Chapter 4

Nitrous oxide emission from rice and rice based production system and its mitigation strategy

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Nitrous oxide (N_2O), with a global warming potential of 298 times more than the carbon dioxide (CO_2) and longer atmospheric lifetime (approximately 120 years) is an important green house gas (GHG) and accounts for about 19% of total global warming effect. Apart from being a major GHG, it is an important air pollutant. On reaction with oxygen, N_2O gives rise to nitric oxide (NO), and NO in turn reacts with ozone, as a result, it is the main naturally occurring regulator of stratospheric ozone. Global average atmospheric concentrations of N_2O have increased from about 270 parts per billion by volume (ppbv) in 1750 to 314 ppbv in 1998, which equates to a 16% increase for the period. In the last two decades, atmospheric concentrations of N_2O continue to increase at a rate of 0.25% per year (IPCC, 2007).

Rice is the main source of food for about half of the world's population. It is cultivated in more than hundred countries. Rice along with wheat and maize accounts for about 60% of total global N consumption, irrigated rice alone consumes about 8 to 9 million tons of fertilizer N annually, which is about 10% of total N production in the world. In general, in Asia 60-150 kg N ha^{-1} is applied per crop but because of poor N recovery efficiency (30-40% even lower) most of the N is lost through various mechanisms like volatilization, denitrification and leaching. Hence, rice systems are major contributor to the accumulation of reactive N compounds in the environment and significant source of emission of N_2O to the atmosphere.

Sources of nitrous oxide

TABLE 1. *Global nitrous oxide emission (Tg N yr^{-1}) from different sources (Adopted from Denman et al., 2007)*

Sources	N_2O emission (Tg N yr^{-1})
Natural	11
Soil	6.6 (3.3–9.0)
Ocean	3.8 (1.8–5.8)
Atmospheric chemistry	0.6 (0.3–1.2)
Anthropogenic	6.7
Energy, industry, biomass burning	2.0 (0.7–3.7)
Agriculture	4.7 (2.3–8.0)
Total	17.7 (8.5–27.7)

Denman et al. (2007)

Nitrous oxide in atmosphere is produced both from natural and anthropogenic sources. Natural emissions of N_2O primarily results from bacterial breakdown of nitrogen in soils and in the earth's oceans. Based on the available data globally (Table 1), soils covered by natural vegetation are estimated to produce 6.6 Tg of N_2O annually and oceans are thought to add around 3.8 Tg of N_2O annually to the atmosphere. Together, these two sources account for about 60% of the natural sources. Whereas anthropogenic activities like agricultural soil management, fossil fuel combustion, nitric acid production, livestock manure management, human sewage, adipic acid production, etc., are responsible for about 30% of total N_2O emission; apart from that anthropogenic activities are the main driver behind the N_2O emission from oceans and estuaries through their contribution of nitrogen to water bodies, however exact quantification of that contribution is not available. Many microbiological, chemical, physical factors affect the emission and a complex interaction among them makes the extrapolation of global budget uncertain and difficult.

Contribution of agriculture to global nitrous oxide emission

Agriculture directly and indirectly contributes significantly to global N_2O emission. There are considerable differences (65-96%) in the estimated share of agriculture in total anthropogenic source of N_2O emission (Mosier et al., 1998; Bouwman et al., 2002; Denman et al., 2007). There are three distinguished sources of agricultural N_2O emission: direct N_2O emissions from fertilized agricultural soils, direct N_2O emissions from animal production and indirect N_2O emissions from nitrogen (N) used in agriculture (Mosier et al., 1998). Recently Syakila & Kroex (2011) estimated the N_2O emission from agriculture (Table 2) using revised emission factor from the IPCC 2006 guidelines (IPCC, 2006) and observed, the share of agriculture to the total anthropogenic source is 60%, lower than the earlier estimation of 80% in 1999 budget (Kroeze et al., 1999).

TABLE 2. *Global nitrous oxide emission (Tg N yr^{-1}) from agriculture in 2006 as estimated following IPCC 2006 guidelines*

Direct emission from agriculture	N_2O (Tg N yr^{-1})
Synthetic fertilizer	0.9
Animal waste	0.4
Biological N_2 fixation	0.1
Crop residue	0.3
Cultivated Histosol	0.1
Total	1.8
Animal production	
Animal waste management system	2.3
Indirect emissions	
Atmospheric deposition	0.4
Nitrogen leaching and runoff	0.6
Human sewage	0.3
Total	1.3
Total emission from agriculture	5.4

Emission of nitrous oxide from rice and rice based production systems

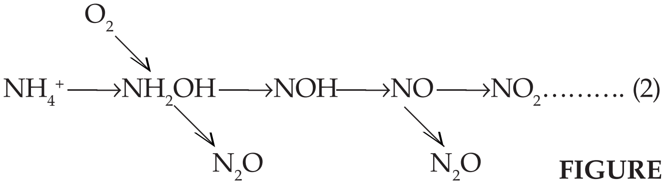
Rice is grown in a wide range of environments under diversified management practices. In general there are three major rice production systems: irrigated rice production systems, rainfed low land and rainfed upland production systems. Each system is different from the other with respect to varieties grown, methods of cultivation and soil and water management practices followed. Irrigated rice is grown in bunded fields with ensured irrigation for one or more crops a year; so that 5–10 cm of water can be maintained in the field. Irrigation is the main source of water in the dry season and is used to supplement rainfall in the wet season. In many humid tropical and subtropical areas, irrigated rice is grown as a monoculture with two or even three crops a year. Significant areas of irrigated rice are also grown in rotation with a range of other crops, including about 20 million ha of rice-wheat systems. Rainfed lowland rice is grown in bunded fields that are flooded with rainwater for at least part of the cropping season. Rainfed rice environments experience multiple abiotic stresses and high uncertainty in timing, duration, and intensity of rainfall. Up to 25% of total lowland areas suffer from uncontrolled flooding, ranging from flash floods of relatively short duration to deepwater areas that may be submerged under more than 100 cm of water for a few months. Widespread incidence of problem soils with poor physical and chemical properties is the constraints of production in this environment. Because of the environment prevailed, the farmers rarely apply fertilizer to the rice crop. Rainfed upland rice is grown under dryland mostly under direct seeded conditions. Upland environments are highly variable with respect to climate, soils type, and topography. Since rice production systems vary widely in their macro and micro environment, each system has its unique effect on carbon nitrogen dynamics in soil-plant-atmosphere continuum and hence there is wide spread variation in N_2O emission.

Mechanisms involved in production of nitrous oxide from rice field

Rice fields remain submerged for most part of the season. Presence of both aerobic and anaerobic layer, alternate wetting and drying cycles makes the rice production system a unique system in which both aerobic and anaerobic nitrogen metabolism take place in close proximity and with tight linkage. Unique physical, chemical and microbiological character of rice soil affects the N transformation process and emission of N_2O in different way than that observed in aerobic soil. Nitrous oxide is a byproduct of both denitrification and nitrification processes in soil. Nitrification is the main source of N_2O under aerobic conditions, while denitrification dominates under flooded rice fields. Denitrification is the microbial reduction of nitrate or nitrite form of N to dinitrogen or N oxides under anaerobic condition and presented as

$$NO_3^- \longrightarrow NO_2^- \longrightarrow NO \longrightarrow N_2O \longrightarrow N_2 \qquad \text{.........} (1)$$

Nitrification is the process of oxidation of ammonium form of N to nitrite or nitrate form and also responsible for the emission of N_2O from soil, though, the exact biochemical pathway of N_2O generation via nitrification is not clear. A series of path ways for the formation of N_2O via the intermediate compounds NH_2OH or NO has been proposed (Ritchie & Nicholas, 1972; Naqvi & Noronha, 1991).

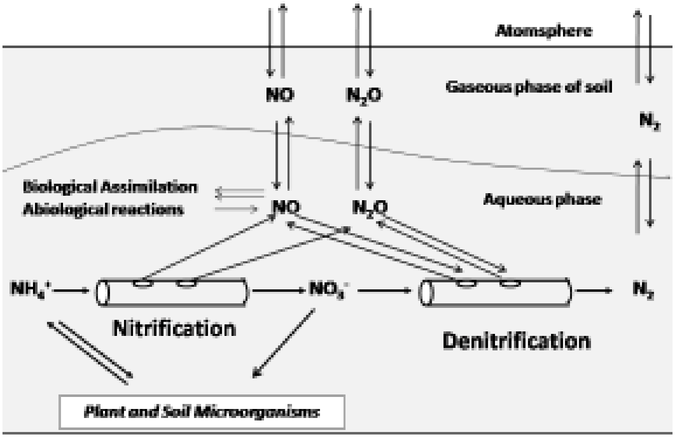


$$\begin{tikzcd}[column sep=small] & O_2 \arrow[d] & & & \\ NH_4^+ \arrow[r] & NH_2OH \arrow[r] \arrow[d] & NOH \arrow[r] & NO \arrow[r] \arrow[d] & NO_2 \text{.......... (2)} \\ & N_2O & & N_2O & \end{tikzcd}$$

Factors affecting nitrous oxide emission from soil

Several microbiological and ecological factors influences N transformation processes in soil and hence N_2O emission. Firestone & Davidson (1989) proposed "hole-in-the-pipe," model to explain the factors that regulate N_2O from soil. This model uses the analogy of a leaky pipe (Fig. 1) to suggest that there are two levels of control that regulate emissions of N_2O and NO from soil.

FIGURE 1. *Hole-in-the-pipe conceptual model*



First, the rate of nitrogen cycling through ecosystems which determines the amount of nitrogen flowing through the pipe and influences the total emission, second is the factors (soil, water content and others) that regulated the ratio of N_2O: NO, these factors are considered as the leakage of the pipe and their influence is symbolized by the relative size of the holes. In fertile soils, flow through the pipe is large, as are the “leaks”. The converse is true in infertile soils, and neither gas is produced in large amounts. In dry soils, where O_2 is present, the nitrification “leak” is greater and NO, which is more oxidized than N_2O and N_2, is the dominant gas. In wetter soils, with less soil O_2, denitrification is dominant process and more N_2O is produced. In very wet soils denitrification process dominates, but N_2O further reduced to produce the end product, N_2 (Davidson et al., 2000).

Type and dose of nitrogenous fertilizer controls the amount of N flows through the system and hence influences the N_2O emission (Mosier, 1994; Cai et al., 1997). Increase in total N_2O emission with the increase in N application rate has been observed (Majumdar et al., 2000, Kumar et al., 2000). Soil water content regulates the transport of oxygen into soil and the transport of NO, N_2O, and N_2 out of soil, hence considered as the most important controller of these ratios. The relative contributions of nitrification and denitrification to NO, N_2O, and N_2 emissions could be expressed as a function of water filled pore space (Davidson et al., 2000). Relative abundance of electron donors (soil organic carbon) and acceptors (primarily oxygen, nitrate, and sulfate) also affects the relative proportions of N_2, N_2O, and NO emissions (Firestone, 1982; Firestone & Davidson, 1989). The rate of biological denitrification and the potential production of N_2O from soil depend upon the presence of readily metabolized organic matter and the availability of water soluble organic matter. In general, addition of degradable organic materials increases N_2O production in soils containing NO_3^- or applied with fertilizer NO_3^- (Murakami et al., 1987). The soil properties like texture, pH and salinity also reported to influence the emission of N_2O through their effect on nitrification and denitrification processes. In coarse-textured soils N_2O production exceeds up to 6-times in comparison to a heavy-textured soils. In the loamy soils, period of N_2O production lasted only 3 days, in the silty soils 10 days, while in the sandy soils about 21 days. High salinity inhibits both nitrification and denitrification (lnubushi et al., 1999). According to Menyailo et al. (1997), N_2O reductase is susceptible to salt, which may result in N_2O accumulation from denitrification under saline conditions. Nitrification is sensitive to extremes in soil pH. The optimal pH for nitrification is approximately 7 to 8 (Haynes, 1986). Laboratory incubations of soils added with NH_4^+ under aerobic conditions showed that N_2O production could increase by many times with increasing pH up to about 8 (Wang & Rees, 1996). At higher pH (pH >8.2), nitrite accumulates in soil, and this is then reduced to N_2O since competitive biological oxidation of nitrite by *Nitrobacter* is prohibited (Chalk & Smith, 1983).

Nitrous oxide emission from rice fields

There is wide spread variation in N_2O emission reported from rice field (Table 3). Denitrification is one of the important mechanisms for production of N_2O. Aulakh & Bahl (2001) estimated that 23 - 33% of the N applied through fertilizer is lost via denitrification during rice cropping. The study conducted at IRRI using ^{15}N tracer technique revealed magnitude of denitrification loss, may vary from negligible to 46% of the applied N depending on urea application and crop establishment methods (Buresh & De Datta, 1990). Fillery & Vlek (1982) reported that denitrification losses of fertilizer N were 5–10% in continuously flooded rice-cropped soils, while in the fallow soil the loss was around 40% of the applied N. Though N_2O is one of the by product of denitrification, continuous submergence condition may further reduce N_2O to N_2 so it has been generally thought that N_2O emission from rice field to atmosphere is very low or negligible. However studies showed N_2O was mainly emitted after the final water drainage for harvest (Chen et al., 1997; Tsuruta et al., 1997). With the current increasing trend in use of N fertilizer in rice with simultaneous increase in acreage, the total global emission is likely to increase appreciably. Bronson et al. (1997a) through an automated chamber sampling system observed N_2O fluxes in an irrigated rice system were generally negligible during the growing seasons, but small peaks (maximum 3.5 mgN_2O-N$m^{-2}d^{-1}$) appeared after N fertilizer applications, the N_2O flux increased sharply during the drainage period at mid-tillering until re-flooding, and seasonal flux was 2.5 times higher with ammonium sulphate than with urea. Higher N_2O flux (up to 80 mg N_2O-N$m^{-2}d^{-1}$) during fallow period due to nitrification of mineralized organic N in the topsoil and possibly from denitrification in the wet subsoil has been reported (Bronson et al., 1997b). Kumar et al. (2000) observed total N_2O-N emissions during crop growth season in an irrigated rice system ranged from 0.08% - 0.14% of applied N, it is 235 g N_2O-N ha^{-1} with application of ammonium sulphate and 160 g N_2O-N ha^{-1} with urea application. Nitrous oxide emissions were low during submergence and increased substantially during drainage of standing water.

Rainfed rice based production system occupies about 25% of the world's rice harvesting area. This system is characterized by alternate wetting and drying cycles as monsoonal rains come and go, hence potential for accumulation and denitrification of NO_3^- is high here (Abao et al., 2000). In this system the rice is grown during wet season followed by fallow or various upland crops in dry season depending upon the agro-climatic condition. Any time of the year rains can flood the soil resulting in denitrification and leaching of accumulated NO_3^-. Abao et al. (2000) observed low and negligible N_2O emission during the rice-growing season however the flux rose significantly as much as 2.5 mgN_2O-N$m^{-2}d^{-1}$ after fertilization events. During fallow period the emission continued at low level (< 2.5 mgN_2O-N$m^{-2}d^{-1}$), but rainfall events during fallow period resulted in increased emission to as high as 8 mgN_2O-N$m^{-2}d^{-1}$. Baruah et al. (2010) estimated the N_2O emission from rainfed rice environment ranged from 1.24 mg to 379.40 mgN_2O-N$m^{-2}d^{-1}$ depending upon the crop cultivar grown. Total seasonal N_2O emission ranged from 77 to 150 mgN_2O-N$m^{-2}d^{-1}$ and varieties with lower grain productivity but profuse vegetative growth, showed higher seasonal N_2O emission.

TABLE 3. *Total seasonal emission of nitrous oxide from rice fields in different locations under different crop management practices*

Production system	Location	N applied	Total N_2O emission	Reference
Continuous flooded	Hailun, China	95.4 kg N ha^{-1} (Urea)	0.06 g m^{-2}	Yue et al. (2005)
Intermittent Irrigation	Hailun, China	95.4 kg N ha^{-1} (Urea)	0.08 g m^{-2}	
Rice (saturated soil)	New Delhi, India	120 kg N ha^{-1}(Urea)	0.073 g m^{-2}	Pathak et al. (2001)
Rice (Intermittent drying)	New Delhi, India	120 kg N ha^{-1} (Urea)	0.09 g m^{-2}	
Irrigated Upland	New Delhi, India	120 kg N ha^{-1} (Urea) 120 kg N ha^{-1} (Ammonium Sulphate) 120 kgN ha^{-1} (Potassium Nitrate)	0.016 g m^{-2} 0.015 g m^{-2} 0.018 g m^{-2}	Ghosh et al. (2003)
Irrigated rice Flooding-mid season drainage-Flooding-Moist	Nanjing,Jiangsu province, China	150 kg N ha^{-1} (Urea) 300 kg N ha^{-1} (Urea) 450 kg N ha^{-1} (Urea)	0.26 g m^{-2} 0.44 g m^{-2} 0.61 g m^{-2}	Zou et al. (2005)
Irrigated Rice Flooding-mid season-reflooding	Jurong, China	100 kg N ha^{-1} (Urea) 200 kg N ha^{-1} (Urea) 300 kg N ha^{-1} (Urea	0.086 g m^{-2} 0.082 g m^{-2} 0.091 g m^{-2}	Cao et al. (1999)

Irrigated upland rice production systems are significant source of N_2O-N emission as soil is subjected to rapid drainage and upper layer of soil remains aerobic for most part of the season, both nitrification and denitrification processes contribute to the emission. Ghosh et al. (2003) estimated depending upon the application of N, total seasonal N_2O emission from upland irrigation system ranged f.rom 0.037 to 0.186 kg ha^{-1} which accounts for about 0.1-0.12% of applied N.

Nitrous oxide emission from rice-wheat system

Rice–wheat systems is the dominant cropping system in south Asia and covers about 32% of the total rice area and 42% of the total wheat area. Most of the rice–wheat cropping is fully irrigated. Under this system, farmers grow rice in the rainy season followed by wheat in winter. Rice is generally grown in flooded fields whereas the wheat crop requires well-drained soil conditions. This fundamental difference in the growing conditions creates a unique environment that influences the N dynamics differently in comparison to that observed in rice-rice system. The continuous submergence condition and anaerobic condition restricts nitrification processes and drying period during wheat season favours nitrification and NO^-_3 - N accumulated during wheat season, is subjected to losses by denitrification and leaching during flooding in subsequent rice cultivation (Pathak et al., 2001). Emission of N_2O-N from rice-wheat systems typical of farmers' field in Indo-Gangetic plains could vary between 654 and 1570 g ha^{-1} depending upon fertilizer application and irrigation. This accounts for 0.38% of applied N, where 240 kg N is applied annually.

Nitrous oxide emission from rice soil is controlled by the real-time field conditions and fluctuations in cultural practices. It is important to monitor N_2O emission from different rice ecosystems and estimate realistic regional and global budgets. Some attempts have been made to predict N_2O-emissions through simulation of soil N pathways. Using DNDC model, Pathak et al. (2005) predicted annual net emission of 0.04–0.05 TgN_2O-N from rice fields (42.25 million ha) of India under continuous flooding condition whereas it is higher (0.05–0.06 TgN_2O-N) under intermittent flooding condition .

Uncertainities in the estimation of nitrous oxide emission and research needs

Agronomic practices such as tillage and fertilizer applications can significantly affect the production and consumption of N_2O because of alterations in soil physical, chemical, and biochemical parameters. These factors interact and the magnitude of interaction results in the temporal and spatial variability in the emission of N_2O, hence the variability associated with estimation of N_2O emission is quite significant. Dobbie et al. (1999) observed 20-fold variation in annual N_2O flux at a grass land site between 1992 and 1998 mainly because of the rainfall around the time of fertilizer application. Field level emission data are used to upscale to regional, national and global level using default emission factors, and the methodologies recommended by the IPCC. The upscaling processes that depend highly on the models and database are responsible for about 63% uncertainties (Xuri et al., 2003).

Most of the reported data on field level N_2O-N emission are obtained from non-flow-through, non-steady-state (NFT-NSS) chambers (Bouwman et al., 2002). Deployment of chambers on soil surface changes energy balance of the enclosed soil surface, which in turn alters the soil and headspace temperatures. Changes in soil temperature may affect N_2O production, flux rate and concentration of gas; therefore, the emission of N_2O-N inside the chamber may differ from that actually happens out side in the field. Though emission data obtained using NFT-NSS chambers can be used for comparison of relative flux between treatments, many times these values are used to estimate mean N_2O emission rates from agricultural soils (Freibauer, 2003; Bouwman et al., 2002; Gregorich et al., 2005) and to develop default soil N_2O emission factors of the IPCC that are currently used in many countries to calculate GHG inventories. Therefore, biases in the accuracy of chamber N_2O data would also result in similar errors in soil N_2O emission inventories (Rochette, 2008). Rochette & Bertrand (2007) have summarized the improvements that were made over time to the NFT-NSS chamber methodology, they observed considerable variations with respect to chamber deployment time and number of air samples taken during deployment. Absence of a standard protocol may lead to biasness in flux estimate. Though these manually operated static chambers are inexpensive, and simple to operate, their coverage is limited over space and time. The covered area per measurement is usually less than 1m^2 and measurements are rarely taken more than once per day. There is report of presence of spots of enhanced N_2O emission from the field (Hellebrand et al., 2008) which is difficult to be taken account with the chamber method. Thus, this method is not well suited to describe daily variations or short-lived emission pulses induced by events such as rainfall, fertilization, re-wetting of dry soil and freeze-thaw. Therefore the uncertainty of annual flux estimates from manually operated chambers can be as high as 50% due to spatial and temporal variability (Flechard et al., 2007). In the absence of provision of air circulation inside the chamber head space, it has been shown that static chambers potentially underestimate fluxes (Pumpanen et al., 2004; Christiansen et al., 2011). Insulation of the chamber, provision of venting tube, power operated fan, use of air circulation pump, temperature correction, use of exetainers for storage of sample, maintenance of positive pressure during storage and handling of air samples and use of nonlinear model for determination of N_2O flux are some measures suggested to improve the reliability of emission data obtained through closed chamber method (Rochette, 2008).

Another approach of monitoring N_2O flux at field scale is use of micrometeorological techniques. This techniques use analyses of the atmospheric concentration of the gas and meteorological measurements such as wind speed, wet- and dry-bulb air temperatures, net radiation, and heat fluxes without disturbing the environmental conditions. The most widely used micrometeorological technique for N_2O flux measurements is the eddy covariance (EC) method, but the Relaxed Eddy Accumulation (REA) and the flux gradient method also have been applied to N_2O emission measurements (Skiba et al., 1996; Pattey et al., 2006; Desjardin et al., 2010). The area over which a flux can be integrated ranges from 0.01–1 km^2, depending on the height of the sampling tower. The limitation of this technology is that this is highly expensive and requires specialized instrumentation such as tuneable diode laser trace gas analyzers.

Strategies for reduction of nitrous oxide-nitrogen emission from rice field

There is direct linkage between nitrogen use efficiency and emissions of N_2O hence the strategies that increase the efficiency of N fertilizer use also reduce N_2O emissions (Aulakh et al. 1992; Monteny et al, 2006). These strategies include: forms of fertilizer (reduce anhydrous ammonia use), rate and method of application, matching N supply with demand, fertigation, applying fertiliser to the plant rather than the soil and the use of slow-release fertilizers, urease and nitrification inhibitors (Freney, 1997).

Matching N supply with crop demand

Application of nitrogen in splits in synchrony with the crop requirement is an important strategy to improve N use efficiency, minimization of N loss and regulation of N_2O emission from the rice field. Leaf color chart, SPAD meter, etc can be used to guide farmers in deciding the number of splits, amount of N applied per split, and the time of applications to match the N supply with real-time demand of rice crop. Site-specific nutrient management approach that includes site-specific quantitative knowledge of crop nutrient requirements, indigenous nutrient supply and the recovery efficiency of applied fertilizer nitrogen ensures about 30-40% increase in nitrogen use efficiency, has the potential of reducing N_2O-N emission from rice field. However these approaches needed to be standardized with respect to cultivars grown and agro climatic condition.

Use of controlled release fertilizers

The use of controlled release fertilizers, which are intended to supply nutrients to the soil solution and hence to the crop roots at a rate which more or less matches plant demand, has attracted considerable interest for many years, as a means of improving fertilizer use efficiency

(Cheng et al., 2002). Minami, (2005) reported that application of controlled-release fertilizers reduced the N_2O emissions. Minami (1994) compared N_2O losses from polyolefin-coated ammonium nitrate with uncoated ammonium sulfate and reported a 3 to 7-fold reduction in the emission of N_2O from arable soil.

Placement and source of fertilizer

Denitrification and N_2O losses of urea from flooded rice systems are further reduced when urea is deep placed as compared to surface broadcast application (Keerthisinghe et al., 1996; Liu et al., 2006). Application of N as anhydrous ammonia led to a much greater increase in emission of N_2O than the application of the same amount of fertilizer N as urea or aqueous ammonia (Breitenbeck & Bremner, 1986). Amendment of soil with NH_4^+ plus glucose resulted in an increased emission of N_2O, compared to treatment with either glucose or NH_4^+.

Use of nitrification inhibitors

Addition of nitrification inhibitors such as nitrapyrin, 2-chloro-6-(trichloromethyl)- pyidine (Pathak & Nedwell, 2001), dicyandiamide (Malla, 2005) and wax-coated calcium carbide (Keerthisinghe et al., 1996) to soil after fertilizer application significantly reduced fertiliser induced loss of nitrous oxide. Addition of dicyandiamide (DCD) to urea reduced total N_2O-N emission at all moisture regimes (Kumar et al., 2000). Vallejo et al. (2005) found that mixing pig slurry with DCD lowered N_2O emissions compared to slurry only.

Water management

In Irrigation systems, timing and frequency of irrigation also influence N_2O production. Negligible N_2O emission under continuous flooded conditions has been reported. In arid and semiarid areas, drip irrigation system reduced the N_2O emissions compared to the furrow irrigation (Rolston et al., 1982).

Tillage management

Tillage practices like no tillage or minimum tillage, bed planting, modifies N_2O emission through their impact on compaction, drainage, and aeration status of soil. However reports on effect of tillage on N_2O emission are highly inconsistent. Some studies showed an increase in N_2O emission with zero and no tillage systems (Aulakh et al., 1984; Ball et al., 1999). There is a need to monitor the N_2O emission under different tillage management in different rice production systems.

Conclusions

Rice and rice based production systems are one of the most intensively cultivated system. Because of excessive use of nitrogenous fertilizer and abysmal poor nitrogen use efficiency, this system is a major contributor of N_2O to the environment. However there are lots of variability in estimate of N_2O emissions from rice fields due to diverse soil and climate conditions and socio-economic status of the farmers. Besides that various crop management practices also influences the emission. Considerable research efforts are needed to improve the quantitative understanding of N dynamics in soil-plant-atmosphere system and reduce the ambiguities and inaccuracies associated with direct measurement of N_2O fluxes. Simulation models can be used for quantifying N_2O emissions under various agro-ecosystem but they need to be properly validated. Predictability of models is often not reliable due to difficulty in calibration of model in the absence of sufficient data. Considering the geographical spread and immense variability in environmental factor and management factor in rice production, ecosystem specific flux measurement is essential to reduce the uncertainties in national N_2O budget and improve the predictability of emission model.

In spite of volumes of research over past fifty years, not much progress has been made in improving nitrogen use efficiency of rice production system. Because of the lack of synchrony in nutrient supply and crop demand, recovery efficiency of applied N is low. Therefore, a strategy that ensures synchrony between N supply and demand, maximizes crop N uptake, minimizes N losses, and optimize indigenous soil N supply should be adopted to improve N use efficiency. Site specific nitrogen management and real time N management options have the potential to improve nitrogen use efficiency and reduce N_2O emission from rice field, but they need to be evaluated and standardized in different agro ecosystems.

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