Methane emission and rice agriculture

A great deal of evidence has accumulated showing that rice agriculture resulted in an increased emission of methane to the atmosphere. The reasons for the interest in methane are that (i) CH_4 is an important energy source, representing a clean and potentially economic alternative fuel[1], (ii) CH_4 has a global warming potential of about 24.5 relative to CO_2, and is responsible for approximately 25% of the anticipated warming[2]. The mixing ratio of CH_4 has been increasing and has reached a level of 1.8 ppmv in the atmosphere[3]. Over the past 20 years, CH_4 growth rate has declined; in the late 1970s, the concentration was increasing by about 20 ppbv yr^{-1}, and during the 1980s, the growth rate dropped to 9–13 ppbv yr^{-1}. Around the middle of 1992, CH_4 concentration briefly stopped growing but since 1993, the global growth rate has returned to about 8 ppbv per year[4]. Dlugokencky *et al.*[5] also reported that the rate of increase of methane concentration has slowed down in the last decade. Atmospheric CH_4 originates mainly from biogenic sources, such as rice paddies and natural wetlands. The rice paddies account for 15–20% of the world's total anthropogenic CH_4 emission[6].

Mechanistically, methane produced by methanogenesis in the soil (an energy-transformation process, mediated by methanogens at a soil redox potential lower than –140 to –160 mV) is transported to the atmosphere by molecular diffusion, ebullition or plant-mediated transport. More than 90% of methane released from rice soil to the atmosphere is emitted via the rice plant[7]. Well-developed intercellular air spaces in leaf blades, leaf sheaths, culm and roots of rice plant provide an efficient gas-exchange medium between the atmosphere and the anaerobic soil. CH_4 dissolved in soil water surrounding the rice root diffuses into the cell wall-water of the root cells, gasifies in the root cortex and is transported in the gaseous state to the shoots via aerenchyma[8]. In addition to the role of rice plant in CH_4 emission, it also plays a significant role in CH_4 oxidation[9] because O_2 transported below the ground by plants, leaks out of the rhizosphere into the sediments, stimulating CH_4-oxidizing activity. Thus rice plants influence the methane dynamics in paddy soil by (1) providing substrate in the form of root exudates to methanogens and thus enhance the production of CH_4; (2) transporting CH_4 from soil to atmosphere (conduit effect), and (3) creating aerobic microhabitat in rhizosphere, which is suitable for growth and multiplication of methanotrophic bacteria[9].

Considering the ecological and economical importance, rice ranks second to wheat in terms of area harvested, but in terms of importance as a food crop, rice provides more calories (accounts for 21% of the total energy content of the world's food) per hectare than any other cereal crop[10]. To feed the increasing global human population, the world's annual rice production must increase from the present 528 million ton to 760 million ton by the year 2020 (ref. 11). According to a current estimate, rice agriculture will expand by up to 70% over the next 25 years. However, intensified global fertilizer application will be necessary. This is expected to exacerbate the CH_4 problem in the future[12]. There are three major types of rice cultivation: dryland (rainfed) rice, irrigated rice and flooded (deep-water) rice. Globally, 60% of the harvested area is managed under a triple cropping, 15% is double cropped and 25% is cropped once a year[13]. The world area under rice cultivation was only 104 million ha in 1951 and has increased to 148 million ha in 1993 (ref. 14). Upland rice covers 17 million ha, but does not have anaerobic conditions that are essential for methanogenesis. Wetland rice covering 131 million ha area includes irrigated (53.4%), rainfed (27.3%) and deep-water (7.7%) rice systems[14]. Irrigated rice accounting for approximately 50% of total harvested rice area contributes about 70% towards total rice production. Most of the CH_4 emitted from rice fields is expected to be from the Asian region as it has 90% of the total world rice harvested area, out of which about 52% is in China and India[15]. Recent results indicated that the CH_4 release per m^2 and per year from different rice ecosystems follows the order: deep-water rice > irrigated rice > rainfed rice[12]. The estimation of CH_4 budget from Indian paddy fields is of special significance as India has an area of about 42.2 m ha under rice cultivation. Of the above, only 16.4 m ha is irrigated; of the remaining area under rainfed conditions, 5.9 m ha is upland and 19.7 m ha is lowland. On the basis of extrapolation of measurements conducted in Europe and USA, the USEPA attributed 37.8 Tg CH_4 yr^{-1} to Indian paddies, which is one order of magnitude more than the estimates for India. A national methane measurement campaign in India yielded a range of CH_4 flux values between -0.20 and 3.6 mg m^{-2} h^{-1} for irrigated, intermittently-flooded rice fields, 0.04–66 mg m^{-2} h^{-1} for flooded fields and between 1.1 and 23.3 mg m^{-2} h^{-1} for deep-water regimes[16]. The uncertainty in these estimates is caused by scarcity of flux measurements, gaps in the knowledge of rice ecologies, the impact of soil types, crop management and lack of data on *in situ* CH_4 oxidation.

Several investigations have demonstrated that CH_4 flux in rice fields is affected by rice varieties[17–19], water level[20], fertilizer application[18,21] and crop phenology[20,21]. As far as ammonium-based fertilizer application is concerned, it has been a common assumption that it enhances the CH_4 emission due to increasing soil pH that stimulates methanogens. Most of the workers have argued that increase in CH_4 emission by rice plants in response to heavy fertilization would be a function of increased biomass production and carbon availability[20–22]. Since all known methanogens use NH_4^+ as nitrogen source[23], the stimulatory effect of ammonium-based fertilizer on CH_4 production is not surprising. Contrary to the above findings, Bodelier *et al.*[24] have found that CH_4 emission decreased by 57% after application of ammonium-based fertilizer. They argued that the increased CH_4 oxidation may be a reason for this reduction. This study also suggested that the NH_4^+-based fertilizer stimulates methane oxidation. This phenomenon may dominate the overall response of CH_4 cycling to fertilization in rice paddy ecosystems.

Because rice agriculture is one of the few sources of CH_4 where emission reduction through management is considered possible, it promises to be a critical focus of mitigation efforts. Possibilities for reducing CH_4 emission in flooded rice field were evaluated in the National Inventories of CH_4 and N_2O Workshop[25]. The upshots regarding principles were (1) yield should not be decreased and probably increased by a mitigation practice; (2) there should be some additional benefit to the farmer, i.e. better water utilization or reduction of labour; (3) rice varieties used should be desired by local consumers; and (4) mitigation practices should not increase emission of other greenhouse gases, particularly N_2O. There is an urgent need, therefore to find feasible methods for mitigating CH_4 emission in the paddy fields. Strategies to mitigate CH_4 emission from paddy soils of the world have been identified. They include (1) form and dose of nitrogen and other chemical fertilizers; (2) the mode of fertilizer application; (3) water management; and (4) cultivation practices. The mitigation option should be selected according to local circumstances because climate, type of paddy field and cultivation practices differ from place to place. Strategies consisted of a number of specific methods to be applied under field conditions. Recent research has begun to identify various mitigation options that could reduce CH_4 emission from paddy fields. They are (a) direct seeding of paddy crop is an option to minimize production cost, while reducing CH_4 emission; (b) intermittent irrigation is an option for minimizing CH_4 emission; (c) soil amendment with sulphate-containing fertilizer reduces CH_4 emission from paddy fields owing to inhibitory effect of SO_4^- ions; and (d) in comparison to fresh organic matter compost addition is very effective in reducing CH_4 emissions for irrigated rice fields. In dryland rice (characterized by low CH_4 emission potential and high CH_4 oxidation potential), mitigation options may be ineffective. Soil aeration in dryland rice will become less frequent with the projected improvement of irrigation facilities, entailing a higher CH_4 source strength of this rice ecology within the next decade[22]. Flooded rice has greater potential for CH_4 emission compared to dryland rice owing to continuous flooding; however CH_4 emission rates are considerably lower than in irrigated rice[22].

In conclusion, a comprehensive strategy could meet both goals for sustainable rice productivity and reduction in CH_4 emission. I see the following research needs: (1) Developing accurate statistics on paddy cultivation area distribution, flooding duration and depth, which are important parameters among various factors influencing CH_4 production and emission. (2) Associating individual mitigation options that can potentially minimize CH_4 emissions in an acceptable manner. (3) Devising an infrastructure that envisages site-specific settings of natural and socio-economic factors. (4) Ascertaining interactions of the CH_4 budget of paddy fields with nitrogen dynamics. (5) Selecting newly-developed cultivars on the basis of their 'methane transport capacity'. (6) Developing knowledge on physiological and morphological characteristics of rice plants in relation to their dual nature in gaseous exchange, which is useful in mitigating CH_4 emission. (7) Detailed study of the measurement of CH_4 oxidation in rice rhizosphere, in order to understand the 'mechanistic basis' of CH_4 turnover in rice field and to develop strategies to enhance the CH_4 oxidation potential.

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S. K. DUBEY

Ecosystems Analysis Laboratory,
Department of Botany,
Banaras Hindu University,
Varanasi 221 005, India
e-mail: dskbhu@rediffmail.com