Antagonism of Methane and Nitrous Oxide Emissions in Asian Rice-Wheat Cropping Systems

Reiner Wassmann

Institute for Meteorology and Climate Research (IMK-IFU), Forschungszentrum Karlsruhe, Kreuzeckbahnstr. 19, 82467 Garmisch-Partenkirchen, Germany, tel.: -49-8821-183139, e-mail: reiner.wassmann@imk.ifu.de

Abstract:

The scope of this paper is to review the current state of knowledge on greenhouse gas (GHG) emissions from a singular, but very important production system, i.e. the rice-wheat system, that comprises 24 - 27 million ha in South and East Asia. Rice and wheat crops differ markedly in nature and intensity of flooding events and thus, in source strengths of methane and nitrous oxide. Wetland rice emits large quantities of methane; strategies to reduce methane emissions include proper management of organic inputs and temporary (mid-season) field drainage. Several of these management options, however, result in an increase of nitrous oxide emissions that would reduce – or even turn around – the intended positive effect on GHG emissions as a whole. In wheat production, the major GHG is nitrous oxide that is emitted in short-term pulses after fertilization, heavy rainfall and irrigation events. Moreover, nitrous oxide is also emitted in larger quantities during fallow periods and during the rice crop as long as episodic irrigation or rainfall result in aerobic-anaerobic cycles. In terms of Global Warming Potential, baseline emissions of the rice-wheat system primarily depend on the management practices during the rice crop while emissions from the wheat crop remain less sensitive to different management practices.

Keywords: GWP, irrigation, manure, organic residues, rice, wheat

1. Introduction

Agricultural production is a major source of greenhouse gases, namely CO_2, CH_4 and N_2O. While net-emissions of CO_2 are associated with long-term changes in soil organic carbon, this paper will assess the (short-term) impacts of different management practices on emissions of CH_4 and N_2O emissions for one of the most important agricultural production systems, i.e. the rice-wheat system. The rice-wheat belt in South and East Asia comprises 24 to 27 million ha of land cultivated with alternating rice and wheat crops (Ladha et al., 2002, Jiaguo, 2000). Millions people rely on food produced under this cropping system -- more than on any other individual food production system of the world. Over the past decades, the rice-wheat belt has experienced rapid development in the agricultural sector leading to very intensive land use in the vast part of the region.

The rice-wheat system is an especially apt example to illustrate the interaction of methane and nitrous oxide emissions because rice is generally grown in flooded fields whereas the succeeding wheat requires well-drained soil conditions. This divergence between the alternating crops could enable successive measures to reduce emission rates of both gases. On the other hand, the desired mitigation of emissions is compounded by complex interaction of the carbon and nitrogen budgets – net-savings in methane emissions often infer higher emissions of nitrous oxide emissions. Mitigation efforts, however, have to aim at full accounting of all greenhouse gases, so that possible off-sets in emission gains could render them ineffective.

2. Mitigation strategies

Options to reduce GHG emissions have to be seen against the specific conditions of the rice and wheat cultivation as well as the distinct mechanisms involved in the emissions of the different greenhouse gases, namely CH_4 and N_2O. Several strategies have been suggested including breeding of new cultivars (Wassmann and Aulakh, 2000; Denier van der Gon et al., 2002). Breeding efforts, however, can only be geared towards a medium- and long-term improvement of the production system. In contrast, this presentation addresses those strategies that could immediately be implemented from a technical point of view:

- Managing organic inputs
- Modifying irrigation patterns
- Adjusting fertilization/ amendments

2.1 Managing organic inputs

Methane emissions are generally enhanced by organic inputs into the soil such as straw or manure amendment. The increment in CH_4 emissions following organic inputs depends on quantity, quality and timing of the application (Yagi and Minami, 1990, Sass et al, 1991, Denier van de Gon, 2000). Rice straw and manure are typically applied before transplanting resulting in an emission peak during the first half of the growing season. High temperatures in the weeks following the incorporation of these materials result in a pronounced emission peak whereas low temperatures during this period diminish this peak (Wassmann et al., 2000a).

Incorporation of organic material also creates a pool of readily available N and therefore often stimulates N_2O emissions (e.g. Flessa and Beese, 1995; Lemke et al., 1999; Rolston et al., 1982). On the other hand, the observed increments in N_2O emissions were not as pronounced as for CH_4 emissions. In fact, there is some evidence that N_2O emissions from rice fields could even be reduced by high straw amendments (Abao et al., 2000, Zheng et al., 2000; Aulakh et al., 2001b), which may be explained by N immobilization (Aulakh et al., 2001a).

2.1.1 Fermentation of manure

Several field studies have compared different types of organic amendments in regard to CH_4 emissions. While the differences between fresh materials, either straw, animal manure or green manure, have been relatively small, field records showed a big disparity between emissions triggered by fresh and pre-fermented material (Yagi and Minami, 1990, Wassmann et al. 1993b, Corton et al. 2000). During the fermentation process, the pool of organic matter is rapidly depleted, so that incorporation of fermented material into the soil entails a lower emission potential. Applying residues from a biogas generator could reduce emissions by approximately 60 % as compared to fresh organic amendments and 52 % as compared to the locally practiced combination of urea and organic amendments (Wassmann et al., 1993b). The combustion of biogas will also save fossil fuel consumption, so that this mitigation option could be considered a win-win solution. Biogas generators are prevalent in China, especially in areas where swine husbandry is common. However, practical problems in operating this device, especially during the cold winter months, pose considerable constraints on its propagation as long as other sources of energy are available.

Composting of organic inputs may offer another agricultural practice that could reduce GHG emissions (Yagi and Minami, 1990, Corton et al., 2000). Moreover, compost application results in very low N_2O emissions during the rice crop that are app. 50 % lower than the emissions from rice fields treated with urea (Zheng et al., 2000). However, methane emissions during anaerobic composting process could counterbalance gains observed after the incorporation into the soil. These emissions during composting can be reduced to a great extent through aerobic composting techniques. Organic amendments derived from aerobic composting of rice straw significantly reduced emissions as compared to fresh straw (Corton et al., 2000).

2.1.2 Adjusting straw incorporation

Crop production inevitably results in large amounts of straw residues that are typically left in the fields. Since the application of organic manure is gradually decreasing, rice soils largely rely on recycling of straw to compensate for carbon losses through soil cultivation and crop harvest (Verma and Bhagat, 1992, Witt et al., 1998). Straw is often burnt to prepare the field for the next cropping cycle; especially the wheat straw is burnt almost all over the Asian rice-wheat belt (Ladha et al., 2000). Removal or burning of residues insures farmers quick seedbed preparation and avoids the risk of N immobilization during decomposition of residues with wide C:N ratio (Beri et al., 1995). Incomplete combustion of carbon – which is generic to smoldering fires of harvest residues – generate substantial amounts of carbon monoxide (CO) and other pollutants and thus, have adverse effects on local air quality. Fire-borne organic compounds and nitrogen oxides lead to tropospheric ozone formation; high ozone concentrations coincide with the peak of the residue-burning season in Asia. Moreover, the burning process also releases methane and nitrous oxide into the atmosphere.

Methane emission rates become very sensitive to the mode of straw management as long as the level of carbon input into the soil is low. If straw is not burnt, the conventional method of straw amendment consists of plowing the straw into the soil before transplanting. Some farming systems within the rice-wheat belt encompass a long winter fallow, e.g. before the early rice crop in China, and therefore, allow alternative timings of straw incorporation. In a field experiment in Hangzhou, Zhejiang Province, the conventional mode of straw incorporation during spring was tested against an early straw incorporation at the start of the winter fallow (Lu et al., 2000). This early incorporation had no effect on emissions in the first part of the early season when temperatures are low and emissions are also on a low level. However, winter fallow incorporation resulted in lower emissions during the latter stage of this season so that seasonal emissions were reduced by 11%. Similarly incorporation of crop residues during pre-rice 60-day fallow period did not increase N_2O emissions and also did not decrease rice yields.

2.2 Modifying irrigation patterns

Under prevailing wetland conditions in rice fields, farmers have options to reduce CH_4 emissions through distinct drainage periods in mid-season or alternate wetting and drying of the soil (Sass et al., 1992, Wassmann et al., 2000b). However, the reductions achieved through alternative irrigation practices varies in a very broad range from 7 to 80 % and imply a number of constraints due to an inverse effect on N_2O emissions. Changes in the soil moisture regime stimulate nitrification (through soil drying) and denitrification (through soil wetting) and thus, enhance emissions of N_2O (Bronson et al., 1997a, 1997b; Zheng et al., 1997, Abao et al, 2000).

2.2.1 Mid-season drainage

This irrigation practice encompasses a distinct period of ca. one week when irrigation is interrupted. Methane emission rates show a short-term peak at the beginning of soil aeration due to the release of soil-entrapped methane that is followed by persistently low emissions even when the fields are flooded again. A properly timed mid-season drainage appears as a promising option to achieve net-gains in greenhouse gas emissions when the baseline of CH_4 emissions is very high (Wassmann et al., 2000b). In low CH_4-emitting rice systems, however, the net effect of modifying water regimes may in fact become negative in terms of GWP of the gases emitted (Bronson et al., 1997b, Tölg, 1998).

Emissions are very sensitive to duration and timing of the drainage period, so that this management practice may further be improved to reduce emissions, especially in areas where the general concept of mid season drainage is already known as a successful agronomic practice by some farmers. Mid-season drainage, however, is not feasible during periods of heavy rainfall and therefore, has limited applicability in time and space.

2.2.2 Alternate flooding/ drying

This water regime refers to alternate flooding and aeration (drying) of the soil throughout the vegetation period. Methane emissions in these systems, e.g. in Northern India, are generally very low, but N_2O emissions from this system vary in a broad range. Mean seasonal emission range from ca. 250 g N_2O ha^{-1} recorded by Kumar et al. (2000) in New Delhi to 6.9 to 12.4 kg N_2O-N ha^{-1} in Punjab (Aulakh et al., 2001b). In contrast to mid-season drainage, the time intervals between wet and dry conditions appear to be too short to facilitate the shift from aerobic to anaerobic soil conditions.

2.3 Adjusting fertilization/ amendments

Even under the best possible fertilization practice, substantial amounts of the N applied to the field are emitted to the atmosphere. In irrigated rice, gaseous losses of N may account for up to 48 % of the N applied (Reddy and Patrick, 1980). The principal mechanisms responsible for gaseous N losses are (a) ammonia volatilization, (b) denitrification (leading to emission of N_2, NO and N_2O), and (c) nitrification (leading to emission of NO and N_2O). The specific significance of these processes may vary depending on crop management as well as natural factors (Freney, 1997).

2.3.1 Matching N supply with demand

A generic strategy to reduce N losses – and thus, to reduce N_2O emissions – is avoiding excesses N in space and time. Several field experiments recorded an instant increase in N_2O emissions triggered by N fertilizer application in rice and wheat fields (Eichner, 1991, Bouwman, 1995). In contrast to the IPCC methodology that defines a default value of 1.25 % (of the added N) is emitted into the atmosphere, the actual fertilizer losses in form of N_2O vary in a broad range from 0.001 to 6.8 % (Freney, 1997; Aulakh et al., 2001b).

Nitrogen use efficiency can significantly be enhanced through splitting of N application. Ideally, the time-dependent N demand of the crop is determined through leaf color via color chart or photometer. The consequent use of site-specific nutrient management in irrigated rice can increase yields by about 10 % as compared to conventional practice as shown in eight key irrigated rice domains of Asia (Dobermann et al., 2002). N_2O emissions have not been recorded in these field experiments, but gains in emissions can be inferred from other experiments in subtropical regions (Matson et al., 1998).

2.3.2 Selecting fertilizer/ amendment

Comparing urea and ammonium sulphate, Cai et al. (1997) showed that the latter released more N_2O than urea. Tablet urea placed into the soil entailed higher N_2O flux rates than broadcasting of granule urea (Suratno et al., 1998). High sulfate levels inhibit CH_4 formation in anaerobic systems due to the substrate competition between sulfate reducing and methanogenic bacteria (Winfrey and Zeikus, 1977). Hence, the use of sulfate-containing fertilizers as well as additional sulfate inputs has been found to reduce CH_4 emission from rice fields. Under field conditions, for example, Schütz et al. (1989) observed that CH_4 fluxes from $(NH_4)_2SO_4$ treated plots were lower as compared to urea fertilized control plots in an Italian rice field over a 3-year period, and were 6, 43 and 62 % lower when $(NH_4)_2SO_4$ was surface applied. Bronson et al. (1997a) reported that seasonal CH_4 flux with $(NH_4)_2SO_4$ fertilizer was one third to one fourth of the flux with urea. Cai et al. (1997) observed 42 and 60 % decrease in average CH_4 emission from rice fields treated with 100 and 300 kg N ha^{-1} as $(NH_4)_2SO_4$. In other locations, however, the impact of sulfate fertilizers on CH_4 emission was marginal (Wassmann et al., 1993a) or even showed a stimulating effect (Cicerone and Shetter, 1981).

Different cost levels for sulfate-containing fertilizers affect cost-benefit calculations of this mitigation option. Provided the proper target areas are selected, the costs for mitigating CH_4 emissions through sulfate-containing fertilizer are estimated at 5-10 US dollar per ton CO_2-equivalent (Denier van der Gon et al., 2001).

Gypsum ($CaSO_4$) inputs into the soil reduced CH_4 emissions by 29 to 46 % in field study in Louisiana (Lindau et al., 1993) and by 55 to 70 % in the Philippines (Denier van der Gon and Neue, 1994). Gypsum application can be beneficial to neutralize the pH of alkaline soils. In the rice-wheat belt, gypsum application may offer some potential to combine the purposes of improving soil fertility and mitigating emissions. Several million hectares of the Indo-Gangetic plains are alkaline soils (Abrol et al., 1985). In China, acidity of rainwater is increasing as consequence of higher atmospheric NO_x and SO_2 concentrations demanding for more liming in soils with low buffer capacity.

3. Conclusion

Mitigation options in the rice-wheat system may individually be of limited scope, but they could achieve a discernable composite effect when implemented in coordinated fashion. Mitigation programs will rely on win-win opportunities when emissions can be reduced with another concomitant benefit such as higher yields, less fertilizer and water needs etc. Spatial heterogeneity of the rice-wheat system entails hot spots of emissions favoring mitigation programs with a regional focus. Targeting one individual gas alone seems inappropriate due to antagonistic effects in the emissions of CH_4, N_2O and CO_2. More research is needed to combine geographic information, emission models, yield models and socio-economic information to devise site-specific packages of mitigation technologies.

4. References

Abao, E.B. Jr., Bronson, K.F., Wassmann, R., and Singh, U.: 2000, 'Simultaneous records of methane and nitrous oxide emissions in rice-based cropping systems under rain fed conditions', *Nut. Cycling in Agroecosystems* **58**,131-139.

Abrol, I. P., Bhumbla, D. R., and Meelu, O. P. (1985). Influence of salinity and alkalinity on properties and management of ricelands. In "Soil Physics and Rice", pp. 183-198. International Rice Research Institute, Los Banos, Philippines.

Aulakh, M.S., T.S. Khera, J.W. Doran, and Bronson, K.F.: 2001a, Managing crop residue with green manure, urea, and tillage in a rice - wheat rotation. *Soil Sci. Soc. Am. J.* **65**: 820-827.

Aulakh M.S., Khera, T.S., Doran, J.W., and Bronson, K.F.: 2001b, 'Denitrification, N_2O and CO_2 fluxes in rice-wheat cropping system as affected by crop residues, fertilizer N and legume green manure, *Biol. Fert. Soils* **34**, 375-389 .

Beri, V., Sidhu, B.S., Bahl, G.S., and Bhat, A.K.: 1995, Nitrogen and phosphorus transformations as affected by crop residue management practices and their influence on crop yields. *Soil Use Management* **11,** 51-54.

Bouwman, A.F.: 1995, *Compilation of a global inventory of emissions of nitrous oxide*, PhD-Thesis, Landbouwuniversiteit Wageningen.

Bronson, K.F., Neue, H.U., Singh, U., and Abao, E.B. Jr.: 1997a, 'Automated chamber measurements of methane and nitrous oxide flux in a flooded rice soil: I. Residue, nitrogen and water management', *Soil Sci. Soc. Am. J.* **61**, 981-987.

Bronson, K.F., Neue, H.U., Singh, U., and Abao, E.B. Jr.: 1997b, 'Automated chamber measurements of methane and nitrous oxide flux in a flooded rice soil: II. Fallow period emissions', *Soil Sci. Soc. Am. J.* **61**, 988-993.

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

Cicerone, R.J. and Shetter, J.D.: 1981, 'Sources of atmospheric methane: Measurements in rice paddies and a discussion', *J. Geophys. Res.* **86,** 7203-7209.

Corton, T.M., Bajita, J., Grospe, F., Pamplona, R., Wassmann, R., and Lantin, R.S.: 2000, 'Methane emission from irrigated and intensively managed rice fields in Central Luzon (Philippines)', *Nutrient Cycling Agroecosystems* **58**, 37-53.

Denier van der Gon H.A.C. and Neue H.U.: 1994, 'Impact of gypsum application on the methane emission from a wetland rice field', *Global Biogeochemical Cycles* **8**, 127-134.

Denier van der Gon HAC (2000) Changes in CH4 emission from rice fields from 1960 to 1990s: 1. The declining use of organic inputs in rice farming. Global Biogeochemical Cycles **13**, 1053-1062.

Denier van der Gon H.A.C., van Bodegom. P.M., Wassmann, R., Lantin, R.S., Metra-Corton T.: 2001, 'Assessing sulfate-containing soil amendments to reduce methane emissions from rice fields: Mechanisms, effectiveness and costs', *Mitigation and Adaptation Strategies for Global Change* **6**, 69-87.

Denier van der Gon, H.A.C., Kropff, M.J., van Breemen, N., Wassmann, R., Lantin, R.S., Aduna,E.A., Metra-Corton, T., and van Laar, H.H.: 2002, 'Optimising grain yields reduces CH_4 emissions from rice paddy fields' *Proceedings of the National Academy of Sciences USA* **99**, 12021-12024.

Dobermann, A., Witt, C., Dawe, D., Abdulrachman, S., Gines, H.C., Nagarajan, R., Satawathananont, S., Son, T.T., Tan, P.S., Wang, G.H., Chien, N.V., Thoa, V.T.K., Phung, C.V., Stalin, P., Muthukrishnan, P., Ravi, V., Babu, M., Chatuporn, S., Sookthongsa, J., Sun, Q., Fu, R., Simbahan, G.C., Adviento, M.A.A.: 2002, 'Site-specific nutrient management for intensive rice cropping systems in Asia', *Field Crop Res* **74**, 37-66

Eichner, M.J.: 1991, 'Nitrous oxide emissions from fertilizer soils: Summary of available data', *Journal of Environmental Quality* **19**, 272-80.

Flessa, H. and Beese, F.: 1995, 'Effects of Sugarbeet Residues on Soil Redox Potential and Nitrous Oxide Emission'. *Soil Sci. Soc. Am. J.* **59**, 1044-1051.

Freney J.R.: 1997, 'Emission of nitrous oxide from soils used for agriculture', *Nutrient Cycling in Agroecosystems* **49**, 1-6.

IPCC (Intergovernmental Panel on Climate Change): 1995, *IPCC Guidelines for national greenhouse Gas Inventories*, Vol II (Workbook), Hadley Centre Meteorological Office, Bracknell (UK).

Jiaguo, Z.: 2000, 'Rice-wheat cropping system in China', in: Hobbs, P.R. and Gupta, R.K. (eds.) *Soil and crop management practices for enhanced productivity of the rice-wheat cropping system in the Sichuan province of China*, Rice-Wheat Consortium Paper Series 9, New Delhi India, pp 1-10.

Kumar, U.; Jain, M.C.; Pathak, H.; Kumar, S.; Majumdar, D.: 2000, 'Nitrous oxide emission from different fertilizers and its mitigation by nitrification inhibitors in irrigated rice', *Biology and Fertility of Soils* **32**, 474 - 478.

Ladha, J.K., Fischer, K.S., Hossain, M., Hobbs, P.R., Hardy, B. (eds.): 2000, *Improving the Productivity and Sustainability of Rice-Wheat Systems of the Indo-Gangetic Plains*, Discussion Paper 2000, No. 40, IRRI, Philippines. pp. 31.

Ladha, J.K., Pathak, H., Padre, A.T., Dawe, D., Gupta, R.K.: 2002, Productivity trends in intensive rice-wheat systems in Asia, in J.K. Ladha (ed.) *Improving the productivity and sustainability of rice-wheat systems: issues and impact*. ASA, Spec. Publ. ASA Madison, WI. (in press).

Lemke, R.L., Izaurralde, R.C., Nyborg, M. and Solberg, E.D.: 1999, 'Tillage and N source influence soil-emitted nitrous oxide in the Alberta Parkland region', *Can. J. Soil Sci.* **79**, 15-24.

Lindau, C.W., Bollich, P.K., Delaune, R.D., Mosier, A.R., and Bronson, K.F.: 1993, 'Methane mitigation in flooded Louisiana rice fields' *Biol. Fert. Soils* **15**, 174-178.

Matson, P.A., Naylor, R. and Ortiz-Monasterio, I.: 1998, 'Integration of environmental, agronomic and economic aspects of fertilizer management', *Science* **280,**112-115.

Reddy, K.R., and Patrick, Jr., W.H.: 1980, 'Losses of applied 15NH4-N urea 15N, and organic 15N in flooded soils', *Soil Sci.* **130,** 326-330.

Rolston, D.E., Sharpley, A.N., Toy, D.W. and Broadbent, F.E. 1982. Field Measurment of Denitrification: III. Rates During Irrigation Cycles. *Soil Sci. Soc. Am. J.* **46**, 289-296.

Sass, R.L., Fisher, F.M., Turner, F.T., and Jund, M.F.: 1991, 'Methane emissions from rice fields as influenced by solar radiation, temperature, and straw incorporation', *Global Biogeochem. Cycles* **5,** 335-350.

Sass, R.L., Fisher, F.M., Wang, Y.B., Turner, F.T., and Jund, M.F.: 1992, 'Methane emission from rice fields: the effect of flood water management', *Global Biogeochem. Cycles* **6**, 249-262.

Schütz, H., Holzapfel-Pschorn, A., Conrad, R., Rennenberg, H., and Seiler, W.: 1989, 'A 3-year continuous record on the influence of daytime, season and fertilizer treatment on methane emission rates from an Italian rice paddy', *J. Geophys. Res*. **94**, 16,405-16,416

Suratno**,** W., Murdiyarso, D.**,** Suratmo, F.G., Anas, I., Saeni, M.S., Rambe, A.: 1998. 'Nitrous oxide emission from irrigated rice fields in West Java', *J. Environ. Pollution.* **102**, 159-166.

Tö lg, M.: 1998, *'Einfluß von Bewirtschaftungsmaßnahmen auf Produktion und Emission von Methan im Naßreisanbau',* PhD Thesis (in German), Schriftenreihe des Fraunhofer-Instituts für Atmosphärische Umweltforschung, Bd. 50, Garmisch-Partenkirchen, Germany, pp. 239.

Verma, T.S. and Bhagat, R.M.: 1992, 'Impact of rice straw management practices on yield, nitrogen uptake, and soil properties in a wheat-rice rotation in northern India',. *Fert. Res.* **33**, 97–106.

Wassmann, R., Schütz, H., Papen, H., Rennenberg, H., Seiler, W., Dai, A.G., Shen, R.X., Shangguan, X.J., Wang, M.X.: 1993a, 'Quantification of methane emissions from Chinese rice fields (Zhejiang Province) as influenced by fertilizer treatment', *Biogeochemistry* **11**, 83-101.

Wassmann, R., Wang, M.X., Shangguan, X.J., Xie, X.L., Shen, R.X., Papen, H., Rennenberg, H., Seiler, W.: 1993b, 'First records of a field experiment on fertilizer effects on methane emission from rice fields in Hunan Province (PR China)', *Geophysical Research Letters* **20**, 2071-2074.

Wassmann, R., Neue, H.U., and Lantin, R.S.: 2000a, 'Characterization of methane emissions from rice fields in Asia. 1. Comparison among field sites in five countries', *Nut. Cycling Agroecosystems* **58**, 1-12.

Wassmann, R., Lantin, R.S., Neue, H.U., Buendia, L. V., Corton T.M., and Lu, Y.H.: 2000b, Characterization of methane emissions from rice fields in Asia. 3. Mitigation options and future research needs', *Nut. Cycling Agroecosystems* **58**, 23-36.

Wassmann, R and Aulakh, M.S.: 2000, 'The role of rice plants in regulating mechanisms of methane missions', *Biol. Fertil. Soils* **31**, 20-29.

Winfrey, M.R. and Zeikus, J.G.: 1977, 'Effect of sulfate on carbon and electron flow during microbial methanogenesis in fresh water sediments', *Appl. Environ. Microbiology* **33**, 275-281.

Witt, C., Cassman, K.G., Ottow, J.C.G., Biker, U.: 1998, 'Soil microbial biomass and nitrogen supply in an irrigated lowland rice soil as affected by crop rotation and residue management', *Biol. Fertil. Soils* **28**, 71–80.

Woodhead, T., Huke, R., Huke, E.: 1994a, *Rice-wheat atlas of Pakistan*. IRRI/CIMMYT/PARC publication, Los Baños (Philippines), pp. 1-32.

Yagi, K. and Minami, K.: 1990, 'Effect of organic matter application on methane emission from some Japanese paddy fields', *Soil Sci. Plant Nut.* **36**, 599-610.

Zheng, XH; Wang, MX; Wang, YS; Heyer, J; Kogge, Papen, H., Jin, JS; Li, LT.: 1997, 'N_2O and CH_4 emissions from rice paddies in Southeats China.' *Chinese Journal of Atmospheric Sciences* **21**, 167-174.

Zheng, XH; Wang, MX; Wang, YS; Shen, RX; Li, J; Heyer, J; Kogge, M; Papen, H; Jin, JS; Li, LT.: 2000, Mitigation options for methane, nitrous oxide and nitric oxide emissions from agricultural ecosystems, *Advances in Atmospheric Sciences* **17**, 83-92.