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Understanding Methane Emission from Rice Paddies in China

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Abstract

China is the largest rice-producing country in the world, accounting for about 30% of total rice production. Methane (CH_4), is produced and emitted in the rice fields under flooded conditions. There are very large temporal and spatial variations of CH_4 emissions from rice fields in China, with seasonal average fluxes in the range 0.14–58 mg CH_4 m^{-2} h^{-1}, mainly dependent on water regime in both off-rice and rice seasons, and availability of labile organic carbon. Based on field measurements, recent estimates of CH_4 emission from Chinese paddy fields, either by modeling or by scaling up, were mostly in the range 3.3–9.6 Tg CH_4 y^{-1}, with a more realistic value of around 8 Tg CH_4 y^{-1}. There is a large potential for mitigating CH_4 from rice paddies by improving water regimes and appropriate management of crop residues.

1.Introduction

China is the largest rice producer in the world. Its rice harvested area increased steadily from 27 Mha in 1961 to 36.97 Mha in 1976, decreased continuously to 26.78 Mha in 2003, and then increased again slowly to around 29.93 Mha in 2009. As rice fields are an important source of atmospheric methane (CH_4). China has been of particular concern in the past two decades as a source of CH_4. The research on CH_4 emissions from Chinese rice paddies started in the late 1980s and the first paper was published in 1988 (Winchester et al. 1988). Since CH_4 fluxes measured in a rice field in Tuzu, Sichuan Province of China were, on average, 60 mg m^{-2} h^{-1} (i.e. 4–10 times higher than emission rates from rice fields in the United States and Europe (Khalil et al. 1991), great attention was drawn to measurement and understanding of CH_4 emissions from rice fields in China. Up to the present, CH_4 and N_2O emissions from rice paddies in China have been intensively measured, the factors affecting their emissions investigated, and the annual emissions at the national and regional scales have been estimated by various approaches.

2. Factors influencing CH_4 emissions from rice fields

CH_4 emission from rice fields is the net result of three processes: production, oxidation and transport. Any factors that affect one or more of these processes may affect CH_4 emission. By analyzing field measurement data of CH_4 emission from rice paddies in Asia, Yan et al. (2005) found that organic amendment, water regime during the rice-growing season, water status in pre-season and soil properties were the main influencing factors.

2.1 Organic amendments

CH_4 is converted from substrate by methanogenic bacteria in strictly reduced environments. Organic amendments directly supply substrate for methanogenic bacteria. The decomposition of organic materials also helps develop a reduced environment for CH_4 generation. CH_4 emission from rice paddies is affected by the type, amount and timing of organic amendment.

A variety of organic fertilizers are used in China, including crop residues, green manure, animal manure, and compost from biogas reactors. The stimulating effect of all these organic fertilizers on CH_4 emission from Chinese rice paddies has been widely studied (Tao et al. 1994, Wang et al. 1995, Zou et al. 2003, Qin et al. 2006, Ma et al. 2007). Yan et al.

(2003) compiled 15 pairs of flux data, comparing CH_4 emissions from Chinese rice fields with and without organic amendment, controlling for other conditions (i.e. site, rice season and water regime). The ratios of CH_4 flux with organic amendment to flux without organic amendment were within the range 0.7–4.2, with an average of 2.08 and standard deviation of 1.16. However, there is a large difference in the effects of different types of organic materials on CH_4 emission. Generally, fresh crop straw shows the largest stimulating effect on CH_4 emission. A seasonal average CH_4 flux of 51.4 mg m^{-2} h^{-1} was reported for rice straw incorporation of 2.63 t ha^{-1}, compared to 10.3 mg m^{-2} h^{-1} without organic input (Qin et al. 2006). Decomposed manure from biogas reactors showed little stimulating effect (Tao et al., 1994). CH_4 emission induced from surface-applied organic materials was less than that from organic materials incorporated into soils, as the former had more chance to be decomposed aerobically than the latter (Xiao et al. 2007).

To prevent air pollution and increase soil fertility, the Chinese government banned field burning and encouraged field application of crop residues. This practice is likely to increase CH_4 emission from rice fields. To mitigate the straw-induced CH_4 emission, Ma et al.(2008) suggested that straw be piled in ridges between rice rows, high above the water layer and be covered with soil. CH_4 emission could be reduced by one third through this practice as compared with direct incorporation of straw into surface soil.

2.2 Water management during the rice-growing season

The water management practice during the rice-growing season is a critical factor influencing CH_4 emission. Mid-season drainage is widely practiced in Chinese rice cultivation. Yan et al. (2003) compiled 11 pairs of data that compared the effects of mid-season drainage and continuous flooding on CH_4 emission from Chinese rice fields, controlling for other conditions (i.e. organic input, rice season and site). On average, CH_4 flux from fields with mid-season drainage was 53% of that from continuously flooded fields. During mid-season drainage, the soil is exposed to air and the redox potential increases rapidly, which inhibits the activity of methanogenic bacteria and so lowers CH_4 production (Xu et al. 2000). The increase in soil redox potential also helps the oxidation of CH_4 (Jia et al. 2001). CH_4 emission may gradually resume when mid-season drainage ends and the rice field is re-flooded. However, if the mid-season drainage was performed until the soils becomes very dry, CH_4 emission may not resume even after an extended period of re-flooding, resulting in a greatly reduced seasonal CH_4 emission (Xu et al. 2000). The earlier the mid-season drainage is started, the greater is the mitigation effect (Li et al. 2007). However, if the mid-season drainage is performed too early, it damages rice growth.

It is worth noting that when drainage begins, the CH_4 trapped in soil may erupt, resulting in a short-term emission peak, which may be overlooked by observers (Xu et al. 2000).

2.3 Water status in preseason

In addition to water management, the water status of rice fields before the rice-growing season also has a strong influence on CH_4 emission in the rice-growing season. Extremely high CH_4 emission was found for rice fields flooded in the winter season (Cai et al. 2003). For four sites across south and southwest China, Kang et al. found that CH_4 fluxes in the rice-growing season from fields that had been flooded in the preceding winter season were 1.2–6.4 times those from fields that were drained in the preceding winter season (Kang et al. 2002).

If the soil is drained in the preseason, ions such as ammonium (NH_4^+), manganese (Mn_2^+) and iron (Fe_2^+) are oxidized. When the soil is flooded for rice-growing, the oxidized ions are gradually reduced, and it takes a long time for the methanogenic organisms to revive, therefore shortening the CH_4 emission period.

There are generally three rice crops in China: single, early and late rice. Single rice is planted on rice fields that are left fallow or planted with upland crops in the preceding season with the fields drained. Early rice is similar to single rice, but the preceding season is shorter. Late rice is usually planted immediately after early rice on the same field. Because the field is usually flooded or kept in moisture conditions suitable for CH_4 production before late rice transplanting, CH_4 fluxes increase sharply soon after transplanting; however, it takes a longer time for CH_4 emission to resume for early rice or single rice (Yan et al. 2003). Due to this difference in water status in preseason, the average CH_4 emission in late rice is 1.5 and 2.3 times that in early rice and single rice, respectively

(Yan et al. 2003). CH_4 emission from rice fields can be dramatically reduced when rice is planted after two consecutive upland crops as compared to the cases where rice is alternated with upland crops or rice is continuously cropped (Cai et al. 1998).

2.4 Chemical fertilizer

Application of chemical fertilizer, especially synthetic N, is necessary in Chinese rice cultivation. The effect of N-fertilizer on CH_4 emission from rice paddies has been studied in many field experiments and the results are mixed. Chen et al.found that the application of urea increased CH_4 emission, as urea increased root growth and root exudates, providing more substrate for methanogenesis (Chen et al. 1995). Another effect of urea application is that NH_4^+, the product of urea hydrolysis, inhibits CH_4 oxidation through competition for methanotrophs and thus increases CH_4 emission. Other studies, however, showed that the use of urea decreased CH_4 emission (Cai et al. 1997, Zou et al. 2005, Ma et al. 2007). It was argued that in an environment of high CH_4 concentration, NH_4^+-based N-fertilizer may inhibit CH_4 oxidation at the beginning, but the coexistence of high CH_4 concentration and NH_4^+ stimulates the growth of methanotrophs and/or their activity for oxidizing CH_4. With the gradual NH_4^+ uptake by rice plants, the increased methanotroph population and/or their activity may consume more CH_4, leading to lower CH_4 emission in later stages (Cai et al. 1997).

Compared to urea, the use of ammonium sulfate, $(NH_4)_2SO_4$, consistently decreased CH_4 emission from rice paddies in all studies that compared the effects of the two fertilizers (Tao et al. 1994, Cai et al. 1997, Lin et al. 2000). This was likely due to the inhibitory effect of SO_4^{2-} on methanogenesis.

3. Estimation of CH_4 emissions from rice fields

As the largest rice producer in the world, China's rice fields have been of particular concern in the past three decades as a source of CH_4, and various estimations have been made (Fig. 1). One of the earliest calculations was made by extrapolating a flux of 58 mg CH_4 m^{-2} h^{-1}, the average CH_4 emission flux for the rice-growing season of two consecutive years in Tuzu, Sichuan Province, to the whole of China. The resulting estimate was 30 Tg CH_4 y^{-1} (Khalil et al. 1991). Similarly, Wassmann et al. extrapolated the results of measurements in Hangzhou, Zhejiang Province to the entire country, and estimated an emission of 18–28 Tg CH_4 y^{-1} (Wassmann et al. 1993). As field measurements accumulated, more flux data were included in upscaling methods. Yao et al. used flux data from six sites to represent 10 agroecological zones, and estimated 15.3 Tg CH_4 y^{-1} (Yao et al. 1996). Evaluating results from 12 field sites, Cai concluded that emission was 8.05 Tg CH_4 y^{-1}, and considered the effects of water regime and organic fertilizer

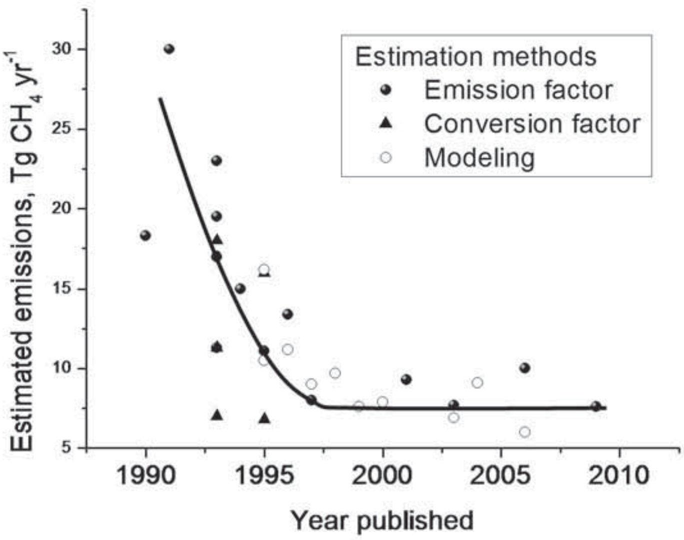

Fig. 1. Various estimations of CH_4 emission from Chinese rice fields, obtained by different methods, and published in different years. Figure was drawn with data from Cai et al. (Cai et al. 2009).

application (Cai 1997). With a total of 204 season-treatment measurements conducted on 23 sites, and considering the effect of water regime and organic amendment, Yan et al. estimated an emission of 7.67 Tg CH_4 y^{-1} (Yan et al. 2003).

Several process-based models of various levels of complexity have been developed to estimate CH_4 emission from rice fields in China. Cao et al. developed a simplified process-based CH_4 emission model. Taking rice primary production and soil organic degradation as supplies of carbon (C) substrate for methanogens, and considering environmental controls of methanogenesis, they estimated a total emission of 16.2 Tg y^{-1} for China (Cao et al. 1995). Huang et al. considered daily CH_4 emission flux as a function of photosynthetic activity, and incorporated the effects of organic matter, soil sand content, temperature and rice cultivar, and estimated the emission to be 9.66 Tg CH_4 y^{-1} (Huang et al. 1998). Based on a rice crop simulation model and integrating the effects of climate, soil, agricultural management and the growing of rice on CH_4 flux, Matthews et al. calculated an emission of 3.35–8.64 Tg CH_4 y^{-1} for China, and concluded that a more realistic estimate was 7.22–8.64 Tg CH_4 y^{-1} (Matthews et al. 2000).

Recently, we applied the tier 1 method of the 2006 IPCC (Intergovermental Panel on Climate Change) guidelines to estimate CH_4 emission from global rice fields – giving global total emission of 25.6 Tg y^{-1}, of which 7.6 Tg was estimated to be emitted from Chinese rice fields (Yan et al. 2009). We have compiled the most up-to-date dataset of CH_4 emissions from Chinese rice fields, with a total of 336 season-treatment measurements; the average of these seasonal measurements was 25.6 g m^{-2}. Simply multiplying this average flux by the total rice cultivation area of about 30 Mha, gives an estimate of 7.68 Tg CH_4 y^{-1}. Considering all the recent estimations obtained with different methods (Fig. 1), we are confident that CH_4 emission from Chinese rice fields is around 8 Tg y^{-1}.

4. Mitigation options for CH_4 emission from rice paddies

CH_4 is the terminal product of soil reduction in the succession of oxidation–reduction. In principle, any factors or practices able to retard soil reduction or reduce organic substrates will mitigate CH_4 emissions from rice fields. Among all factors, water regimes and organic substrates and their combination are crucial for controlling CH_4 emissions from rice fields.

Water regimes are important not only during the rice growing period, but also in the off-rice season, in determining CH_4 emissions from rice fields. Flooding, or at least water-saturation of soil, is a prerequisite but not sufficient condition for CH_4 production, since CH_4 is a terminal product of soil reduction. Only when active oxidants such as oxygen, NO_3^-, Mn_4^+, Fe_3^+ and SO_4^{2-} are consumed and anaerobic conditions have developed in soil (at least at micro-sites) is detectable amounts of CH_4 produced, given available organic substrates. The history of soil moisture before flooding for growing rice determines the duration of the development of anaerobic conditions after flooding (Xu et al. 2003), thus affecting CH_4 emissions from rice fields during the rice growing period. Since year-round flooding is the extreme water regime most favorable for CH_4 production, the largest CH_4 emissions were observed in rice fields in China that experienced these conditions (Cai et al. 2000). CH_4 emission also occurs if a rice field is flooded in the off-rice season (Cai et al. 2000). Therefore, draining rice fields sufficiently in the off-rice season will mitigate CH_4 emission in the off-rice season and also significantly during the rice growing period. Shiratori et al. (2007) found that subsurface drainage of waterlogged rice fields in Japan in the off-rice season mitigated CH_4 emissions significantly during the rice growing period. They established a linear relationship between soil moisture before flooding for rice transplanting and CH_4 emissions in the following rice-growing period. For various reasons, such as poor drainage in topographic depressions, lack of well-developed irrigation systems to ensure flooding of the rice field for rice transplanting, and poor management in the off-rice season, there is about 2.7–4.0 Mha of rice fields flooded year-round in China, and this is estimated to contribute CH_4 emission of 2.44 Tg y^{-1} (Cai et al. 2005). If flooding of some rice fields in the off-rice season is only due to poor management then lowering CH_4 emissions is relatively easy. For year-round flooded rice fields due to poor drainage and irrigation conditions, mainly distributed in hilly and mountainous areas in South and Southwest China, local farmers have developed a ridged cultivation system, in which ridges are built and maintained before rice transplanting every year. Rice is planted in both sides of the ridges, flooded water is kept in ditches, and the water level is raised to the top of ridges during the rice growing period and lowered to a certain level in the off-rice season. This practice raises soil redox-potential in the ridges and reduces CH_4 emissions by about 33% (Cai et al. 2003). Xu and Hosen demonstrated that keeping the soil water content in the range of 38–59% water holding capacity in the fallow season is important to lower CH_4 emissions (Xu and Hosen 2010).

It has been well documented that drainage in mid-season during the rice growing period mitigates CH_4 emission. As mentioned previously, Yan et al. found that, on average, CH_4 emission from rice fields with mid-season drainage was 53% that from continuously flooded fields. The effectiveness of mid-season drainage depends on the number of drainage events, and the timing and duration of each drainage event (Yan et al. 2003). Mid-season drainage has been widely practiced in China for > 30 years. The original objective of mid-season drainage was to control the number of rice tillers and promote root growth, and thus increase rice yield, rather than to mitigate CH_4 emission. The potential of this practice to mitigate CH_4 emissions from rice fields in China is expected to be limited since only for a small area of rice fields is mid-season drainage not currently practiced. Furthermore, a great attention is needed on the trade-off relationship between CH_4 and N_2O emissions from rice fields. Very large N_2O emissions were observed from rice fields with soil moisture close to water-saturation (Xu et al. 2004, Zheng et al. 2000), although this water regime significantly inhibited CH_4 emissions (Xu et al. 2004).

Increases in supplies of organic substrate under flooded conditions stimulates CH_4 emission. Therefore, amendments of organic manure, and incorporation of crop straw and green manure usually increase CH_4 emissions from rice fields. However, these practices may be essential for maintaining soil fertility. It has been demonstrated that at the same amount of organic C input, the CH_4 emissions induced by compost and biogas residues were less than that by crop straw (Wassmann et al. 2000). Incorporation of crop straw in the off-rice season when fields are drained stimulates CH_4 emissions less than incorporation just before rice transplanting (Cai and Xu 2004, Wassmann et al. 2000). CH_4 emissions induced by straw incorporation varies also with the patterns of straw incorporation (Ma et al. 2009). So, selecting an appropriate incorporation pattern should reduce the stimulation of CH_4 emissions. In the case of straw incorporation just before transplanting, practicing mid-season drainage earlier than usual can also reduce the stimulation of CH_4 emission (Cai et al. 2009).

CH_4 emissions from paddy fields are affected by planting density. Higher rice planting density leads to higher CH_4 emission fluxes because a high-density crop has more stems, leaves and roots, which speed up transmission and emission of CH_4. To ensure good crop yield, the rice planting density can be adjusted only within a very limited range, and hence there is limited potential of reducing planting density to reduce CH_4 emissions. The effect of rice variety on paddy CH_4 emissions varies. Ding et al. found that CH_4 emission was positively related to rice plant height, and the emission from paddy fields grown with tall-stalk rice (120-cm plant height) was 2.9 times that from fields sown with dwarf rice (90-cm height) (Ding et al. 1999). However, crop yield is the current priority for selection of rice varieties.

Application of electron acceptors such as NO_3^-- and SO_4^+-containing fertilizers, and Fe and Mn oxides mitigates CH_4 emissions from rice fields (Cai et al. 1997, Wassmann et al. 2000, Ali et al. 2009, Kara and Ozdilek 2010); however, they are less feasible. Chemicals that inhibit the activities of methanogenic bacteria depress CH_4 emissions during the rice growing period. Commonly used nitrification inhibitors can mitigate CH_4 emissions from rice fields (Li et al. 2009). It has also been reported that CH_4 emissions from rice–duck systems are less than from pure rice fields in south China (Zhan et al. 2011).

References

Ali, M. A., C. H. Lee, S. Y. Kim and P. J. Kim (2009) Effect of industrial by-products containing electron acceptors on mitigating methane emission during rice cultivation. Waste Management, 29: 2759-2764.

Cai, Z. and H. Xu (2004) Options for mitigating CH_4 emissions from rice fields in China. In: Material Circulation through Agro-Ecosystems in East Asia and Assessment of its Environmental Impact, ed. by Hayashi.

Cai, Z. C. (1997) A category for estimate of CH_4 emission from rice paddy fields in China, Nutrient Cycling in Agroecosystems, 49: 171-179.

Cai, Z. C., G. D. Kang, H. Tsuruta and A. Mosier

(2005) Estimate of CH_4 emissions from year-round flooded rice fields during rice growing season in China. Pedosphere, 15: 66-71.

Cai, Z. C., H. Tsuruta, M. Gao, H. Xu and C. F. Wei (2003) Options for mitigating methane emission from a permanently flooded rice field. Global Change Biology, 9: 37-45.

Cai, Z. C., H. Tsuruta and K. Minami (2000) Methane emission from rice fields in China: Measurements and influencing factors. Journal of Geophysical Research-Atmospheres, 105: 17231-17242.

Cai, Z. C., G. X. Xing, X. Y. Yan, H. Xu, H. Tsuruta, K. Yagi and K. Minami (1997) Methane and nitrous oxide emissions from rice paddy fields as affected by nitrogen fertilisers and water management. Plant and Soil, 196: 7-14.

Cai, Z. C., H. Xu, W. S. Lu, Z. W. Liao, J. G. Zhang, C. F. Wei and D. T. Xie (1998) Influence of water management in winter crop season on CH_4 emission during rice growing season. Chinese Journal of Applied Ecology, 9: 171-175 (in Chinese with English abstract).

Cai, Z. C., H. Xu and J. Ma (2009) Methane and Nitrous Oxide Emissions from Rice-Based Ecosystems. Hefei: Press of China Science and Technology University.

Cao, M., J. B. Dent and O. W. Heal (1995) Methane emissions from China's paddyland. Agriculture, Ecosystems & Environment, 55: 129-37.

Chen, G. X., G. H. Huang, B. Huang, J. Wu, K. W. Yu, H. Xu, X. H. Xue and Z. P. Wang (1995) CH_4 and N_2O emission from a rice field and effect of Azolla and ertilization on them', Chinese Journal of Applied Ecology, 6: 378-382 (in Chinese with English abstract).

Ding, A., C. R. Willis, R. L. Sass and F. M. Fisher (1999) Methane emissions from rice fields: Effect of plant height among several rice cultivars. Global Biogeochemical Cycles, 13:1045-1052.

Huang, Y., R. L. Sass and F. M. Fisher (1998) Model estimates of methane emission from irrigated rice cultivation of China. Global Change Biology, 4: 809-821.

Jia, Z. J., Z. C. Cai, H. Xu and X. P. Li (2001) Effect of rice plants on CH_4 production, transport, oxidation and emission in rice paddy soil. Plant and Soil, 230: 211-221.

Kang, G. D., Z. C. Cai and Z. H. Feng (2002) Importance of water regime during the non-rice growing period in winter in regional variation of CH_4 emissions from rice fields during following rice growing period in China. Nutrient Cycling in Agroecosystems, 64: 95-100.

Kara, E. E. and H. G. Ozdilek (2010) The Effect of Nitrogenous Fertilizers on Methane Oxidation in Soil. Ekoloji, 19: 1-9.

Khalil, M. A. K., R. A. Rasmussen, M. X. Wang and L. X. Ren (1991) Methane Emissions from Rice Fields in China, Environmental Science & Technology, 25: 979-981.

Li, X. L., H. Xu, J. L. Cao, Z. C. Cai and K. Yagi (2007) Effect of water management on CH_4 emission during rice-growing season. Soils, 39: 238-242 (in Chinese with English abstract).

Li, X. L., X. Y. Zhang, H. Xu, Z. C. Cai and K. Yagi (2009) Methane and nitrous oxide emissions from rice paddy soil as influenced by timing of application of hydroquinone and dicyandiamide. Nutrient Cycling in Agroecosystems, 85: 31-40.

Lin, K. F., Y. L. Xiang, D. B. Jiang, Q. L. Hu, Z. H. Li, D. D. Du and Z. Tao (2000) Methane emission flux from paddy fields and its control in Hubei. Agro-environmental Protection, 19: 267-270 (in Chinese with English abstract).

Ma, J., X. L. Li, H. Xu, Y. Han, Z. C. Cai and K. Yagi (2007) Effects of nitrogen fertiliser and wheat straw application on CH_4 and N_2O emissions from a paddy rice field. Australian Journal of Soil Research, 45: 359-367.

Ma, J., E. D. Ma, H. Xu, K. Yagi and Z. C. Cai (2009) Wheat straw management affects CH_4 and N_2O emissions from rice fields. Soil Biology & Biochemistry, 41: 1022-1028.

Ma, J., H. Xu, K. Yagi and Z. C. Cai (2008) Methane emission from paddy soils as affected by wheat straw returning mode. Plant and Soil, 313: 167-174.

Matthews, R. B., R. Wassmann, J. W. Knox and L. V. Buendia (2000) Using a crop/soil simulation model and GIS techniques to assess methane emissions from rice fields in Asia. IV. Upscaling to national levels. Nutrient Cycling in Agroecosystems, 58: 201-217.

Qin, X. B., Y. E. Li, K. Y. Liu and Y. F. Wan (2006) Methane and nitrous oxide emission from paddy field under different fertilization treatments. Transactions of the CSAE, 22: 143-148 (in Chinese with English abstract).

Shiratori, Y., H. Watanabe, Y. Furukawa, H. Tsuruta and K. Inubushi (2007) Effectiveness of a subsurface drainage system in poorly drained paddy fields on reduction of methane emissions. Soil Science and Plant Nutrition, 53: 387-400.

Tao, Z., D. D. Du, Y. Zhou, G. X. Mai and X. W. Liu (1994) Effect of applying biogas pit sediment on methane emission fluxes from paddy field. Rural Eco-Environment, 10: 1-5 (in Chinese with English abstract).

Wang, M. X., X. J. Shangguan, R. X. Shen, Y. S. Wang, R. Wassmann, H. Renenberg, W. Seiler, X. L. Xie and W. D. Wang (1995) The effect of fertilization on methane emission from rice fields in central China region and methane mitigation strategy. China Agricultural Meteorology, 16: 1-5 (In Chinese with English abstract).

Wassmann, R., R. S. Lantin, H. U. Neue, L. V. Buendia, T. M. Corton and Y. Lu (2000) Characterization of methane emissions from rice fields in Asia. III. Mitigation options and future research needs. Nutrient Cycling in Agroecosystems, 58: 23-36.

Wassmann, R., H. Schütz, H. Papen, H. Rennenberg, W. Seiler, D. Aiguo, S. Renxing, S. Xingjian and W. Mingxing (1993) Quantification of methane emissions from Chinese rice fields (Zhejiang Province) as influenced by fertilizer treatment. Biogeochemistry, 20: 83-101.

Winchester, J. W., S. M. Fan and S. M. Li (1988) Methane and nitrogen gases from rice fields of China—possible effects of microbiology, benthic fauna, fertilizer, and agricultural practice. Water, Air, & Soil Pollution, 37: 149-155.

Xiao, X. P., F. L. Wu, F. Q. Huang, Y. Li, G. F. Sun, Q. Hu, Y. Y. He, F. Chen and G. L. Yang (2007) Greenhouse air emission under different pattern of rice- straw returned to field in double rice area. Research of Agricultural Modernization, 28: 629-632 (in Chinese with English abstract).

Xu, H., Z. C. Cai and X. P. Li (2000) Effect of soil drying on CH_4 flux from rice paddy soil. Acta Pedologica Sinica, 37: 69-76 (in Chinese with English abstract).

Xu, H., Z. C. Cai and H. Tsuruta (2003) Soil moisture between rice-growing seasons affects methane emission, production, and oxidation. Soil Science Society of America Journal, 67: 1147-1157.

Xu, H. and Y. Hosen (2010) Effects of soil water content and rice straw incorporation in the fallow season on CH_4 emissions during fallow and the following rice-cropping seasons. Plant and Soil, 335: 373-383.

Xu, Y. C., Q. R. Shen, M. L. Li, K. Dittert and B. Sattelmacher (2004) Effect of soil water status and mulching on N_2O and CH_4 emission from lowland rice field in China. Biology and Fertility of Soils, 39: 215-217.

Yan, X. Y., H. Akiyama, K. Yagi and H. Akimoto (2009) Global estimations of the inventory and mitigation potential of methane emissions from rice cultivation conducted using the 2006 Intergovernmental Panel on Climate Change Guidelines. Global Biogeochemical Cycles, 23, GB2002, doi:10.1029/2008GB003299.

Yan, X. Y., Z. C. Cai, T. Ohara and H. Akimoto (2003) Methane emission from rice fields in mainland China: Amount and seasonal and spatial distribution. Journal of Geophysical Research-Atmospheres, 108, D16, 4505, doi:10.1029/2002JD003182.

Yan, X. Y., K. Yagi, H. Akiyama and H. Akimoto (2005) Statistical analysis of the major variables controlling methane emission from rice fields. Global Change Biology, 11: 1131-1141.

Yao, H., Y. B. Zhuang and Z. L. Chen (1996) Estimation of methane emission from rice paddies in mainland China. Global Biogeochemical Cycles, 10: 641-649.

Zhan, M., C. G. Cao, J. P. Wang, Y. Jiang, M. L. Cai, L. X. Yue and A. Shahrear (2011) Dynamics of methane emission, active soil organic carbon and their relationships in wetland integrated rice-duck systems in Southern China. Nutrient Cycling in Agroecosystems, 89: 1-13.

Zheng, X., M. Wang, Y. Wang, R. Shen, J. Gou, J. Li, J. Jin and L. Li (2000) Impacts of soil moisture on nitrous oxide emission from croplands: a case study on the rice-based agro-ecosystem in Southeast China. Chemosphere-Global Change Science, 2: 207-224.

Zou, J. W., Y. Huang, J. Y. Jiang, X. H. Zheng and R. L. Sass (2005) A 3-year field measurement of methane and nitrous oxide emissions from rice paddies in China: Effects of water regime, crop residue, and fertilizer application. Global Biogeochemical Cycles, 19, GB2021, doi:10.1029/2004GB002401 .

Zou, J. W., Y. Huang, L. G. Zong, Y. S. Wang and

R. L. Sass (2003) Integrated Effect of Incorporation with different organic manures on CH_4CH_4 and N_2ON_2O emissions from rice paddy. Chinese Journal of Environmental Science, 24: 7-12 (in Chinese with English abstract).