ecosystems at high latitude because of the temperature effects (Zhu et al., 2013). The average N_2O emission found in this research is lower than that reported for boreal and Antarctic lakes (Huttunen et al., 2003; Y. Liu et al., 2011). The low N_2O emission of Miyun Reservoir might because of relatively good water quality or high soil pH (Van den Heuvel et al., 2011).

4.2   Relative greenhouse gas effect: comparison with CH_4

Elsewhere, we presented data on methane emissions from this reservoir (M. Yang et al., 2014). The Global Warming Potential (GWP) of N_2O over a 100 year time-span

is 298 while CH_4 is 34 (Stocker et al., 2013). We can use the GWPs to calculate the emissions as CO_2-equivalent emissions, and thus compare the warming effect of the two gases. The mean N_2O emission in this study was $2.0\,mg\,CO_2$-equivalent $m^{-2}\,h^{-1}$. The CH_4 emission was $44.2\,mg\,CO_2$-equivalent $m^{-2}\,h^{-1}$ (M. Yang et al., 2014), which is 22.1 times that of N_2O. This contrasts with our previous findings, where the ratio of $CH_4 : N_2O$ was 1.5 (Li et al., 2014). But in our earlier report there were more observations after flooding and this may have biased the comparison. In general, the flux ratio of CH_4 to N_2O in aquatic environments varies considerably. For example, the $CH_4 : N_2O$ ratio of permanent flooded areas at Poyang Lake was 1.1 (Liu et al., 2013) while the ratio was 0.6 for the pelagic zone of a fluvial reservoir in central Indiana (Jacinthe et al., 2012b). In a study which monitored the flux of both littoral and pelagic zone of a temperate lake, the average $CH_4 : N_2O$ ratio is 7.2 (Soja et al., 2014). For a freshwater marsh at northeast of China, it was found to be as high as 66.5 (Yang et al., 2013). Although the ratio varies greatly, there is nevertheless a considerable contribution of N_2O emission from aquatic ecosystem to global warming, whose importance may have been somewhat understated in relation to the large CH_4 emission.

4.3   Environmental controls: comparison with CH_4

N_2O and CH_4 are both important greenhouse gases, but we found N_2O and CH_4 emissions are influenced by different factors and in different ways, depending on soil conditions, meteorology and vegetation. In relation to global change, we expect temperatures to increase, patterns of inundation to alter with rainfall, and the supply of nitrogenous fertilizers to increase in countries like China, Brazil and India, as agriculture becomes more intensive. Here we examine how the factors of global change may determine emissions.

4.3.1 Flooding

Unlike the specific influence of flooding on CH_4 emission (M. Yang et al., 2014), flooding effects on N_2O emission was not very clear in this study. The N_2O flux of seasonal flooded area SF was as high as its control area SFC which escaped flooding because of higher elevation (Fig. 4). Inundation nearly always causes a drop of N_2O emissions (Yang et al., 2013). Standing water could inhibit N_2O emission through slowing down the diffusive transportation of gas and enhancing the reduction of N_2O to N_2 (Hernandez and Mitsch, 2006). Our result did not reject those possibilities when looking into the seasonal variation of N_2O flux of seasonal flooded sites (Fig. 5c). After flooding, the fluxes of two sites (SF-A and SF-B) were no higher than before flooding and no higher than their control sites. However, a single extraordinary observation showed the highest emission during flooding (Fig. 5c, SF-C). A somewhat similar result was also observed at an artificial wetland (Hernandez and Mitsch, 2006). In riparian zones, floods may influence N_2O production both in the long-term and short-term (Jacinthe et al., 2012a). One study carried out at a coastal marsh showed a quick response of N_2O flux after flooding, i.e. N_2O emission decreased in 2.5–5 h after flooding and then increased to the original level after flooding for 7.5 h (Sun et al., 2014).

Such observations are hard to explain solely by denitrification, at least based on present understanding of this process, although it is considered to be the most common and major way of N_2O production in natural environments (Senbayram et al., 2009). Our extraordinary observation during flooding at site SF-C might be a result of nitrification or nitrate ammonification, or a combined result of denitrification, nitrification and nitrate ammonification. Nitrification was found to be the predominant N_2O-producing process in a laboratory study on the effect of soil and fertilizer types using the ^{15}N tracer technique, accounting for more than 80 % of the total N_2O emission (Uchida et al., 2012). Denitrification and nitrate ammonification is found occur simultaneously in soil (Fazzolari et al., 1990). Even thought there are uncertainties about the mechanisms, this study suggested that flooding introduces a complex set of processes

that influence N_2O flux, when compared to non-flooded areas whose fluxes were all coordinated with temperature variation (Fig. 5a, b and d). The increasing possibility of changes in worldwide rainfall patterns (Stocker et al., 2013) would make prediction of the N_2O emission more challenging. Thus we propose that more studies should focus on the N cycle in the flooding affected zone of aquatic ecosystem considering of the mechanism's complexity and the significant contribution of innundation to N_2O emission (Wang et al., 2006).

4.3.2 Other soil conditions

Beside soil moisture, other soil conditions are also important for the processes involved in the carbon and nitrogen cycles (Butterbach-Bahl et al., 2013; Serrano-Silva et al., 2014). But not surprisingly, we found that the soil factors correlated with CH_4 and N_2O fluxes were totally different from each other (M. Yang et al., 2014). N_2O flux was only influenced by soil NO_3^-, while CH_4 flux was affected by another five variables. Soil NO_3^- is the substrate for denitrification (Pilegaard, 2013), and positive correlations with nitrate are reported broadly (Soja et al., 2014; X. L. Liu et al., 2011, Y. Liu et al., 2011). It is therefore not surprising to find a significant correlation between the N_2O flux and the NO_3^- in the soil. A global analysis based on 233 studies pointed out that the N_2O response to N inputs usually grow significantly faster than expected from the linear model (Shcherbak et al., 2014). N additions to soil in a temperate forest in China were followed by N_2O emission pulses and the emissions were only significantly correlated with soil NO_3^- and temperature, but not soil NH_4^+, pH, clay and moisture (Bai et al., 2014). Another study at a tropical forest in the Andes pointed out the role of soil NO_3^- more specifically (Teh et al., 2014). A nitrogen input experiment provided an explanation for such correlation: the N_2O to N_2 ratios increased from 0.18 ± 0.03 to 0.68 ± 0.16 with the addition of NO_3^- (Zhao et al., 2014). Higher NO_3^- concentrations are suggested to suppress the reduction of N_2O to N_2 via enzymic processes involving, for example nitrous oxide reductase (*nos*) (Silvennoinen et al., 2008; Beaulieu et al., 2011). Those findings suggested that intensive agriculture increased greenhouse gas

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emission while the difference responses of CH_4 and N_2O to soil conditions indicated a further challenge for climate change adaptation.

4.3.3 Wind speed

Wind speed influenced N_2O flux significantly but was not correlated with CH_4 flux. We believe this contrast to be caused by the different responses of soil and water to wind disturbance. Wind influences gas exchange through increasing turbulence in the surface water, thus increasing the diffusion velocity (Schilder et al., 2013). But it also causes pressure fluctuations on the soil environment and produces the so-called "bellows effect" which squeezes and pumps out gas from the soil pore space (Reicosky et al., 2008). We also assume that wind might influence gas exchange more at the air–soil interface than at the air–water interface. The effect of wind is presumably short-term, as it merely speeds up the flux of gas stored in pockets with the soil and sediment, but does not influence the fundamental production rate. To understand wind effects thoroughly, any future study should focus on long-term responses of gas exchange to wind, using continuous measurement systems such as eddy covariance (Merbold et al., 2013).

4.3.4 Water DO

In this study the dissolved oxygen concentration of water also influenced CH_4 and N_2O in different ways. When CH_4 is produced in sediments, a large proportion of it may be oxidized into CO_2 (Guerin and Abril, 2007). For N_2O, negative relationships are reported in both laboratory experiments and field researches (Sarma and Rao, 2013; Rosamond et al., 2012; Zhao et al., 2014). The denitrification process (activated in the anaerobic environment) is assumed to be controlling the N_2O emission (Xia et al., 2013). However our present result contradicted those previous conclusions. Significantly positive correlation was observed between N_2O flux and DO. This might imply that in some environments different process control the emission rate. N_2O accumu-

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lation in the water column is reported depending not only on production rate, but also on the extent of N_2O reduction to N_2 by reductase enzymes (Zhao et al., 2014). That might provide an explanation for our finding. However, it was difficult to exclude the possibility of that the positive correlation was an apparent relationship masking by other stronger factors. A decrease in DO is commonly seen in a polluted water body, and any future study of the relationship between emissions and water quality might be important for future reservoirs where global warming mitigation may be required as a design criterion.

4.4 Comparison with farmland

The responses of N_2O and CH_4 emissions to soil water condition are quite different. But the littoral zone provides a seasonally variable water level, providing conditions for both N_2O and CH_4 production in different stages of inundation, from dry to extremely wet. This explains the rather high N_2O and CH_4 emission rates in the littoral zone. Reservoirs are being developed, in part, for "clean energy", and reports of high greenhouse gas emissions from reservoirs have already led some authors to question the "clean" concept, especially in relation to the mitigation of climate change (Gunkel, 2009).

To evaluate the role that reservoirs play in climate change, their greenhouse gas emissions ought to be compared with those of the prior ecosystem (Tremblay et al., 2005). Farmland is one of the several ecosystems which are lost by flooding during reservoir construction in China. The range of soil water content of most farmland soils in this part of China is relatively narrow, and may not provide conditions that are particularly conducive for either N_2O or CH_4 emissions. However, because of the applied fertilizer, the greenhouse gas emission of farmland is often higher than that of the littoral zone, especially in terms of N_2O (Table 2). Reservoir construction does bring an appropriate environment for greenhouse gas production, especially methane, but agricultural soils emit more nitrous oxide, perhaps because fertilizer application rates are often excessive.

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Table 1. Spearman's Rank Correlation (r) between flux and environmental variables, included in the table are data from Yang et al. (2014b) on the flux of CH$_4$, collected at the same time as the N$_2$O. ** indicates significant correlation ($P < 0.01$), * indicates significant correlation ($P < 0.05$).

	N$_2$O flux	CH$_4$ flux	Wind speed	Air temp	Water depth	SWC	Water DO	Biomass	Bulk density	Soil pH	Soil TC	Soil TN	Soil NH$_4^+$	Soil NO$_3^-$
N$_2$O flux	1													
CH$_4$ flux	−0.10	1												
Wind speed	0.14*	0.03	1											
Air temp	0.19**	0.25**	0.30**	1										
Water depth	−0.02	0.75**	0.06	0.16**	1									
SWC	−0.12*	0.70**	0.03	0.29**	0.87**	1								
Water DO	0.35**	−0.28**	0.43**	−0.15	0.24**	0.00	1							
Biomass	−0.08	−0.26**	−0.15**	−0.34**	−0.38**	−0.52**	−0.48**	1						
Bulk density	0.00	−0.53**	−0.01	−0.05	−0.78**	−0.67**	−0.26**	0.35**	1					
Soil pH	0.08	−0.17**	−0.02	−0.03	−0.25**	−0.18**	−0.14	0.06	0.35**	1				
Soil TC	−0.04	0.62**	0.01	0.05	0.81**	0.74**	0.13	−0.35**	−0.77**	−0.26**	1			
Soil TN	0.03	0.56**	0.03	0.05	0.76**	0.67**	0.15	−0.33**	−0.73**	−0.21**	0.96**	1		
Soil NH$_4^+$	0.01	0.18**	−0.14*	0.02	0.06	0.23**	−0.21**	−0.16**	−0.12*	−0.02	0.08	0.06	1	
Soil NO$_3^-$	0.25**	−0.02	0.04	−0.01	0.09	0.10	0.28**	−0.07	−0.20**	0.27**	0.17**	0.19**	−0.11*	1

n is from 168 to 324.

Table 2. Comparison of N$_2$O and CH$_4$ emission from reservoir and farmland (both expressed as CO$_2$ equivalent, see text).

	Study area		N$_2$O (mg CO$_2$ m^{-2} h^{-1})	CH$_4$ (mg CO$_2$ m^{-2} h^{-1})	Sum (mg CO$_2$ m^{-2} h^{-1})	Data source
Reservoir	Three Gorges Reservoir	littoral zone	9.2	227.8	237	(Chen et al., 2010, 2009)
		pelagic zone	4.2	8.8	13	(Zhu et al., 2013; Chen et al., 2011)
	Miyun Reservoir	littoral zone	2.0	44.2	46.2	This study; (Yang et al., 2014b)
		pelagic zone	ND	10.2	10.2	(Yang et al., 2011)
Farmland	China-IPCC		2.5–16.7	ND	2.5–16.7	(Xu et al., 2014; Smith et al., 2002)
	Hubei-DNDC		26.8	85	111.8	(Li et al., 2003)
	farmland near Three Gorges Reservoir-observed	rice	24.1	100.6	124.7	(Zhang et al., 2012)
		rice and rape	33.7	47.6	81.3	(Zhang et al., 2012)
	Beijing-DNDC		17.9	6.8	24.7	(Li et al., 2003)
	farmland near Miyun Reservoir-observed	wheat	4.8	0.4	5.2	(Hu et al., 2013)
		maize	24.1	0.5	24.6	(Hu et al., 2013)

ND indicates no data. Flux was transformed into CO$_2$ equivalent according to the Global Warming Potential (Stocker et al., 2013), i.e. 1 N$_2$O = 298 CO$_2$, 1 CH$_4$ = 34 CO$_2$. Hubei is the province where part of the Three Gorges Reservoir is situated. Beijing is the city which includes the Miyun Reservoir.
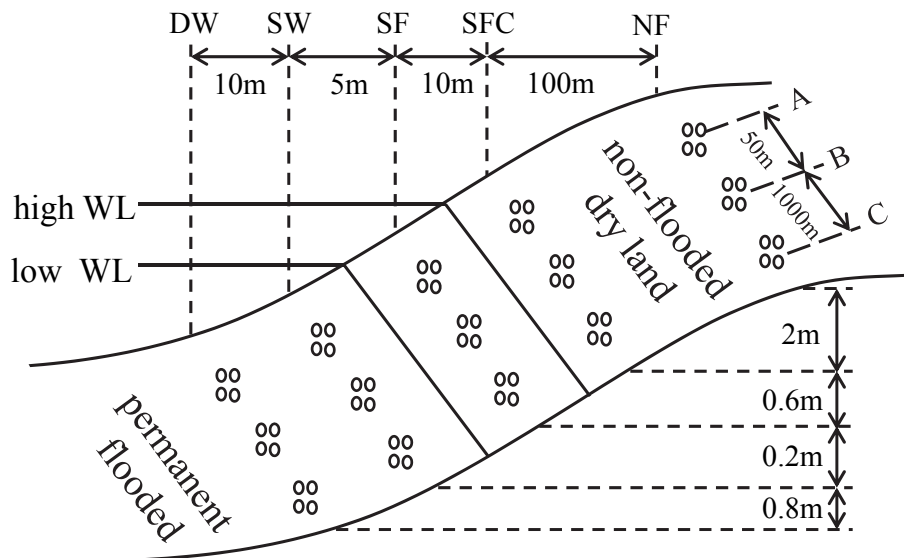
Figure 1. Experimental design. WL: water level. The sites are grouped at different heights. DW: deep water site; SW: shallow water site; SF: seasonally flooded site; SFC: "control site" for the seasonally flooded site; NF: non-flooded site. A, B and C denote samples from different vegetation types within each height band, species details see (Yang et al., 2014b). There were four replicates in each case, repeatedly sampled six times (also repeatedly sampled seven times in a day) in the year. For more details on water depth and other environmental parameters, see Figs. 2 and 3.
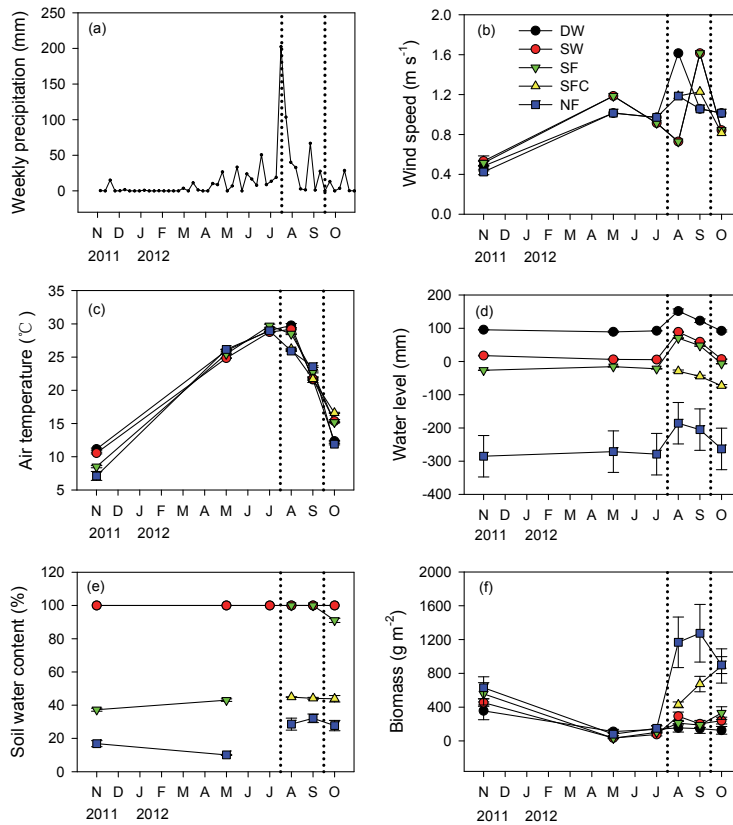
Figure 2. Environmental characters (Mean ± SE) of each sampling area. Some SE bars are not visible. Days between dotted lines was the high water level period and thus the seasonal flooded site (SF) was under water. DW: deep water site; SW: shallow water site; SF: seasonally flooded site; SFC: "control site" for the seasonally flooded site; NF: non-flooded site. There was no soil water content data at July because of instrument malfunction.
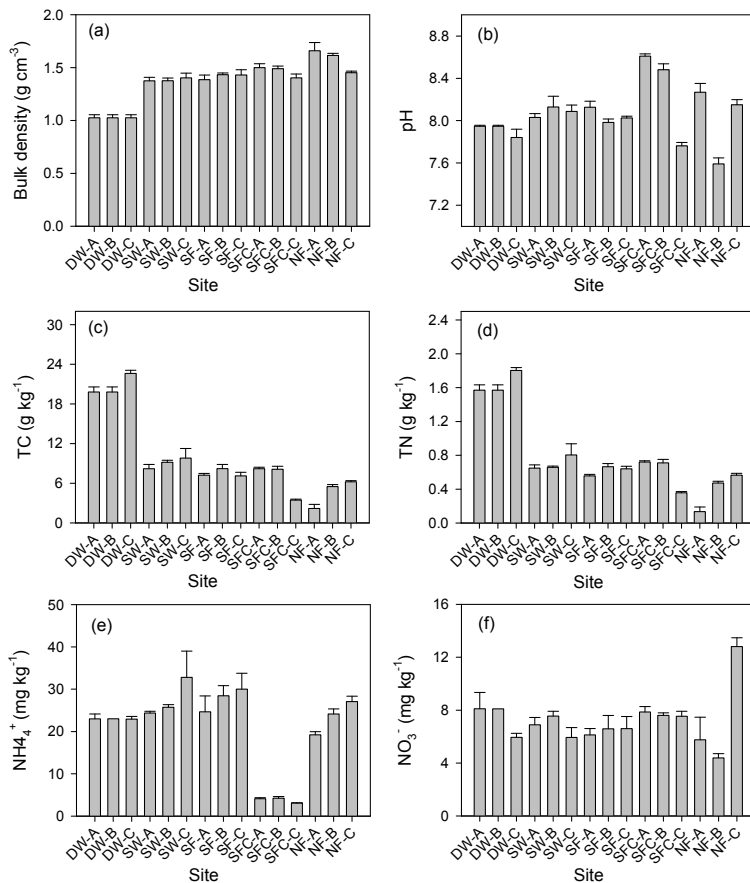
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Figure 3. Physicochemical properties (Mean ± SE) of soil/sediment of each site. Some SE bars are not visible. DW: deep water site; SW: shallow water site; SF: seasonally flooded site; SFC: "control site" for the seasonally flooded site; NF: non-flooded site. A, B and C denote samples from different vegetation types within each height band.
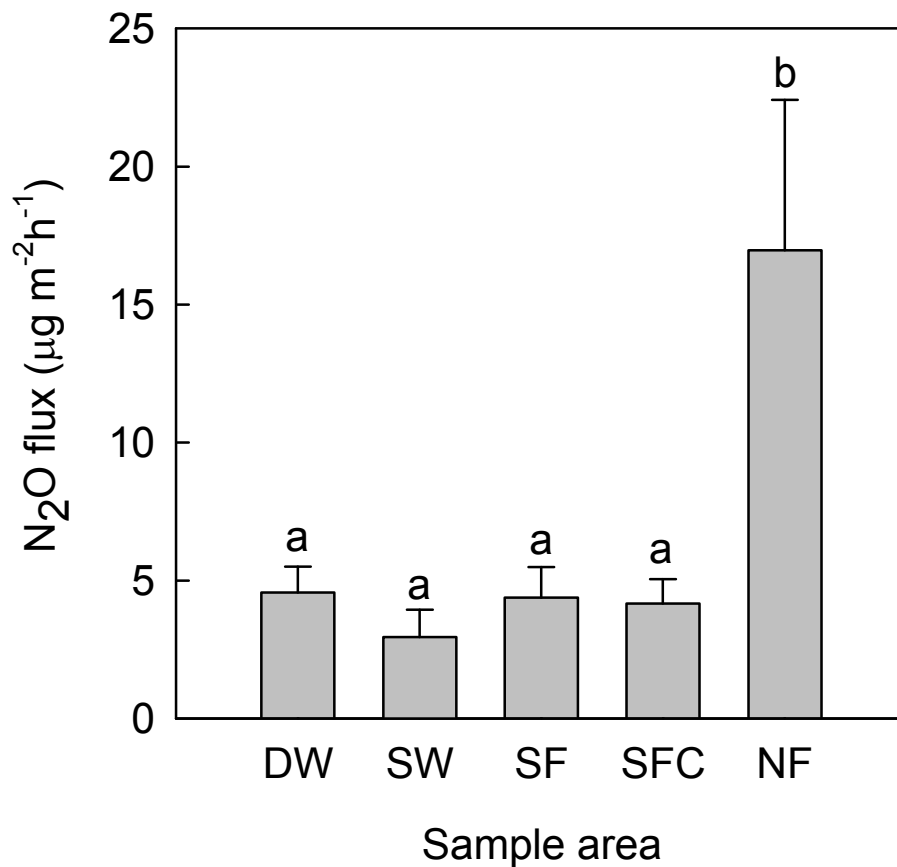
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Figure 4. N_2O flux (Mean ± SE) of each area. Bars with different letters indicate a significant difference at $p < 0.05$. DW: deep water site; SW: shallow water site; SF: seasonally flooded site; SFC: "control site" for the seasonally flooded site; NF: non-flooded site.
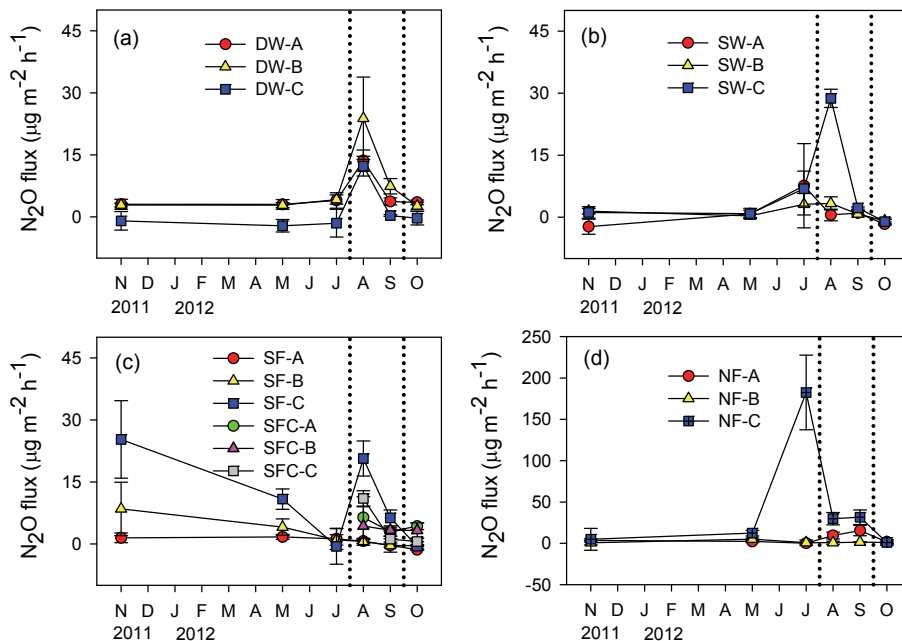
Figure 5. Monthly N$_2$O flux (Mean ± SE) of each site. Days between dotted lines was the high water level period and thus the seasonal flooded site (SF) was under water. DW: deep water site; SW: shallow water site; SF: seasonally flooded site; SFC: "control site" for the seasonally flooded site; NF: non-flooded site. A, B and C denote samples from different vegetation types within each height band.
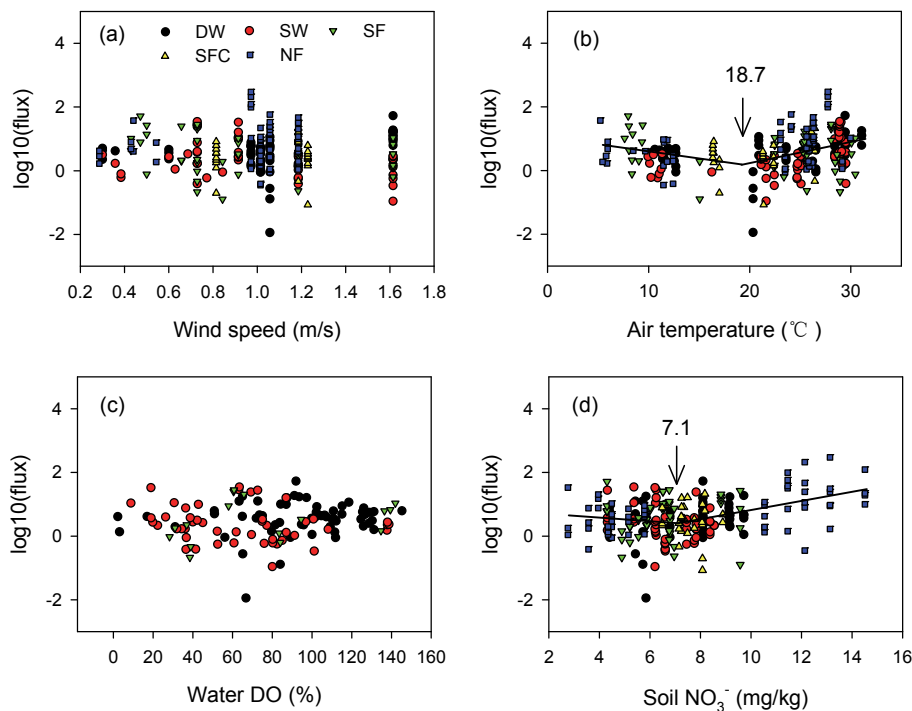
Figure 6. Relationship between flux and wind speed, air temperature, water DO and soil NO$_3^-$. DW: deep water site; SW: shallow water site; SF: seasonally flooded site; SFC: "control site" for the seasonally flooded site; NF: non-flooded site. There was no standing water at site SFC and NF thus no data of water DO. Negative fluxes (which ranged from 0 to −27.3 µg m^{-2} h^{-1}) were excluded from the analysis.