unaffected. What distinguishes humans from all other life, is ethics, morality and spirituality. This is so because it is a thinking species. These are not values of the bygone eras, but today there is a far greater need to ponder on these issues which are relevant. *Abandon greed and take to need.* This is going to be the biggest *mantra* for the 21st century. If we all stick to this, the next century would be different. It would become environmentally liveable, economically sustainable and socially benign.

A society is an extension of individuals; if individuals are 'greened' then, in course of time, the society as a whole will follow suite. Therefore, the human race has to make a firm resolve in this direction at the individual level, only then the battle can be won.

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ACKNOWLEDGEMENT. Grateful thanks are due to Dr R. K. Pachauri, Director, TERI for providing facilities.

Received 9 August 2000; revised accepted 28 September 2000

Monitoring and mitigation of nitrous oxide emissions from agricultural fields of India: Relevance, problems, research and policy needs

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The farming community should be made aware of the harmful effects of N_2O emission from agriculture and should feel the need to mitigate its emission through optimum crop management practices. Inexpensive soil and plant tissue testing facilities should be made available to farmers.

EMISSION of nitrous oxide (N_2O) from agricultural ecosystems and its loading in the atmosphere are of considerable environmental importance. N_2O is a greenhouse gas and leads to global warming (it is 30 and 200 times more potent than CH_4 and CO_2, respectively, as a greenhouse gas)[1], apart from taking part in atmospheric reactions to destroy ozone, allowing more solar UV-B radiation to penetrate[2]. Its emission from soil is a loss of resource, as it removes nitrogen from the soil to the atmosphere, rendering it unavailable for plants. Importance of N_2O as a greenhouse gas and as an ozone-depleting agent in atmosphere is further accentuated due to its long residence time in the atmosphere (166 ± 16 years, approximately)[3]. Presently, N_2O concentration in the atmosphere stands at 311 ppbv, which is increasing at a rate of 0.22% per year[4,5]. According to Intergovernmental Panel on Climate Change (IPCC)[6], global mean annual atmospheric N_2O loading was 16.2 Tg in 1997, to which agricultural soils contributed about 3.3 Tg. Due to rapid increase in world population, humanity is striving to produce more and more food to sustain itself and in the process is putting more and more fertilizer nitrogen input to agriculture. Therefore, it seems more than probable that N_2O emission from agriculture will keep on increasing and its increased

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loading in the atmosphere will aggravate global warming and ozone depletion.

Present state of N_2O research in India

In India, N_2O emissions from crop fields are monitored mainly by the researchers at IARI (Indian Agricultural Research Institute), CRRI (Central Rice Research Institute), both under the behest of ICAR (Indian Council of Agricultural Research), and NPL (National Physical Laboratory) under the behest of CSIR (Council of Scientific and Industrial Research). Experience at IARI shows that N_2O emissions from the soil under different crops in different seasons have wide variation. N_2O emissions from rice fields were negligible, with only 0.01–0.1% of applied nitrogen lost through N_2O emission[7,8]. Ammonium sulphate led to significantly more N_2O emission than urea from rice field[8]. Nitrification inhibitors like DCD, thiosulphate, neem-coated urea and nimin-coated urea were low to moderately successful in mitigating N_2O emission under rice (4–26% mitigation in total N_2O–N emission during the whole crop season)[7]. N_2O–N emissions were much higher from wheat, ranging from 0.56 to 1% (approx.) of applied nitrogen. Nitrification inhibitors (DCD, thiosulphate, neem-coated urea, nimin-coated urea) were more successful under wheat crop compared to rice, in mitigating N_2O emission (9 to 63% mitigation of total N_2O–N emission during the whole crop growth period) under wheat[9]. Pot culture experiments have shown that N_2O–N emissions from kharif and rabi pulses (e.g. black gram, bengal gram and lentil) were as high as 3.5 to 5.7% of the fertilizer-N applied[10].

One recent estimate puts N_2O emission from rice and wheat fields of India at 0.19 and 0.27 Tg yr^{-1}, respectively[11]. The estimate has been made by taking the amount of fertilizer and manure input for these crops in India into account. The effort is praiseworthy, but in no way is it an estimate of total N_2O emission from the Indian agriculture. Although rice and wheat cover most of the cultivable area in India, many important cultivated crops, e.g. sugarcane, maize, pulses, millets, etc. have been left out. To quantify N_2O emission from Indian agriculture, fertilizer and manure inputs in these crops have to be taken into account, if the same procedure is used for estimation. Moreover, the estimate has not considered the factors (soil type, tillage practices, irrigation, type of fertilizer, method of fertilizer application, soil temperature, etc.) which strongly control real time emissions of N_2O.

Do we need to monitor N_2O emission from Indian agriculture?

Extensive database is available on N_2O emissions from different fertilizers, crops, soil types and crop management practices[12–20]. Although considerable work has been done in many other countries, only a limited number of studies on N_2O emission from Indian agriculture have been taken up till now[7–10,21–24]. Detailed monitoring of N_2O emission from Indian agriculture is worthwhile, as agriculture is widely practiced all over the country in several agro-ecological regions, having different soil types, rainfall characteristics, cropping patterns, cropping systems and crop management practices. The need becomes greater due to lack of information on N_2O emission from different regions of India and the non-existence of a national N_2O budget. Usage of organic matter (FYM, compost, crop residue, cattle dung, etc.) in Indian agriculture is extensive and the type and amount varies within the country and differs widely from organic matter used in other countries. Organic matter breakdown is also high in Indian soils due to high temperature and consequently, nitrogen mobilization from organic matter is also high. Therefore, organic matter application might strongly influence N_2O emission from Indian agriculture. On the other hand, total N_2O emission from fertilizer in India may be significant due to high fertilizer consumption[25] and very little usage of nitrification inhibitors.

Problems of N_2O monitoring and quantification from crop fields

Under rice, N_2O emission sometimes becomes undetectable because of entrapment of N_2O in the soil under the pressure of standing water due to further conversion of N_2O to N_2 (ref. 26), dissolution of N_2O in standing water due to high solubility of N_2O in water[27], removal of N_2O from surface layers through leaching, etc. During drainage, N_2O emissions increase considerably and thus the real time N_2O emission fluctuates extremely. There may be high diurnal variations in N_2O emission in a single field due to changes in soil water content and soil temperature. Within a particular crop season, emissions are expected to be higher when rice plant canopy enlarges with growth, thereby increasing N_2O emission through the plant body. During rice season, undecomposed organic matter and applied NH_4^+ accumulate in large amounts due to low mineralization under standing water which undergoes rapid mineralization during harvesting and dry post-harvesting periods and may produce N_2O vigorously. If N_2O is not monitored during these periods, total N_2O emission may be underestimated. Another problem encountered in monitoring N_2O emission from rice fields is the transparent plexiglas static chambers which allow sunlight inside to help plants grow during confinement, but act as a little greenhouse. Temperature inside the chambers may attain levels appreciably higher than ambient if the chambers are kept for long, which may affect N_2O emission from the soil apart from influencing plant growth. This problem becomes more acute in kharif rice, when chambers are kept longer on the plots to get detectable N_2O concentration, as emissions of N_2O are low under flooded soil condition. To prevent temperature build-up, boxes may be coated with sunlight-reflecting agents, which would imply that plants would be deprived of light. Moreover, chambers are usually made big, larger than the maximum attainable plant height, so that they can be used for the entire crop growth period. But, large boxes have to be kept longer to hold enough N_2O for detection. Using boxes of different sizes based on maximum plant height at different crop growth stages can resolve the problem. Higher N_2O emission under wheat compared to rice[4] has alleviated the problems associated with the use of large plexiglas boxes, as detectable N_2O concentration develops within a shorter time frame in the box. Manual gas collection by removable plexiglas chambers becomes less labour-intensive due to friendly field conditions under wheat.

Wide spatial and temporal variations of N_2O emissions make N_2O estimation a tough proposition[18]. Even within small fields, there may be high spatial variation of N_2O emissions because of uneven distribution of applied nitrogen and organic matter. Soil water content may also differ within a small area depending on slope of land or vegetation cover, leading to spatial variation in N_2O emission. Within a big farming zone, there may be difference in the package of practices or time schedule of the same local management practices, which may result in different patterns of N_2O emission. With so much spatial variation within even small farms, it becomes difficult to estimate N_2O emission from an area to near accuracy. Any correct estimation thus will need thorough details of very minute farming units, which becomes a very difficult task to accomplish. Temporal variations (diurnal and seasonal) of N_2O emission also make estimation and prediction of N_2O emission very difficult.

Utility of models in estimation and prediction of N_2O emissions

Use of mathematical models may be the right choice to predict N_2O emissions from agricultural ecosystems. Development of mathematical models for simulating N_2O emission is knowledge-intensive and time-consuming. Development of any model is a group activity, involving people from different research interests working together for a co-operative output. With the present Indian expertise, it seems within reach but not without a concerted effort. Presently, models developed elsewhere, calibrated and validated for Indian conditions, may be an ideal platform to start working on. Models, whether developed indigenously or hired from other countries, may not simulate N_2O emission quite accurately all the time, as biological systems do not always behave in the same manner. Moreover, there may be numerous processes operating in the soil producing N_2O, which remain undescribed in models. If not excellent, a fairly good accuracy should be a satisfying experience at the present state of knowledge.

Research needs

The above discussion underlines some very important areas, which need extensive research in future. In brief, the research needs are:

1. For developing a national N_2O budget from agriculture, detailed experiments have to be carried out in different agro-ecological regions of India. The regions will cover all types of soils and cropping systems present in India. N_2O emission should be monitored from all the crops grown in these regions. Magnitude of N_2O emissions under different crops is due to variation in climatic condition; soil type; crop management practices like tillage; water management; crop residue management; type, amount and stage of fertilizer and manure application and plant factors like amount and nature of root exudates; amount of plant biomass added to the soil; aid of plants in N_2O transport; N uptake by plants; plant N_2 fixation; root respiration, etc. All these factors are to be studied in detail in order to determine their individual and interaction effects on N_2O emission. Studies on the effects of types and modes of fertilizer application (viz. broadcasting/band application/fertigation/foliar spray/injection) coupled with stage of application and water management practices on N_2O emission should be prioritized as these factors have drastic control on N_2O emission. Special emphasis should be given to rice, wheat, pulses, maize, sugarcane and millets as these are the main crops grown in India. Although N_2O emissions from irrigated rice have been found to be low from a limited number of experiments, further research should be carried out on irrigated rice. N_2O emission should also be monitored from upland and wetland rice as very little information on N_2O emission has been generated from these ecosystems in India. The sink potential of water-logged rice soils has to be studied, as it checks N_2O emission from the soil and thus reduces its atmospheric loading. Detailed data on soil sink potential of water-logged soils in the country may reduce uncertainties in the estimation of a national N_2O budget. Studies should also be made to determine how much N_2O different cropping systems can generate on a long-term basis. It is also important to monitor N_2O emissions during post-harvest fallow

periods, as considerable amounts of N_2O can be produced and emitted from residual nitrogen in the soil.

2. At present, N_2O emission from crop fields is mainly monitored by the static chamber method in India. For correct estimation of N_2O through static chambers, temperature correction has to be made during calculation of N_2O emission, to nullify the effect of elevated temperature on N_2O emission under static chambers. Static chambers have to be fitted with battery-driven air mixers for mixing of the air inside. Use of pressure vents in the chambers is also necessary to equilibrate pressure within the chamber with the outside environment, which would offset the influence of elevated pressure on N_2O emission within the chamber.
3. For accurate measurement of real time N_2O emissions from crop fields, computer-driven, automatic N_2O monitoring systems have to be used. The system can periodically measure N_2O emissions in a 24 h cycle from specific points on the study area by manoeuvering permanently installed boxes. As the system can considerably reduce the errors in N_2O estimation by offsetting temporal variation, it offers an opportunity to determine N_2O emission more precisely. A system similar to the one used by the scientists of Division of Environmental Sciences at IARI, New Delhi, for estimation of methane emission from rice fields, can be used for long-term N_2O emission studies from different cropping systems. As the installation and use of the instrument involves considerable investment, proper allocation and mobilization of funds is necessary. As a beginning, the automatic system may be installed in some areas of prime agricultural importance. Inaccuracy in N_2O estimation due to spatial variability of emission can be effectively reduced by the use of the micrometeorological technique, which integrates N_2O fluxes from large areas. It can be used in conjunction with a *tunable diode laser trace gas analyser* for accurate and continuous monitoring of N_2O for long periods[28].
4. Simulation models have to be developed or existing models have to be calibrated and validated for predicting N_2O emissions accurately from Indian agriculture. Existing models like DNDC (denitrification–decomposition)[29] and NGAS[30] can be used after calibration and validation. Extensive data have to be generated through detailed and precise laboratory and field experiments for the development of any new model for N_2O estimation. A correct model development approach should include detailed inputs of climatic variables, soil characteristics and crop management practices. New model development requires collaborative effort of experts from different disciplines.
5. Research should be carried out to find out the contribution of different processes, viz. nitrification and denitrification in N_2O production. This can be achieved through the use of fertilizers tagged with isotopes. By differential ^{15}N labelling of NO_3^- and NH_4^+ pools in soil and then by periodical measurement and comparison of accumulation of N_2O, NO_3^-, NH_4^+ pools, the relative importance of the two processes can be determined[31]. A relatively good measure of the contribution of nitrification and denitrification in N_2O production may help researchers formulate N_2O mitigation strategies under different conditions.
6. Detailed research with different species and varieties of plants is needed to determine the role of plants in N_2O emission. There may be appreciable interspecies and intervarietal differences with regard to the N_2O emission potential. Data available on CH_4 emission through plants may give an idea about possible magnitude of gaseous transport of N_2O through plants, but appreciable difference may be encountered due to unidentical solubility of CH_4 and N_2O in water. A different N_2O solubility in water implies that it will be retained and released from the plant body in a different manner compared to methane.
7. Substitution of inorganic fertilizers with FYM, compost, green manures and crop residues and evaluation of the overall effect on N_2O emission should be made. If there is a significant reduction in total N_2O emission and overall crop yield benefit on substitution, then the practice of substitution can be followed.
8. Availability of primary N_2O standards is very less in the Indian market and it has to be imported from foreign countries. A ready availability of primary N_2O standards in the Indian market should be ensured, to minimize wastage of time in procuring the standards.
9. Scientists from different parts of the country should come forward with research proposals for their respective regions. Research funds should be granted by different funding agencies in India like ICAR, CSIR, UGC, DST, INSA, DAE, etc.

Policy needs

The following policies should be formulated in India to educate the farming community about the damaging effects of N_2O emission from agriculture on the environment and the need to mitigate its emission:

1. Indian farming community should be made environmentally aware and educated. Farmers have to understand the harmful effects of N_2O emission from agriculture and should feel the need to mitigate its emission through optimum crop management practices. Environment awareness is a prerequisite for this. Environment education has to be done patiently and carefully and a long time-frame is required. The

process is already underway, but has to be strengthened.

2. Nitrogen (nutrient) loss through N_2O emissions from crop fields seems to be too negligible for the farmers to be concerned about, if at all they know that there is a loss of N. It is for the scientists to formulate N_2O mitigation strategies from agriculture, without making any compromise with the crop yield and quality, soil health and environment as a whole. Easily adaptable N_2O mitigation strategies should be formulated and popularized among farmers. N_2O mitigation strategies should also be capable of increasing crop yields, as this will increase the farmers' income and will thus easily be adopted by them. Farmers should be taught to apply irrigation and fertilizers in optimum amounts, according to the crop's need only. Split application of nitrogenous fertilizers should be encouraged to reduce gaseous loss of nitrogen. Foliar application of nitrogenous fertilizers should be encouraged to reduce loss of nitrogen through N_2O emission. Till date, slow release fertilizers and nitrification inhibitors have largely been ignored by farmers in India due to low publicity, low availability and high price. Nitrification inhibitors should be made available to the farmers at a cheap price for quick adoption. Major emphasis can be laid on the use of plant materials (e.g. neem, karanja, etc.) available in rural India. Pilot projects may be taken up for low cost production of nitrification inhibitors from plant materials and efforts are to be made for their commercialization. Subsidies may also be given on nitrification inhibitors to popularize them. Proper extension activities also have to be taken up for their popularization.
3. Cheap soil and plant tissue testing facilities should be made available to farmers to help them determine the soil nutrient availability and nutrient uptake by plants, which in turn will assist them to utilize fertilizers, irrigation and other crop management practices optimally. Practices in fine tune with crop requirements will increase crop yields, apart from mitigating N_2O emission.
4. Farmers should be encouraged not to practice fallow culture, as it will result in the loss of residual soil nitrogen in gaseous forms, e.g. N_2O, N_2, etc. Cultivation of short-duration crops in fallow periods will ensure optimum utilization of residual soil nitrogen.

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Received 10 July 2000; revised accepted 16 October 2000