Atmospheric Environment 59 (2012) 202–206

Contents lists available at SciVerse ScienceDirect

Atmospheric Environment

journal homepage: www.elsevier.com/locate/atmosenv

Phosphorus availability as a primary constraint on methane emission from a freshwater wetland

Changchun Song, Guisheng Yang, Deyan Liu, Rong Mao*

Northeast Institute of Geography and Agroecology, Chinese Academy of Sciences, 3159 Weishan Rd, Changchun 130012, China

HIGHLIGHTS

- The effect of P enrichment on CH_4 emission is unclear in wetlands.
- 4-year P addition decreased CH_4 emissions in a temperate freshwater marsh.
- P addition's effect on CH_4 emissions was time-dependent.
- P addition's effect on CH_4 emissions did not vary with fertilization rates.
- Elevated P loading would suppress CH_4 emissions in freshwater wetlands.

ARTICLE INFO

Article history:
Received 5 March 2012
Received in revised form
29 May 2012
Accepted 1 June 2012

Keywords:
Deyeuxia angustifolia
Methane
Trace-gas flux
P enrichment
Eutrophication
Temperate wetlands
The Sanjiang Plain

ABSTRACT

Human activities have increased phosphorus (P) loading in wetland ecosystems worldwide. However, little is known about the effect of P enrichment on CH_4 emissions from these ecosystems. In this study, a 4-year P addition experiment was conducted to examine the effects of increased P availability on CH_4 emission in a *Deyeuxia angustifolia*-dominated freshwater marsh in the Sanjiang Plain in northeastern China. Phosphorus was added at four rates (0, 1.2, 4.8 and 9.6 g P m^{-2} $year^{-1}$). We investigated CH_4 emission during the growing season (early May to late September) using opaque chamber and gas chromatography method. Our results indicated that the effect of P enrichment on CH_4 emission was time-dependent. Increased P availability did not affect CH_4 emission in 2007 and 2008, but decreased in 2009 and 2010. Notably, four years of P addition decreased cumulative CH_4 emission during the growing season in the freshwater marsh, and the effect did not change with fertilization rates. From 2007 to 2010, P additions of 1.2, 4.8 and 9.6 g P m^{-2} $year^{-1}$ caused a decline in growing-season CH_4 emissions by averages of 23%, 38% and 26%, respectively. Our results suggest that long-term P enrichment driven by agricultural activities would reduce CH_4 emission from temperate freshwater wetlands. This study also highlights the impact of experimental duration on accurate assessments of the effect of P addition on wetland CH_4 budget.

1. Introduction

Methane (CH_4) is the second-most important anthropogenic greenhouse gas in the atmosphere after carbon dioxide (CO_2) and has 25 times the global-warming potential of CO_2 over a 100-year horizon (IPCC, 2007). Global atmospheric CH_4 concentration has increased from 700 ppb in pre-industrial times to 1782 ppb in 2006 (Wuebbles and Hayhoe, 2002; Fowler et al., 2009). Wetlands, excluding non-rice agriculture, are the largest natural source of CH_4 to the atmosphere, and they contribute approximately 20% of the global CH_4 budget (IPCC, 2007; Fowler et al., 2009). Of this contribution, one-third is derived from temperate and boreal northern wetlands (Gauci et al., 2004). In wetland ecosystems, CH_4 emission generally exhibits drastic temporal and spatial variations (Fowler et al., 2009; Song et al., 2009) and varies with water table level (Christensen et al., 2003; O'Connor et al., 2010), temperature (Christensen et al., 2003; Sun et al., 2011), substrate C availability (Bubier and Moore, 1994; O'Connor et al., 2010), pH (Dunfield et al., 1993), redox state (Bubier and Moore, 1994), nutrient availability (Keller et al., 2006) and vegetation community and production (Whiting and Chanton, 1993).

Phosphorus (P) is one of the most important elements limiting plant primary production and other ecosystem processes in most terrestrial and aquatic ecosystems (Elser et al., 2007; Filippelli, 2008). In recent decades, anthropogenic P enrichment in most ecosystems worldwide has been driven by P mining and P transportation in

* Corresponding author. Tel.: +86 431 85542204; fax: +86 431 85542298.
E-mail address: maorong@neigae.ac.cn (R. Mao).

1352-2310/$ – see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.atmosenv.2012.06.003

fertilizers, animal feed, agricultural crops and other products (Bennett et al., 2001; Filippelli, 2008). Similar to other natural ecosystems, wetlands are currently experiencing increased P loading as a result of human activities (Keller et al., 2005; Song et al., 2011). In wetland ecosystems, P enrichment is assumed to stimulate plant growth and increase plant production, enhancing substrate availability for methanogens through root exudates and litter turnover, which increases CH_4 fluxes to the atmosphere. However, previous studies have found that the response of plant productivity to P addition is often species-specific and that this response varies by wetland type (Verhoeven and Schmitz, 1991; Chapin et al., 2004; Keller et al., 2006). Moreover, increased P loading to wetlands may change soil microbial community and activity (Keller et al., 2006) and alter plant-mediated transport of CH_4 (Lu et al., 1999). Given that emission of CH_4 from the soil to the atmosphere is dependent on the balance among CH_4 production, transport and oxidation, the effect of P enrichment on CH_4 emission is still uncertain in wetlands. An improved understanding of the response of CH_4 flux rates to P enrichment in specific wetland ecosystems is essential for accurately assessing the global CH_4 budget from wetlands and projecting the future climate through global climate models.

The Sanjiang Plain, located east of Heilongjiang Province in northeastern China, is an alluvial floodplain that includes one of the largest freshwater wetland areas in China (Zhao, 1999). In the past 50 years, marshes have been extensively drained and used for agriculture in the Sanjiang Plain (Yan et al., 2001). Therefore, the formerly pristine wetlands in this region generally have been subjected to increased P loading, mainly due to fertilization application in the adjacent agricultural lands. Will increased P input alter CH_4 flux rates in the wetland ecosystems in the Sanjiang Plain? To answer this question, we established a P fertilization experiment in 2007 in a *Deyeuxia angustifolia*-dominated freshwater marsh in the Sanjiang Plain of northeastern China. We subsequently collected one 4-year (from 2007 to 2010) continuous observational dataset to assess the effect of P enrichment on wetland CH_4 emission during the growing season (early May to late September).

2. Material and methods

2.1. Site description and experimental design

The study was conducted in a *D. angustifolia*-dominated freshwater marsh located near the Sanjiang Mire Wetland Experimental Station (47°35′N, 133°31′E, 56 m a.s.l) in the Sanjiang Plain, Heilongjiang Province, northeastern China. *D. angustifolia*-dominated freshwater marsh is one of the main wetland types in the Sanjiang Plain, as this ecosystem type accounts for approximately 31% of the wetland area in this region (Zhao, 1999). The study site has a temperate continental monsoon climate with a mean annual (1990–2010) temperature of 2.53 °C (month range −20.4 to 21.6 °C), a mean annual precipitation of 566 mm (approximately 50% fall in July and August) and a frost-free period of approximately 125 days per year. The soil in the study site is a typical meadow marsh soil and is classified as an Inceptisol in the US soil taxonomy classification system. Mean soil organic C at 0–15 cm depth is 95 mg g^{-1}, total N concentration is 8.5 mg g^{-1}, bulk density is 0.67 g cm^{-3} and pH is 5.35. The dominant plant species at this site are *D. angustifolia* and *Glyceria spiculosa*, which comprise more than 90% of the total aboveground biomass. Detailed information regarding the study site was described by Song et al. (2009).

We used a complete randomized block design with four P addition treatments (control, 0 g P m^{-2} $year^{-1}$; P1, 1.2 g P m^{-2} $year^{-1}$; P2, 4.8 g P m^{-2} $year^{-1}$; P3, 9.6 g P m^{-2} $year^{-1}$) that was replicated three times, resulting in 12 plots of 1 m × 1 m. During autumn 2006, plastic (PVC) frames (1 m × 1 m, 0.5 m in depth) were installed to prevent horizontal movement and lateral loss of the added P, and each plot was separated by a 1-m buffer zone. Meanwhile, board walks giving access to the whole experimental area were established to minimize further disturbance on the plots. Phosphorus was added as NaH_2PO_4. Phosphorus fertilizer was dissolved in 1 L distilled water and applied at 2-week intervals from early May to late August. At the same time, the control plots were treated with the same volume of distilled water. We chose a P amendment of 1.2 g m^{-2} $year^{-1}$ because it was comparable to the amount of the background increased P input in wetlands during the growing season in this region. To examine the probable increases in P input to these wetlands in the future, we experimentally increased the ambient growing season P loading rate by factors of 4 and 8.

2.2. CH_4 flux measurement

CH_4 emission was measured at weekly to biweekly intervals using an opaque static chamber (constructed from stainless steel, 0.5 m × 0.5 m × 0.5 m) during the growing seasons of 2007, 2008, 2009 and 2010. Before sampling, the chambers were placed into collars (also made from stainless steel) that were permanently installed in the soil. Inside the chamber, two fans were used to keep the air homogenized during gas sampling, and a thermometer sensor and a trinal-venthole were installed. Gas sampling was usually carried out at 9:00 AM local time and lasted half an hour; four gas samples were collected using polypropylene syringes at 10-min intervals. Meanwhile, air temperatures inside and outside the chamber were recorded using a thermometer sensor, and the surface water table was measured using a ruler near the chamber in each plot. When the water level was below the soil surface, the water table was determined by digging a small well near the chamber in each plot. The gas samples were stored in syringes less than 12 h before being measured, and CH_4 concentration was analyzed by a gas chromatogram (Agilent 4890D, Agilent Co., Santa Clara, CA, USA) using flame ionization detection. CH_4 emissions were calculated from the linear changes in chamber gas concentration with an average chamber temperature and were expressed as mg C m^{-2} h^{-1}. Sample sets were rejected when the R^2 of the linear regression of CH_4 concentration over time was lower than 0.9. Total annual CH_4 emissions were linearly and sequentially calculated from the emissions between each pair of adjacent measurement intervals during the growing season and expressed as g C m^{-2} $year^{-1}$. Detailed information about gas sampling using an opaque static chamber was described by Song et al. (2009).

2.3. Statistical analyses

Data were tested for normality using the Levene's test, and all non-normal data were transformed prior to analysis. Repeated measures analysis of variance tests (ANOVAs) were used to examine inter-annual variability in the CH_4 budget during the growing season in combination with P addition treatments. If there were significant interactions between time and P addition levels on annual CH_4 budget, we conduct further tests for significant differences in CH_4 budget among all treatments using a Fisher's least significant difference test. For each year, we tested the effect of P addition level on seasonal CH_4 fluxes using repeated measures ANOVAs. All statistical analyses were conducted with SPSS 11.5 for Windows, and the accepted significance level was $\alpha = 0.05$.

3. Results

Precipitation in the growing season (May–October) changed substantially over the 4-year study interval with 529 mm in 2007, 372 mm in 2008, 529 mm in 2009 and 504 mm in 2010. Mean air

temperatures were 18.0, 17.7, 17.2 and 18.6 °C in 2007, 2008, 2009 and 2010, respectively (Fig. 1).

Temporal dynamics of CH_4 emissions in the freshwater marsh followed a one-peak pattern in 2007 and 2009 and a two-peak pattern in 2008 and 2010 (Fig. 2). During the growing season, peak CH_4 emissions occurred in June in 2007 and 2008, but in August in 2009 and 2010 (Fig. 2).

During 4 years of growing seasons, the P1, P2 and P3 treatments decreased CH_4 emissions by 23%, 38% and 26%, respectively (all $P < 0.05$, Fig. 3). However, there was a significant interaction between P addition level and year on CH_4 emission ($P < 0.001$, data not shown). Over the growing season, P addition had no effect on CH_4 emissions in 2007 and 2008, but decreased in 2009 and 2010 (Fig. 3). However, there was no significant difference in CH_4 emissions among the P1, P2 and P3 treatments (Fig. 3).

4. Discussions

Notably, four years of P addition decreased CH_4 emissions during the growing season in the freshwater marsh in the Sanjiang Plain in northeastern China (Fig. 3). Lu et al. (1999) also found that increased P availability caused a decline in CH_4 emission in paddy soils. Moreover, Zhang et al. (2011) observed that three years of P addition increased CH_4 uptake in an old-growth tropical forest in southern China. However, previous studies found that P addition caused a short-term increase in CH_4 emissions from peat soils (Aerts and Toet, 1997) or paddy soils (Han et al., 2002). In addition, Keller et al. (2005) found that six years of P fertilization had a limited effect on rates of CH_4 production and consumption and thus CH_4 emission in a Minnesota fen. Lund et al. (2009) also found that a two-year P fertilization experiment had no effect on CH_4 exchange in two northern peatlands with contrasting N deposition rates. The inconsistent impacts of P enrichment on CH_4 emission may be explained by differences in experimental duration and ecosystem type (Keller et al., 2006). Indeed, we also found that the impact of P addition on CH_4 emission varied with experimental duration, although the cumulative relationship was negative (Fig. 3). Therefore, long-term field experiments would need to be conducted to examine temporal changes in the P addition effect on CH_4 emission and accurately predict the response of CH_4 emissions to P enrichment in wetland ecosystems. However, our results to date suggest that increased P loading caused by agricultural activities constrains CH_4 emissions in temperate freshwater wetlands.

In the present study, we inferred that the decrease in CH_4 emission under P addition treatments may be driven by several related mechanisms. First, increased P availability may reduce root biomass and exudation, reducing the substrate for methanogenesis (Lu et al., 1999; Mer and Roger, 2001). In the adjacent freshwater marshes, Song et al. (2011) found that P fertilization did not affect plant aboveground biomass. Considering that P addition generally increased the plant shoot/root ratio (Macek and Rejmánková, 2007), we speculated that increased P availability would decrease root biomass in this freshwater marsh. Second, P enrichment may inhibit methanogenesis in soils (Conrad et al., 2000; Keller et al., 2006) and increase soil methanotrophic potential (Joulian et al., 1998). Third, P fertilization may decrease root porosity and inhibit

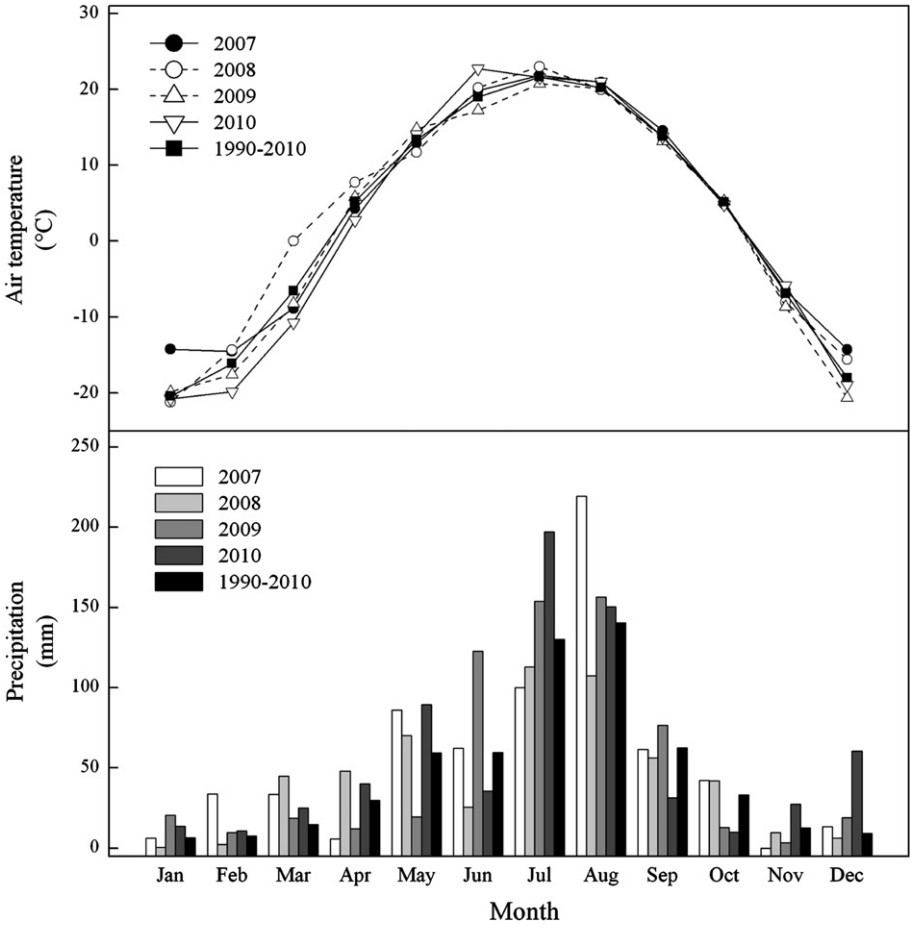

Fig. 1. Temporal changes in monthly mean air temperature (lines) and precipitation (bars) from 2007 to 2010 in the study site.

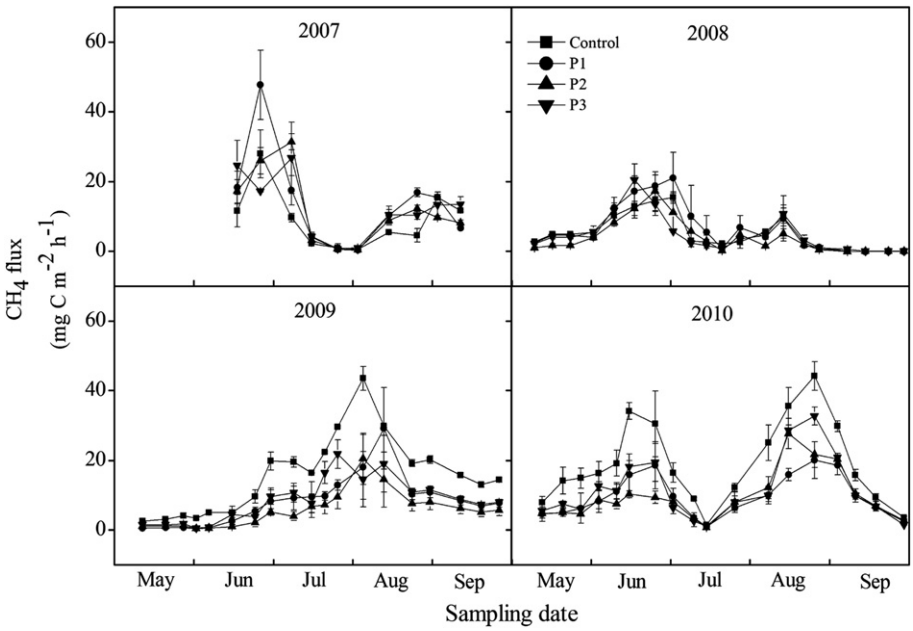

Fig. 2. Temporal dynamics of the CH_4 flux in the control and phosphorus addition treatments during the growing seasons from 2007 to 2010. Error bars represent ±SE ($n = 3$). Control, 0 g P m^{-2} $year^{-1}$; P1, 1.2 g P m^{-2} $year^{-1}$; P2, 4.8 g P m^{-2} $year^{-1}$; P3, 9.6 g P m^{-2} $year^{-1}$.

the development of root aerenchyma (Lu et al., 1999). In addition, changes in plant community structure induced by nutrient addition may alter soil carbon quality and potentially influence CH_4 flux from wetlands (Keller et al., 2006).

Interestingly, the amount of P added had no additive effect on CH_4 suppression in the freshwater wetland, and adding P with different rates had the same negative effect on CH_4 emission (Fig. 3). In a previous study conducted in an adjacent freshwater marsh, Song et al. (2011) observed that aboveground biomass did not change in response to different levels of P fertilization, suggesting that P may not limit plant growth in these wetlands. These findings revealed that there was a threshold for P-induced effects on aboveground biomass and CH_4 emission, and the critical value for CH_4 emission was below 1.2 g P m^{-2} $year^{-1}$ in this freshwater wetland. This finding implies that elevated P loading would exert a consistent suppression of CH_4 emission in temperate freshwater wetlands.

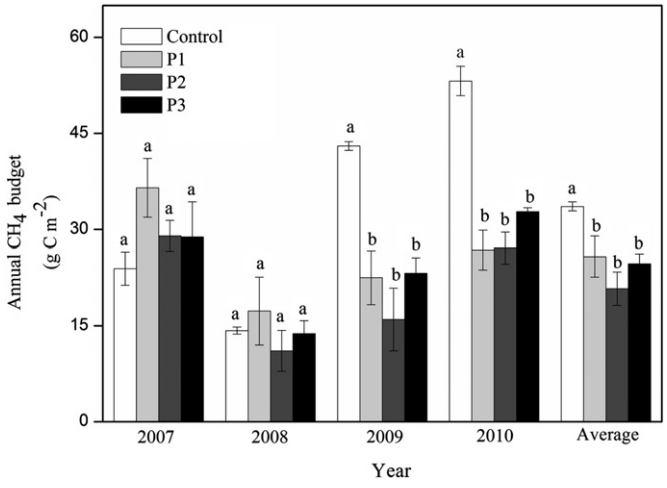

Fig. 3. CH_4 budgets during the growing season from 2007 to 2010 in the control and phosphorus addition treatments. Error bars represent ±SE ($n = 3$). Means with different lowercase letters in the same column are significantly different at $P < 0.05$. Control, 0 g P m^{-2} $year^{-1}$; P1, 1.2 g P m^{-2} $year^{-1}$; P2, 4.8 g P m^{-2} $year^{-1}$; P3, 9.6 g P m^{-2} $year^{-1}$.

The mean CH_4 budget in the control plots averaged 33.6 g C m^{-2} during the growing season and ranged from 14.3 g C m^{-2} in 2008 to 53.2 g C m^{-2} in 2010 (Fig. 3). The mean CH_4 budget in this freshwater marsh was comparable to that in an adjacent *Carex lasiocarpa*-dominated freshwater marsh (36.6 g C m^{-2} from 2002 to 2005, Song et al., 2009) but was greater than the value observed in the adjacent *D. angustifolia*-dominated freshwater marsh (3.15 g C m^{-2} from 2002 to 2005, Song et al., 2009) and lower than the CH_4 budget in a *Carex schmidtii* and *D. angustifolia*-dominated freshwater marsh in the Xiaoxing'an Mountains of northeastern China (90 g C m^{-2} from May to October in 2008, Sun et al., 2011). The magnitudes of our results during the growing season were similar to the previous studies performed in temperate wetlands in North America (Bubier et al., 1993; Treat et al., 2007). Moreover, CH_4 emissions exhibited large seasonal and inter-annual variations over the study period (Figs. 2 and 3) and were positively correlated with air temperature and the height of the water table (all $P < 0.001$, data not shown). These results imply that air temperature and the water table are important factors controlling CH_4 emissions in the study site and also indicate that CH_4 emissions in temperate freshwater wetlands are sensitive to climate change.

Although our study focused on the effect of P addition on CH_4 emission, the natural wetlands in this region of China also received elevated N input, due to fertilization application in the adjacent agricultural lands. Keller et al. (2006) found that N and P fertilization acted independently on CH_4 production and oxidation in peatlands. However, Zhang et al. (2011) observed that increased P availability mitigated the inhibition of N enrichment on CH_4 uptake in an old-growth tropical forest. Therefore, how increased N availability interacted with increased P availability to affect CH_4 emissions is still unclear, and therefore the net effect of nutrient enrichment on CH_4 emission remains uncertain in this ecosystem. Further study is needed to assess the combined effect of N and P additions on CH_4 emission in temperate freshwater wetlands.

5. Conclusions

In the present study, we have assessed the effect of P enrichment on CH_4 emission in a *D. angustifolia*-dominated freshwater marsh in the Sanjiang Plain in northeastern China. Notably, four years of P addition suppressed CH_4 emissions in this wetland, and the negative effect did not vary with fertilization rates. These results suggest that long-term increased P loading from agricultural activities reduces the emission of CH_4 from temperate freshwater wetlands. Given widespread eutrophication by anthropogenic P input for temperate freshwater wetlands, our results will help to develop an accurate C budget for wetland ecosystems.

Acknowledgments

We gratefully acknowledge one anonymous referee, Michele Raychaudhuri and Xiaoxin Sun for their helpful comments on an earlier draft of this manuscript. This research was supported by the "Strategic Priority Research Program – Climate Change: Carbon Budget and Related Issues" of the Chinese Academy of Sciences (Nos. XDA05050508 and XDA05020501), National Natural Science Foundation of China (Nos.40930527, 41125001 and 41103037) and National Basic Research Program (973) of China (No.2009CB421103).

References

Aerts, R., Toet, S., 1997. Nutritional controls on carbon dioxide and methane emission from Carex-dominated peat soils. Soil Biology & Biochemistry 29, 1683–1690.

Bennett, E.M., Carpenter, S.R., Caraco, N.F., 2001. Human impact on erodable phosphorus and eutrophication: a global perspective. BioScience 51, 227–234.

Bubier, J.L., Moore, T.R., Roulet, N.T., 1993. Methane emissions from wetlands in the Midboreal region of northern Ontario, Canada. Ecology 9, 2240–2254.

Bubier, J.L., Moore, T.R., 1994. An ecological perspective on methane emissions from northern wetlands. Trends in Ecology & Evolution 9, 460–464.

Chapin, C.T., Bridgham, S.D., Pastor, J., 2004. pH and nutrient effects on aboveground net primary production in a Minnesota, USA bog and fen. Wetlands 24, 186–201.

Christensen, T.R., Ekberg, A., Ström, L., Mastepanov, M., Panikov, N., Öquist, M., Svensson, B.H., Nykänen, H., Martikainen, P.J., Oskarsson, H., 2003. Factors controlling large scale variations in methane emissions from wetlands. Geophysical Research Letters 30 (7), 1414. http://dx.doi.org/10.1029/2002GL016848.

Conrad, R., Klose, M., Claus, P., 2000. Phosphate inhibits acetotrophic methanogenesis on rice roots. Applied and Environmental Microbiology 66, 828–831.

Dunfield, P., Knowles, R., Dumont, R., Moore, T.R., 1993. Methane production and consumption in temperate and subarctic peat soils: responses to temperature and pH. Soil Biology & Biochemistry 25, 321–326.

Elser, J.J., Bracken, M.E.S., Cleland, E.E., Gruner, D.S., Harpole, W.S., Hillebrand, H., Ngai, J.T., Seabloom, E.W., Shurin, J.B., Smith, J.E., 2007. Global analysis of nitrogen and phosphorus limitation of primary producers in freshwater, marine and terrestrial ecosystems. Ecology Letters 10, 1135–1142.

Filippelli, G.M., 2008. The global phosphorus cycle: past, present, and future. Elements 4, 89–95.

Fowler, D., Pilegaard, K., Sutton, M.A., Ambus, P., Raivonen, M., Duyzer, J., Simpson, D., Fagerli, H., Fuzzi, S., Schjoerring, J.K., Granier, C., Neftel, A., Isaksen, I.S.A., Laj, P., Maione, M., Monks, P.S., Burkhardt, J., Daemmgen, U., Neirynck, J., Personne, E., Wichink-Kruit, R., Butterbach-Bahl, K., Flechard, C., Tuovinen, J.P., Coyle, M., Gerosa, G., Loubet, B., Altimir, N., Gruenhage, L., Ammann, C., Cieslik, S., Paoletti, E., Mikkelsen, T.N., Ro-Poulsen, H., Cellier, P., Cape, J.N., Horváth, L., Loreto, F., Niinemets, Ü., Palmer, P.I., Rinne, J., Misztal, P., Nemitz, E., Nilsson, D., Pryor, S., Gallagher, M.W., Vesala, T., Skiba, U., Brüggemann, N., Zechmeister-Boltenstern, S., Williams, J., O'Dowd, C., Facchini, M.C., de Leeuw, G., Flossman, A., Chaumerliac, N., Erisman, J.W., 2009. Atmospheric composition change: ecosystems-atmospheric interactions. Atmospheric Environment 43, 5193–5267.

Gauci, V., Matthews, E., Dise, N., Walter, B., Koch, D., Granberg, G., Vile, M., 2004. Sulfur pollution suppression of the wetland methane source in the 20th and 21st centuries. Proceeding of the National Academy Sciences of the United States of America 101, 12583–12587.

Han, S.H., Zhuang, Y.H., Zhang, H.X., Wang, Z.J., Yang, J.Z., 2002. Phosphine and methane generation by the addition of organic compounds containing carbon-phosphorus bonds into incubated soils. Chemosphere 49, 651–657.

IPCC, 2007. Climate Change 2007: the Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom.

Joulian, C., Ollivier, B., Patel, B.K.C., Roger, P.A., 1998. Phenotypic and phylogenetic characterization of dominant culturable methanogens isolated from ricefield soils. FEMS Microbiology Ecology 25, 135–145.

Keller, J.K., Bridgham, S.D., Chapin, C.T., Iversen, C.M., 2005. Limited effects of six years of fertilization on carbon mineralization dynamics in a Minnesota fen. Soil Biology & Biochemistry 37, 1197–1204.

Keller, J.K., Bauers, A.K., Bridgham, S.D., Kellogg, L.E., Iversen, C.M., 2006. Nutrient control of microbial carbon cycling along an ombrotrophic–minerotrophic peatland gradient. Journal of Geophysical Research 111, G03006. http://dx.doi.org/10.1029/2005JG000152.

Lu, Y., Wassmann, R., Neue, H.U., Huang, C., 1999. Impact of phosphorus supply on root exudation, aerenchyma formation and methane emission of rice plants. Biogeochemistry 47, 203–218.

Lund, M., Christensen, T.R., Mastepanov, M., Lindroth, A., Ström, L., 2009. Effects of N and P fertilization on the greenhouse gas exchange in two northern peatlands with contrasting N deposition rates. Biogeosciences 6, 2135–2144.

Macek, P., Rejmánková, E., 2007. Response of emergent macrophytes to experimental nutrient and salinity additions. Functional Ecology 21, 478–488.

Mer, J.L., Roger, R., 2001. Production, oxidation, emission and consumption of methane by soils: a review. European Journal of Soil Biology 37, 25–50.

O'Connor, F.M., Boucher, O., Gedney, N., Jones, C.D., Folberth, G.A., Coppell, R., Friedlingstein, P., Collins, W.J., Chappellaz, J., Ridley, J., Johnson, C.E., 2010. Possible role of wetlands, permafrost and methane hydrates in the methane cycle under future climate change: a review. Reviews of Geophysics 48, RG4005. http://dx.doi.org/10.1029/2010RG000326.

Song, C., Xu, X., Tian, H., Wang, Y., 2009. Ecosystem-atmosphere exchange of CH_4 and N_2O and ecosystem respiration in wetlands in the Sanjiang Plain, Northeastern China. Global Change Biology 15, 692–705.

Song, C., Liu, D., Song, Y., Wan, Z., Li, Y., Xu, X., 2011. Effects of exogenous phosphorus addition on soil respiration in *Calamagrostis angustifolia* freshwater marshes of Northeast China. Atmospheric Environment 45, 1402–1406.

Sun, X., Mu, C., Song, C., 2011. Seasonally and spatial variations of methane emissions from montane wetlands in Northeast China. Atmospheric Environment 45, 1809–1816.

Treat, C., Bubier, J., Varner, R., Crill, P., 2007. Timescale dependence of environmental and plant-mediated controls on CH_4 flux in a temperate fen. Journal of Geophysical Research 112, G01014. http://dx.doi.org/10.1029/2006JG000210.

Verhoeven, J.T.A., Schmitz, M.B., 1991. Control of plant growth by nitrogen and phosphorus in mesotrophic fens. Biogeochemistry 12, 135–148.

Whiting, G.J., Chanton, J.P., 1993. Primary production control of methane emission from wetlands. Nature 364, 794–795.

Wuebbles, D.J., Hayhoe, K., 2002. Atmospheric methane and global change. Earth-Science Reviews 57, 177–210.

Yan, M., Deng, W., Ma, X., 2001. Climate variation in the Sanjiang Plain disturbed by large scale reclamation during the last 45 years. Acta Geographica Sinica 56, 159–170.

Zhang, T., Zhu, W., Mo, J., Liu, L., Dong, S., 2011. Increased phosphorus availability mitigates the inhibition of nitrogen deposition on CH_4 uptake in an old-growth tropical forest, southern China. Biogeosciences 8, 2805–2813.

Zhao, K.Y., 1999. Mires in China. Science Press, Beijing (in Chinese).