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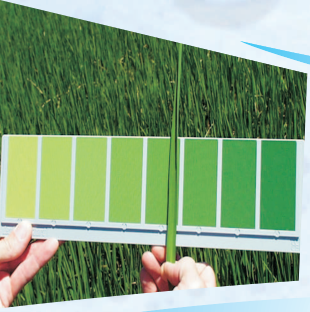

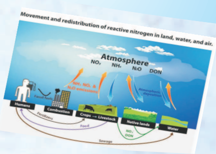

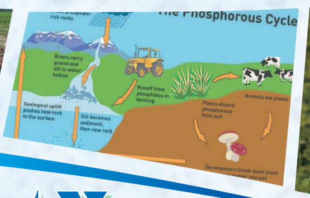

Fertilizers and Environment News

Society for Fertilizers and Environment
Bidhan Chandra Krishi Viswavidyalaya
Mohanpur, Nadia,
West Bengal, India

From President's Desk

The issue of environmental concern of fertilizer use though well appreciated by most of the persons involved in farm operations, particularly in the recent times more than anytime earlier, did not find a formal platform to be discussed or deliberated upon before 2010 in India, when a small group of scientists and technologists from all over the country, involved in fertilizer and environment related research and development, assembled at the University of Calcutta to discuss on this theme area in remembrance of Professor N.P. Datta, the doyen in fertilizer chemistry and technology, and former Head of the Division of Soil Science & Agricultural Chemistry, IARI and Director Nuclear Research Laboratory. With the passage of three years hence, the Society of Fertilizers & Environment was formed with a national base headquartered at Kolkata and now at BCKV, Kalyani, West Bengal. As one of the major activities SFE Newsletter was first published in January 2015, and since then six such issues were published till 2017 by the Society of Fertilizers and Environment, twice in a year, on a variety of theme areas of global concern. After devoting the initial three on the role of major nutrients on environmental degradations, I commented later in this column while dealing with soil health, a key area, that "to me 'soil health' per se is not a nomenclature in its simplistic term but a 'concept' to qualify agricultural and environmental sustainability urging for renewed efforts if necessary to have a relook into the entire domain and reinvent the methodologies and the parameters in tandem".

I now think it to be appropriate at this stage to have a relook and draw a long-term vision for a systematized approach. Following could be the approaches or theme areas complimentary to each other. We have plans to prepare compendia, other than Newsletter publications and interaction programmes arranged at regular intervals with different stakeholders down to farmers and school children, for prioritizing and refining in our future deliberations. I throw these ideas, for the first time, inviting comments through this release from scientists, technologists, planners, NGOs, and other field level workers.

Soil health & fertilizer use

A. Quality of soil – a systems approach & risk assessment during green revolution era
B. Soil biology and their interactions with soil physical properties-impact on soil quality
C. Soil health and farm management – in the user-friendly language for different stakeholders

Fertilizer use and climate change

A. Impact during post-industrial era
B. Impacts since green revolution
C. Mitigating climate change by moderating fertilizer use pattern

Fertilizer use and soil & water degradation

A. Impact of human activities on the nitrogen cycle, and vice-versa
B. Systems damage in soil, water and biological properties
C. Contamination of groundwater with nitrates, and of soil with cadmium, fluoride, mercury, lead, selenium, radioactive minerals, other metals, as well as trace mineral depletion
D. Soil acidification
E. Eutrophication of river and lake waters due to phosphorous contamination and loss of aquatic organisms
F. Storm water loss of fertilizers into river & lake waters and their impacts on aquatic organisms.

Planetary boundaries & biogeochemistry with respect to fertilizer use vis-à-vis environmental protection

A. Biodiversity loss
B. Biogeochemical flows: nitrogen cycle and phosphorus cycle
C. Land and freshwater use
D. Chemical pollution

Industry-Application interface

A. Central innovation base on a public-private partnership (PPP) mode, and creation of a network for information exchange amongst all stakeholders on environmental degradation and human/animal health
B. Customised and fortified fertilizers use utilizing improved technology without compromising on safety, quality and reliability for minimal impact on environmental degradation and human/animal health
C. Field testing of fertilizers and impacts on environmental degradation and human/animal health

HSSen
President

NEWS

Farmers/Students-Scientists Interaction programme on Soil Health Management for Murshidabad district

Date: 22-23 September, 2017

Venue: Ramakrishna Mission Ashrama, Sargachi, Murshidabad

A Workshop on 'Farmers/Students-Scientists Interaction programme on Soil Health Management for Murshidabad district' was jointly organized by Society for Fertilizers and Environment Kalyani, KVK Murshidabad and Ramakrishna Mission Ashrama, Sargachiin the Auditorium of Ramakrishna Mission Ashrama, Sargachi, Murshidabad from 22nd September to 23rdSeptember, 2017 under the chairmanship of Swami Viswamayananda, Ramakrishna Mission Ashrama, Sargachi.

On the first day of this programme, around 80 farmers from different blocks of the district were assembled and interacted with experts.The programme was started with registration of participants followed by an inaugural speech by Swami Viswamayananda, Ramakrishna Mission Ashrama, Sargachi, Murshidabad. In his inaugural speech he welcomed all the dignitaries and farmers in the workshop. In this speech he added that this type of workshop will be beneficial for the farming community. As the soil health of our nation is degraded day by day. He elaborately discussed about theactivity of Ashrama and lightens up on the major farmer's problem in Murshidabad.

Dr. (Mrs) S. Chandra, Associate Professor, Durgapur Govt College elaborated the Soil Health improvement through organic matter decomposition.

Dr. H. S. Sen, President, SFE in his speech he expressed his gratitude to the Sargachi Mission asrama and KVK Murshidabad for rendering all sort of help to organize the workshop. He also welcome all the participants and narrated the importance of soil health in agriculture and he also emphasis on organic cultivation.

Prof B. Mandal, Secretary, SFE in his speech he highlighted on soil health management. He mentioned that soil health card may reduce the fertilizer subsidy rate which is borne by the government.

Dr. F. H. Rahman, Joint Secreratry, SFE delivered his lecture on the different initiatives undertaken towards the improvement of soil health through the KVKs.

Dr.Krisna Karmakar, Professor, BCKVelaborately discussed about the different plant protection measure. He focused on control of aphid, jassids, mites & flies in the crops which damaged a major portion of our agriculture produce.

Also,a farmers-scientist interaction programme which was chaired byProf. B. Mandal, Secretary, SFE.

During interaction session different quarries from the participants arises. Most of the problems were related to soil acidity, availability of good quality seed, application of boron in wheat, application of zinc in paddy, preventive measure of collar rot of some vegetables. There were some quarries related to application of salt in the paddy field.

The programme was ended with the vote of thanks offered by Dr. F.H. Rahman, Jt. Secretary, SFE.

On the second day i.e. Sept 23, 2017, there was an interaction with the Students of the RKM Ashrama Sargachi. Around 200 students attended the programme. Students were aware about the soil health management issues. The programme started with the inaugural speech by Swami Viswamayananda, Ramakrishna Mission Ashrama, Sargachi, Murshidabad. In his inaugural speech he welcomed all the dignitaries and students in the interaction programme. In this speech he added that this type of programme will be enrichment of knowledge of the students about the soils, environment and natural resources.

Dr. F. H. Rahman, Jt. Secretary coordinated the programme and he informed the students about the importance of management of soils and overall initiatives are being undertaken for sustainable foodgrain production to feed up the increasing population of the country.






Environmental impact of excess fertilizer nitrogen – Indian scenario

Nitrogen cycle has been anthropogenically the most affected biogeochemical cycle leading to its exceeding the planetary boundary. Being the most common yield-limiting nutrient in agriculture production, use of fertilizer-N completely changed the scenario across the world, including in India. It is stated that out of the present global population of ~7 billion, one out of every three living human is fed by crop produced exclusively through fertilizer-N. Such increasing dependence on fertilizer-N coupled with generally low N-use efficiency and associated leakage to the environment of the unused chemical-N, started adversely affecting the ecosystem and environment. Improvement in the lifestyle of the people resulting into increased demand for energy and transport further complicated the scenario through interference in global N-cycle through ever-increasing value of "Reactive Nitrogen" (N_R).

Nitrogen in the form of chemical fertilizers, and seeds of improved crop varieties and associated agronomic practices resulted in a dramatic increase in agricultural productivity in India in the sixties and is now popularly known as 'green revolution'. With deficient nitrogen status of most of the Indian soils and demand to feed population increasing from around 250 million to around 1.3 billion, consumption of fertilizer-N increased from 0.6 Mt in 1965-66 to 17.4 Mt in 2015-16. The country has now emerged as the second largest producer and consumer of fertilizer in the world. It is estimated that demand of N in India by 2030 would be 23.45 Mt. Consuming around 15.5% of the global production of fertilizer-N in 2015-16, dependence of India on the use of fertilizer to drive the crop productivity remains undisputed. Considering that India needs to double its food production by 2050, growth trend of fertilizer-N use is currently growing at a rate of ~1.9%, almost at par with the population growth rate, is likely to continue.

Like many countries, in India too fertilizer-N is highly subsidized and cash subsidy of around US$ 7 billion puts a heavy burden on the country's exchequer. In addition to this, N-use efficiency (NUE) in India is appallingly low. It has been estimated that average use efficiency of N by crops in 2008 was 22% and full-chain NUE (including livestock) was 20%, suggesting that a major amount of applied N_R is wasted, making it a nonperforming subsidy. Hence, the alternative is to increase the NUE so that considerable savings could be made on fertilizer-N use and subsidy without adversely affecting the crop yield. Necessity for considering the usefulness of the N_R challenge for India is apparently more of economic nature considering the huge subsidy burden to the country's exchequer for fertilizer-N and additionally the environmental burden including adverse climate and associated health impacts, converted into absolute economic values. Thus, an in-depth analysis and policy interventions to stem the tide should be a win-win option.

Agro-ecosystems constitute the most predominant terrestrial ecosystems in India accounting for the most amount of fertilizer-N use. Although the largest proportion of fertilizer-N is applied for growing cereals, the use efficiency is also the lowest causing ~65% of applied N being subject to loss including to the environment. Among the other terrestrial ecosystems, horticultural crops have a lower N content than the agricultural crops, but modern high intensity horticultural production system causes leakage of considerable amount of N_R into the environment. A major negative impact of N_R originating from inorganic fertilizer and atmospheric deposition on soil quality is acidification. Indian soils mostly have low total N concentration and crop plants respond, at least in terms of growth, to application of fertilizer-N. Hence, application of excessive amounts of N fertilizers may impair soil health through acidification, long-term soil carbon degradation and adverse impacts on the structure and function of the soil biological community. As enough data are not available to understand these complex interactions, there is an urgent need to conduct intensive studies on novel crop management practices including balanced application of organic and inorganic fertilizers that are being promoted for maintenance of soil health and crop productivity.

Being water soluble, excess nitrogen leaks out of agro-ecosystem and leads to enrichment of aquatic systems causing deleterious effects on the water quality of rivers, lakes, aquifers and coastal and marine waters, and contributes to the phenomenon of eutrophication. Based on extent of groundwater development, average fertilizer-N consumption (118-163 kg N ha^{-1}), and average NO_3 in groundwater (55-100 mg l^{-1}), Punjab and Haryana have been placed in high-risk category. An analysis of the NO_3 content of groundwater samples collected by Punjab and Haryana State Ground Water Boards showed that more than 33% of the samples in the two states had NO_3 level above the permissible limit (10 mg NO_3N l^{-1}) for drinking purposes and about 17% samples had NO_3-N level greater than 22 mg L^{-1}. Apparently, the very high NO_3 content of the groundwater could be because of the sources other than fertilizer. While monitoring of Indian rivers for reactive nitrogen is scanty, some data that are available for rivers in the country indicate high levels of nitrates e.g., in the inflow water samples of Vrishabhavathi river valley treatment plant, Bengaluru, Karnataka (35-40.2 mg l^{-1}), Vaigai River, in Thenur, Tamil Nadu at 1.5 mg l^{-1}, Cauvery River around Krishna Raja Sagara (KRS) Dam, Karnataka (0.037-4.04 mg l^{-1}, river Sutlej in Nangal area of Punjab in the range of 95-120.0 mg l^{-1}.

Gaseous emissions of N_R from agricultural application of fertilizer-N, in the form of ammonia (NH_3), nitrogen oxides (NO_x) and nitrous oxide (N_2O) to the atmosphere is also influencing the planet leading to human health impacts, diminished ecosystem services, biodiversity loss and climate change. Loss of NH_3 not only reduces the N use efficiency but is also an indirect source of N_2O emission. Ammonium aerosols contribute to fine particulate matter and regional haze concentrations in the atmosphere. Infrared atmospheric sounding interferometer (IASI) satellite pictures for global ammonia column (mg m^{-2}) indicate massive atmospheric column over the

Indo-Gangetic Plains and adjoining areas, suggesting it to be a hotspot for N losses, especially from N-fertilizer use and livestock sector. Fertilizer contribution of NH_3 loss was estimated at 2696.6 Gg for India. The scenario is further complicated by the livestock sector where cattle and buffaloes are the largest contributors of ammonia accounting for 56.1% and 23.6% respectively, and estimated at 1704.8 Gg. The poultry industry, on the other hand, with a projected annual growth rate of 6% is estimated to excrete N_R to the tune of 0.415 M tons in 2016 that is anticipated to increase to 1.089 M tons by 2030.

N_2O as a greenhouse gas is responsible for global warming and climate change. NO_x influences the oxidation capacity of the atmosphere through OH and nitrate and also influences the radiation budget of the atmosphere indirectly through O_3 formation, representing about 10–15% of the total anthropogenic greenhouse effect. Total N_2O emission has increased during 2000-2010 from 264.16 Gg to 370.38 Gg with a compounded annual growth rate of 3.44%. Emission of N_2O is increasing over the years because of increased N fertilizer use as the N fertilizer contributes about 70% of the emission. The entire scenario, therefore, becomes quite alarming from the viewpoint of total environmental impact of N_R.

Once emitted, gaseous N_R species are transported and transformed in the atmosphere before their deposition to any surface. These are removed through wet and dry deposition processes. Annual N_R depositions in India are estimated to be 3.61 Tg per year. Wet deposition (1.97 Tg) of N_R species is almost equal to the dry deposition (1.67 Tg) and the Indo-Gangetic plain is reported as the region of high deposition of NH_4 and NO_3. The total deposition of N (3.61 Tg) in India is almost 57% of the total emissions of N_R as N (6.24 Tg). This indicates that remaining 43% of N is distributed among various intermediate stages between emission and deposition.

Anthropogenic nitrogen (N) deposition has been identified as one of the main potential causes of global biodiversity loss, next only to habitat destruction and climate change. Increase in N deposition pose a major ecological threat as availability of nutrients is one of the key factors in determining plant community composition. The connectivity between N deposition and changes in the structure and functioning of ecosystems is now widely acknowledged with N being cited as one of the leading drivers of loss of biodiversity on a global scale. Unfortunately, only limited studies from India are available on the effects of N loading in natural terrestrial ecosystems. In a study on the plant communities of the montane grasslands of the Western Ghats of India, N enrichment positively affected species richness and diversity of grassland species. High N led to an overall increase in occurrence of 40–51% of plant species especially C_3 grasses and significantly depressed the abundance of *common* C_4 *grass.*

India clearly illustrates a dual N challenge for food and environment, consuming 17 Mt of N fertilizer annually (14% of the global total), which has increased since 1970 at 6% year^{-1} approximately. Emissions of nitrogen oxides (NO_x) from combustion sources are also increasing rapidly at 6.5% year^{-1} currently. By comparison, population growth rate is lower (1.9% year^{-1}), while ammonia (NH3) emission increase is even less (1%), pertaining to smaller changes in livestock numbers. At current rate, Indian NOx emissions will exceed NH_3 emissions by 2055. India currently loses N_R worth US$10 billion year^{-1} as fertilizer value and while societal costs of N_R to health, ecosystems, and climate have not been quantified they are estimated at US $ 75 (38-151) billion year^{-1}. While producing more to feed the growing billions is sacrosanct, fertilizer-N use remains an important cog in the wheel of agricultural production. However, considering the overall harmful impact on the environment and ecosystems appropriate research to increase the N-use efficiency remains an important precinct.

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Comparison of fertilizer use efficiency vs. environmental impact of applied fertilizers under irrigated and dryland/rainfed situations

Long ago (in the 19th century) Carl Sprengel and Justus von Liebig put forth the Law of the Minimum, in which they described how plant growth is limited by the nutrient that is available in shortest supply. Thus, the crop response to additional increments of nitrogen might be nil if potassium or phosphorus or some other essential nutrient is limiting. The same can be said for soil moisture. Plant nutrients, alone, are not sufficient to grow or sustain plant growth without water, and vice versa. And in this day and age of increasing economic and physical water scarcity and an increasing portion of farm expenses attributed to chemical fertilizer, farmers must manage both inputs very closely to ensure they achieve high yields and obtain good returns on their investments, while reducing the possible negative impacts of water and nutrient use on the environment and ecosystem services.

Fertilizer use under irrigated condition

Irrigation along with fertilizers and improved seeds has been essential components of a global strategy for increasing agricultural productivity. During the past decades emphasis on improved agricultural water management has been on increasing irrigation water use efficiency, but more recently enhanced emphasis is placed on producing more with relatively less water – increasing water productivity. Water availability, water use and nutrient supply to plants are closely interacting factors influencing plant growth and yield production. It is generally reported that application of fertilizers enhances water use efficiency by causing greater increase in yield relative to that in evapotranspiration. Water supply has been observed to increase fertilizer use efficiency by increasing the availability of applied nutrients. Combine effects of nitrogen (N) and irrigation are generally more than the sum of their individual effects (Table 1). Similarly, water use efficiency was 119% and 150% higher when only pre-sowing irrigation and pre-sowing irrigation plus P application were made, respectively, to the wheat crop, as compared to control. Applying P fertilizers increases root density and rooting depth and the amount of water available to plants is increased. The uptake of water by the plant roots and the transport of the water to other parts of the plant are significantly determined by K. Potash fertilizers are directly involved in the water management of the plant since it reduces water loss through transpiration.

On-farm water use efficiency can be further improved by moving to a more efficient irrigation system. Micro irrigation has developed rapidly in recent years and adopted for a variety of high-value crops in water-scarce regions.

Table 1. Nitrogen and irrigation effects on water use efficiency (kg grain ha^{-1} mm^{-1}) and N-use efficiency (kg grain (kg fertilizer N)$^{-1}$) in wheat at Ludhiana, India (Sharma et al., 2015)

Irrigation (mm)	Water use efficiency N rate (kg ha^{-1})				N-use efficiency N rate (kg ha^{-1})		
	0	40	80	120	40	80	120
No irrigation (rain-fed)	2.8	4.4	6.3	3.6	5.3	4.8	0.9
50	5.2	9.4	10.3	10.9	23.3	12.0	9.8
120	5.7	8.4	10.3	9.0	23.0	17.6	8.8
300	5.1	7.0	8.6	8.8	19.5	20.0	14.8

Fertilizer use under rainfed condition

Insufficient and highly variable precipitation, and frequently low soil fertility are the major biophysical constraints to agricultural productivity in farming systems in the dry areas which account for about 40% of the earth's surface land area. Soil fertility in intensified farming in the semiarid zones can be maintained through the use of chemical fertilizers combined with the efficient recycling of organic materials, such as crop residues and farm manure, and the adoption of rotations with legumes, pulse crops, and green manures that fix nitrogen and improve soil quality.

Multi-location, on-farm field experiments in India demonstrated the importance of balanced fertilization in increasing yield of rain-fed crops and improving N use efficiency. Based on several balanced nutrient management experiments, agronomic efficiency of applied N was improved by applying P and K fertilizers, by 6.7 kg sorghum grain kg^{-1} N, 10.3 kg pearl millet grain kg^{-1} N and 19.5 kg maize grain kg^{-1} N (Singh et al., 2015).

Along with macro nutrients, secondary and micro nutrients are also important in dryland region. In on-farm nutrient diagnostic studies during 2002-2004 in the semiarid zone of India spread over the states of Andhra Pradesh, Tamil Nadu, Karnataka, Madhya Pradesh, Rajasthan and Gujarat it was found that 73-95% of the fields were deficient in S, 70-100% in B, and 62-94% in Zn. The consequent on-farm field trials showed significant yield increases of maize, castor, groundnut, and mungbean with applications of S, B and Zn, especially when combined with applications of N and P. The results from long-term field experiments show that integrated use of soil and water conservation practices along with balanced plant nutrient management can sustain increased crop productivity. Thus, exploiting the synergy between soil and water conservation practices and integrated nutrient management at the watershed level in the Indian semiarid tropics is vital to improve and sustain dryland farming (Singh et al., 2004).

Methods of enhancing fertilizer use efficiency

The main objective of fertilizer use is to increase the overall performance of cropping systems by providing economically optimum nourishment to the crop while minimizing nutrient losses from the field. Balanced nutrition is the key to maximizing efficient water use. All macro, secondary, and micronutrients must be present at the desirable levels; otherwise yield will be limited by the absence of that nutrient.

Integrated soil fertility management (ISFM) is a set of soil fertility management practices that necessarily include the use of fertilizer, organic inputs, and improved germplasm with greater yield potential combined with the knowledge on how to adapt these practices to local conditions, aiming at optimizing agronomic use efficiency of the applied nutrients and improving crop productivity. All inputs need to be managed following sound agronomic and economic principles.

Adding fertilizer to meet crop needs can result in greater productivity per unit of water input. The role of fertilizers in alleviation of drought stress is likely limited to cases where crops are nutrient-limited. In these situations, addition of fertilizer results in plants that are more vigorous in growth and thus more capable of using available water. Nitrogen fertilizer addition typically increases plant size, root growth and total leaf area. The role of Kin plant water relations is a critical one. Potassium functions in the opening and closing of stomata, in water transport in the plant vascular system, in regulation of cell turgor pressure, and in the process of cell elongation. Thus it is obvious that K plays a key role in response to water deficit.

Fertilizer placement influences rooting distribution, but generally not the length or volume of the overall root system. However subsurface placement of fertilizer has been recommended as a tool to influence root proliferation in deeper soil zones to avoid short-term soil drying that typically occurs near the soil surface. Starter fertilizer, placed in a concentrated band near the seed, can increase early season growth and hasten maturity in many crops including maize and vegetables. This encouragement of rapid early season development can carry through the entire season resulting in crops to avoid drought that occurs later in the season.

The standard fertilizer recommendation to rain-fed crops in semiarid regions in India is to drill or place the basal application 5 to 10 cm deep in the root zone. In the rainy season, a portion of the N dose and all P and K are applied basally. During the dry season, when little or no rainfall is expected, full amounts of nutrients for the entire crop season are recommended to be applied basally. The yield gains by adopting the recommended fertilizer placement method can vary from 340 to 1,500 kg grain ha^{-1} (Singh et al., 2015). To achieve high fertilizer N use efficiency and to avoid adverse effect of fertilizers during drought spells, split application is essential. Amount and timing of the fertilizer application have to match the rainfall distribution; 2-3 split applications are recommended depending on the crop growth period. Split application of fertilizer N along with drilling and band placement of P fertilizers lead to substantial increases in crop yield as well as nutrient use efficiency in rain-fed crops (Sharma *et al.,* 2007).

Integrated plant nutrient supply systems advocated in arid and semiarid regions of India, involve monitoring all pathways of flow of plant nutrients in agriculture. It involves judicious and integrated use of fertilizers, biofertilizers, organic manures (farmyard manure [FYM], compost, vermicompost, biogas slurry, and green manures), and growing of legumes in the cropping systems. Legumes, including twigs of N-fixing trees, are sometimes as effective as 40-80 kg urea N ha^{-1} and constitute an important component of the integrated plant nutrient supply system. Apparent recovery of N applied entirely through urea and that of conjunctive use of loppings and twigs of N fixing trees such *as Gliricidia maculata or Leuceana leucocephala* and urea in 1:1 ratio (equivalent to 40 and 80 kg Nha^{-1}) was similar. Application of 10 t FYM ha^{-1} (wet weight) along with recommended fertilizer rates stabilized the productivity of finger millet at about 3,400 kg ha^{-1} with a crop yield index of 0.66 compared to 0.36 when only chemical fertilizer was applied.

One important key to improve N use efficiency is achieving synchrony of N delivery from soils and fertilizers and the plant's N uptake demand. Site-specific nutrient management (SSNM) is an approach of supplying plants with nutrients to optimally match the inherent spatial and temporal needs for supplemental nutrients.

Improving water use efficiency to enhance fertilizer efficiency

The overall strategies to improve the efficiency of crop water use and total crop production are likely those that capture water that would otherwise escape the plant root zone and develop it for use by crops (Table 2).

There are two main avenues for mitigating poor rainfall partition and agricultural dry spells: 1) increase the water uptake capacity of plants; or 2) increase availability of water to plants. Even though these strategies focus on water, the approaches and practices to achieve them are not restricted to water management. Partitioning of rainfall and uptake of soil water by plants are good performance indicators for all land management practices and crop and soil management can improve water uptake capacity (Table 2).

In many parts of rainfed zones rainfall is highly erratic and falls as intensive convective storms with high rainfall intensity and extreme spatial and temporal rainfall variability. The result is a high risk of intra-seasonal dry spells. Such short periods of water stress can have a disproportionate effect on crop yields if they occur during water-sensitive development stages such as during flowering or yield formation. Erratic and intense rainfall can also affect nutrient losses, especially N. Flooded soil conditions result in N losses via denitrification, while N leaching is generally increased with greater water flow through soils.

Table 2. Strategies for improving rain-fed agriculture through integrated soil and water management (adapted from Falkenmark and Rockstrom, 2005)

Strategy for upgrading	**Management**	**Methodology**	**Target parameter**
Plant water-uptake capacity	Soil management	Tillage, Crop rotation Mulching, Organic manures/fertilizers	Root length and density Crop development
	Crop management	Crop choice, Inter-cropping Timing of operations, Pest management	
Plant water Availability	Soil management	Tillage, Soil and water conservation, Mulching Crop rotation, Organic manures	Soil infiltrability Water-holding capacity
	Water management	Water harvesting	Dry spell mitigation

Nutrient and fertilizer management in rice systems

Global production of rice relies heavily on the use of well-adapted high-yielding rice varieties, fertilizer, and irrigation. Rice is a major beneficiary of irrigation water resources, receiving an estimated 34-43% of global irrigation water. An estimated 24-30% of the world's freshwater resources are used for irrigation of rice. Based on 2010 statistics, global rice production accounts for 15% of global fertilizer nitrogen (N) use and 13% of global fertilizer P and potassium (K) use. In Asian rice production, fertilizer is often the second most important input cost, after labour, accounting for 15-30% of total production costs for irrigated rice in Asia depending on government subsidies and labour costs.

Approximately 90% of the global rice production area undergoes periodic or prolonged submergence of soil with water originating from rain and irrigation. Soil submergence and corresponding restriction of soil aeration create a favourable environment for sustained production of continuous rice. Soil submergence helps control weeds, alters soil biological and chemical processes leading to increased supply of plant-available soil N and P, and maintains soil organic matter. Competing non-agricultural demands for irrigation water will reduce its supply for rice production in the future. Rice can also be planted by direct seeding, using either wet seeding, with pre-germinated seed broadcast on a puddled soil surface or dry seeding after normal soil tillage with flooding after the seedlings are established. More recently, aerobic rice, system of rice intensification (SRI) technique and irrigating rice fields with drips and micro sprinklers are also gaining ground. A corresponding reduction or elimination of soil submergence and saturation during rice production would increase penetration of air into soil (i.e., soil aeration). This could decrease the supply of plant available N and P from soil leading to a need for additional N and P fertilizer to achieve a target yield. Irrigation water contains K, and reduced input of irrigation water can consequently increase the need for K fertilizer to meet crop requirements for K. Regardless of the extent of soil submergence, N fertilizer should be managed to ensure adequate supply of plant-available N to match crop demand at critical growth stages of tiller development and panicle initiation. When changes in water supply alter anticipated crop yield, fertilizer use should be adjusted to match crop needs for added nutrients at a revised target yield. Nitrogen fertilizer broadcast (Photo 1) into lowland rice fields is susceptible to gaseous losses, especially by ammonia volatilization. To increase the efficiency of urea (main source of N fertilizer) it should be mixed with 2-5 times of clay soils and make dough and can be applied in the rows of crop. Neem or lac or sulphur quoted urea or prilled urea mixed with wet soils, 48 hours before its application can decrease of N losses through NH_3 volatilization and nitrification-denitrification. The N fertilizer broadcast before tillering is most prone to loss because of the low demand of the rice crop for N. The efficiency of N fertilizer use can be increased by avoiding excess early supply of N before tillering and ensuring N is supplied at rates matching the crop's need for supplemental N.

All P fertilizer is normally recommended immediately before or soon after crop establishment to ensure ample P for early root development. All or most of the required K is typically recommended for application immediately before or soon after crop establishment. In fields with high requirement for fertilizer K, where yields are high and there was partial or complete removal of crop residues from the previous crop, upto half of the total K fertilizer can be applied with N fertilizer at panicle initiation. This application of K can improve grain filling.

Organic materials have been promoted as nutrient sources for rice production in response to rising costs of industrial fertilizers. Organic materials includes crop residues, farm yard manure, livestock excreta, green manure, compost, vermin-compost, farm waste, municipal waste etc. Rice and wheat crop residues produced annually in Punjab state only are to the extent of 20.8 and 23.3 Mt, respectively (Mandal, 2011). While most of the wheat residue is removed from the field and used as animal fodder, majority of rice residue is burnt in the field itself resulting in not only loss of C and N present in the straw but also loading of green house gases to the environment. However, removal or burning of residue ensures the farmers to quickly prepare seedbed and simultaneously circumvent the risk of reduced crop growth due to N immobilization during decomposition of the residue having wide C:N ratio. Therefore, effective residue management practices should aim at minimizing the risk of N immobilization and improving soil fertility without degrading the environment. In rice-wheat cropping system in the north-western India, decomposition of rice residue to the extent of ~25% during the pre-wheat fallow period was sufficient to avoid any detrimental effects on wheat yields. Rice and wheat productivity was not adversely affected when rice residues were incorporated at least 10 days and preferably 20 days before sowing of wheat as the succeeding crop. A small starter dose of fertilizer N may also accelerate the process of decomposition and avert the problem of N-immobilization. Another easy and cost –effective option to minimize the adverse effects associated with the burning or direct incorporation of wide C: N ratio, crop residues is to compost the rice straw and thus to narrow C: N ratio prior to its application in fields. The compost thus produced could safely be applied in the field without any risk of N –immobilization. The value of the compost could be improved if rock phosphate is mixed with the straw while composting. There is also a huge amount of city wastes including municipal solid wastes produced and left almost unused, if properly managed would be a cheap source of soil C and nutrients. The practice of raising a pre-kharif crop like greengram, cowpea, sunnhemp or Sesbania for use as green manure helps ensure production sustainability in rice-based cropping systems. Biofertilizers such as blue-green algae or Azolla are capable of providing 20-25 kg N/ha, if added as partial supplemental to inorganic fertilizers. The incorporation of organic materials, including crop residues, to submerged soil can also accelerate conversion of sulfate to sulfide that can precipitate zinc and thereby reduce its availability to the rice crop, enhance production and emission of methane, and favour formation of organic acids that can adversely affect rice growth. Soil drying and aeration can reduce these effects.

The use of irrigation water on puddled soils can be reduced by lowering the depth of floodwater and by allowing the soil surface to dry before the next application of irrigation water. The practice of withholding irrigation until several days after the disappearance of floodwater has been referred to as 'controlled irrigation', 'intermittent irrigation', and 'alternate wetting and drying' (AWD). Safe AWD, as compared to irrigation with continuous soil submergence, can reduce use of irrigation water, reduce accumulation of arsenic and cadmium in grain, increase zinc availability in acid soil, but it can decrease zinc and iron availability on high-pH soils, leading to a need for iron and zinc fertilization for dry-seeded aerobic rice and reduce methane emissions. It can however require more labour for weed control, and the absence of floodwater increases risk of crop damage from rats. This water saving systems hardly curbs emission of total GHGs from the system compared with the conventional practice because of increased formation of N_2O under alternate wetting and drying water regime of SRI.

Fertilizer use and the environment

Fertilizer, despite being very effective in driving crop yield improvements, has been found to have negative impacts on the environment. Fertilizers are responsible for the eutrophication of surface water, contamination of ground water, accumulation of dangerous or toxic chemicals and emission of greenhouse gases (Table 3). Nitrogen fertilizers acidify soils and that may reduce nutrient availability. In few districts of West Bengal under high cropping intensity soil acidification has been on the rise. Nitrate contamination in ground water poses a significant health hazard. Also, significant portion of the unabsorbed nitrogen fertilizer volatizes in the form of N_2O a major greenhouse gas, having 298 times more global warming potential than carbon dioxide.

The degradation of the soil fertility and other environmental concerns are widespread in South Asia including India mainly due to the high use of nitrogenous fertilizers, inadequate knowledge of farmers, and availability of low quality fertilizers. Relatively strong consumption towards nitrogenous fertilizer use is mainly due to low prices of nitrogenous fertilizers caused by the subsidy policy systems. Despite the fact that plants absorb K in equal quantity as N, soil potassium mining due to negative potassium balances is prevalent in entire south east Asia. FAO statistics show that the NK ratio in India and Bangladesh varies between N:K =1:0.10 to 1:0.15. It may be emphasized here that K is responsible for plant's metabolism, translocation of other nutrients, and many more tasks essential for crop development. Adequate K is also needed to increase the efficiency of N. Most farmers use fertilizers indiscriminately without adequate information on actual soil/plant requirements and they often fail to synchronize fertilizer application and crop uptake. The high fertilizer application by farmers for over-optimistic yield expectations often leads to considerable leaching of nitrate. Moreover, the delay between fertilizer application and crop uptake increases the chance for environmental losses through leaching, volatilization, and denitrification. Furthermore, the loss of nitrate is further increased due to other limiting factors such as deficiencies of secondary or micronutrients.

It is often argued that one of the ways to reduce the adverse environmental impacts of fertilizer is through increasing the use of organic fertilizer. However, organic fertilizers cannot exclusively help attain the production sustainability of soil and crops under high-intensive cropping systems.

Like inorganic fertilizers, organic fertilizers also pose a potential risk to the environment. Only proper planning and management will minimize the risk.

Table 3. Environmental consequences of excessive N use (Mujeri et al., 2012)

Environmental consequence	Causative Mechanism
Groundwater contamination	Nitrate leaching from soil
	Erosion, surface runoff, and seepage of N
Eutrophication	From agricultural fields
Acid rain and ammonia redeposition	Ammonia volatilization
Global warming	Nitrous oxide emissions from soil
Stratospheric Ozone depletion	Nitrous oxide and nitric oxide emissions from soil

Conclusion

In order to address the issue of food security in India with very high density of population is destined to stay dependent on fertilizer use to increase food production. However, the negative impacts of fertilizer on the environment pose a threat to the sustainability of the agriculture system. So, it is now imperative to ensure balanced and efficient use of organic and inorganic fertilizers through improved soil and water management practices and policy making so that the primary nutrients, secondary nutrients, and various micro nutrients are available in the soil in correct amounts for proper nutrient intake by crop plants and that there is minimal negative effects on the environment.

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Fertilizers: good and bad

India occupies an area of 329 M ha and ranks 7th in the world. While it has only 2.5% of the world area, it is home to 17% of the world population. The net sown area of 141 million hectare (M ha) has remained nearly constant during the last 50 years, but the per capita availability of gross sown area has declined from 0.36 to 0.16 ha per person. Foodgrains cover an area of 122 M ha, out of 191 M ha gross sown area. The area under rice and wheat has increased at the expense of area under coarse grains but overall area under foodgrains remained almost constant. There is a large increase in fertilizer consumption since 1950s. The fertilizer (N, P and K) consumption, which was only 0.07 million tonne (Mt) in 1950-51 increased to 28 Mt in 2010-11. The increase has been greatest in fertilizer N use (from 1.6 kg N ha^{-1} in 1961 to 87 kg N ha^{-1} in 2014) followed by P (0.39 to 31.4 kg P_2O_5 ha^{-1}) and the least in K (0.18 to 13.03 kg K_2O ha^{-1}). As a result, N, P and K use ratio is highly skewed towards N (6.7:2.4:1 in 2014-15). Increase in fertilizer use coupled with improved crop varieties, access to irrigation water and farm mechanization resulted in more than 5-fold increase in foodgrain production; from 52 Mt in 1951-52 to 265 Mt during 2013-14 (Fig. 1). On an average, each tonne of fertilizer NPK consumed in the country, since 1960s, enhanced foodgrains production by 6.6 tonnes. Despite the large gains in foodgrains production with fertilizer consumption, a debate rages among experts and the planners on the impact of mineral fertilizers on environment and human health. While exponents of fertilizer use believe that intensification of agriculture with increased use of inputs is the best way to produce more food and ensure national food security, the others argue that fertilizers adversely impact the environment and soil fertility and have economic implications. In favour of fertilizer use it may be argued that fertilizer use, particularly N, is the most important factor that has been able to sustain growing world population. There is a strong parallelism between world population and N-fertilizer consumption because of latter's role in cereal production. As the global population increased from 3 to 7 billion during 1961 to 2011, the world cereal production and N fertilizer consumption increased from 876 to 2582 Mt and ~12 to 108 Mt, respectively. Similarly, in India as the population grew from 0.46 to 1.3 billion during 1961 to 2014, the food grain production increased 3.2 fold and the fertilizer consumption increased 67.8 and 11.4 fold since 1961 and 1970, respectively. The dissimilarity between increase in foodgrains production and fertilizer consumption particularly of nitrogen, suggests that much of the added N has been lost to the environment as reactive N (Nr) species (nitrogen forms other than N_2). The reactive N produced disturbs the natural N cycle, which directly and indirectly impacts the environment and human health (Table 1).

Soil degradation

Crop response trends over the last five decades show that foodgrain crops are no longer exhibiting increased productivity with increase in input use. The partial factor productivity of fertilizer NPK for foodgrain production in India has gradually declined from ~50 in 1970-71 to ~10 in 2014-15 (Fig. 2). This shows that the nutrient use efficiency of the added fertilizers is dropping implying thereby that the farmers have to add increasing amounts of fertilizers, and thus spend more money, to merely maintain yields. There could be many reasons for the decline in the crop response to applied fertilizer nutrients. First, it is natural, since the law of diminishing returns will operate and show its effect with each successive increase in fertilizer nutrient dose. But a large part of this decrease could also be ascribed to imbalanced application of fertilizers (skewed N: P: K ratio) leading to nutrient depletion in soil and gradual decline in the supply of soil nutrients. Therefore, imbalanced application of fertilizers not only impacts crop productivity but also leads to soil degradation. The problem is further aggravated by non-recycling of organic sources, soil erosion and leaching. Globally, nutrient depletion is the major form of chemical degradation of soils and covers 135 Mha, which represents 7%of the area affected by human induced soil degradation. In India, about 18 Mha area is affected by chemical degradation.

The addition of N fertilizers can play both positive and negative roles in the maintenance of soil health. The positive role includes C sequestration in soil and the negative role includes mineral N induced mineralization of soil organic matter and release of CO_2 to the atmosphere (Nieder and Benbi, 2008). The long-term use of N fertilizers besides causing soil acidification can lead to leaching of soil cations (Ca, Mg, K) with NO_3^- from applied fertilizers or removal of soil cations in increased harvests of agricultural produce. If soil acidity is not controlled this will lead to deterioration of soil health and yield loss due to Al and Mn toxicities. Soil acidity adversely impacts nutrient availability and life and activities of soil microorganisms and increases the concentration and bioavailability of toxic metals in the soil solution.

Environmental and human health impacts

Inefficient and excessive use of fertilizers not only makes fertilizer consumption uneconomical but also produces adverse effects on the environment such as ground and surface water contamination (leaching of nitrate, phosphate and heavy metals), eutrophication of inland and coastal waters, emission of greenhouse gases causing global warming, formation of aerosols and particulate matter and acid rain and nitrogen deposition leading to loss of biodiversity and acidification of surface water (Table 1). A number of studies have shown that the leaching losses of N are related to the amount of fertilizer input, particularly under rapidly percolating coarse-textured soils (Benbi *et al.*, 1991). Nitrate drained into surface water bodies, e.g., rivers, lakes, or estuaries, can cause deterioration of surface water quality, resulting in eutrophication, algal bloom, and fish poisoning. High concentration of NO_3^- in drinking water is deemed harmful to

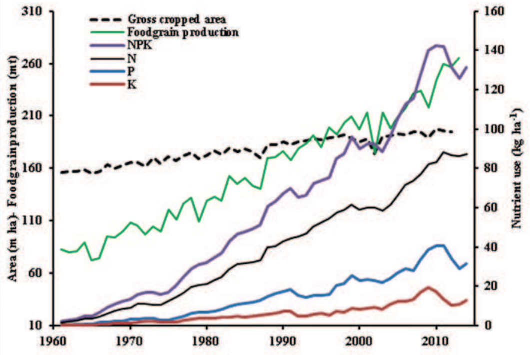

Fig. 1. Trends in fertilizer consumption, foodgrains production and gross cropped area in India during 1960 to 2015 (Source: Directorate of Economics and Statistics, Govt. of India)

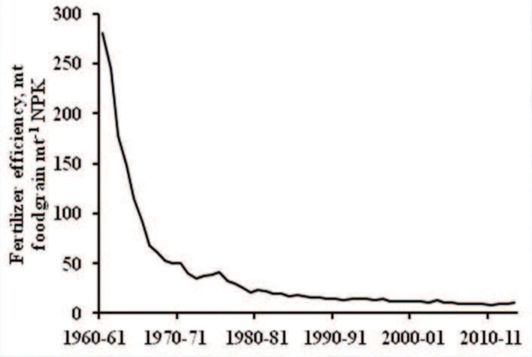

Fig. 2. Efficiency of fertilizer N, P and K use for food grains production in India during 1960-61 to 2014-15

human health. As per World Health Organization (WHO) standards, groundwater having more than 10 mg NO_3-N l^{-1} is unfit for drinking. Reports from some developed countries show that the critical limit has been exceeded in a significant proportion of water samples. However, studies from different regions of India show that though the NO_3^- content in groundwater shows an increasing trend with fertilizer use, particularly in shallow aquifers, but the permissible limit of 10 mg NO_3-N l^{-1} has not been exceeded.

Besides leaching, nitrates in soil may be denitrified to N_2O and NO and emitted to the atmosphere. Nitrous oxide is one of the greenhouse gases that is believed to be forcing a global climate change. About two-thirds of the total global N_2O emissions emanate from nitrification- denitrification processes in soils. The emissions increase with increasing input of fertilizer N. About 1.25% of the fertilizer N is lost as N_2O from soil though some studies in India put this figure at 0.4% for rice-wheat system. Oxides of N, ammonia, sulfur dioxide, and non-methane volatile organic compounds can become gaseous precursors of aerosols. The aerosols may influence climate in several ways: directly through scattering and absorbing radiation and indirectly by acting as cloud condensation nuclei or ice nuclei, modifying the optical properties and lifetime of clouds. The aerosols play a role in human health, in acid rain that threatens land and aquatic eco-systems, and soil fertility. Clearly, N fertilizers have negative effects on the climate.

Table 1. Environmental and human health effects associated with fertilizer use

Impact	Cause
Ground and surface water contamination	Nitrate leaching and runoff
Eutrophication of inland and coastal water; hypoxia of coastal waters	Excessive N and P loading in water caused by soil erosion, surface runoff and submarine groundwater discharge
Acidification of surface water	Acidification of soils, streams and lakes caused by atmospheric deposition of sulphur, HNO_3, NH_3 and its compounds
Acid rain and nitrogen deposition	Nitric acid originating from reactions of N oxides with moisture in atmosphere, ammonia volatilization
Loss of biodiversity	Nitrogen deposition in excess of critical load
Global warming	Denitrification, nitrous oxide emissions from soil
Aerosol formation	Gaseous precursors such as oxides of nitrogen, ammonia, sulfur dioxide, and non-methane volatile organic compounds (secondary particles)
Forest decline	Ozone and acid deposition
Methaemoglobinaemia	Consumption of high nitrate through water and food
Gastric cancer	Excessive intake of nitrate in food and water leading to endogenous formation of carcinogenic N-nitroso compounds
Human illnesses and mortality	$PM_{2.5}$, ozone and related toxins caused by NO_x and NH_3 emissions, formation of aerosols

Besides environmental degradation, excessive application of fertilizer nutrients and their accumulation in plants can have adverse effects on food production and human health. Excessive N fertilizer application could increase the concentration of nitrate in crops, especially vegetables such as spinach, parsley, lettuce, cabbage, cauliflower, celery etc. The excessive intake of nitrate in vegetables is often associated with methaemoglobinaemia (blue baby syndrome) and the possibility of endogenous formation of carcinogenic N-nitroso compounds in humans. However, opinions differ on the effects of high dietary intake of nitrate on human health.

Fertilizers, indisputably, are the best hope for meeting the food challenges of the future. However, inefficient use of fertilizers can have adverse impacts on environment and soil as well as human health. In order to minimize environmental footprint it is imperative to improve fertilizer use efficiency. The strategies to improve fertilizer use efficiency, *inter alia*, include soil-test based balanced application, adoption of proper source, rate and method of application. Obviously, improvements in fertilizer use efficiency in crop production are critical for addressing the twin challenge of food security and environment conservation in India.

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Reactive N and climate change

Nitrogen is the most limiting nutrient controlling production of all agricultural systems. Application of N fertilizer has increased food production tremendously all over the world. However, it also contributes towards global warming and ozone layer depletion through emission of nitrous oxide (N_2O), a greenhouse gas (GHG). The N_2O emissions from Indian agricultural soils is estimated to be 0.26 m tons (BUR1, 2014). Burning of crop residues in field and management of manure also emit N_2O. Emission of N_2O is increasing over the years because of increased N fertilizer use as the N fertilizer contributes about 70% of the emission Worldwide, use efficiency of external nitrogen supply is as low as 33 per cent and rest remains unaccounted for. A single nitrogen molecule (N_2) introduced anywhere in system can have cascading effects in various parts of the environment, after it has been converted to reactive nitrogen forms, such as ammonia (NH_3), nitrogen oxides (NO_x), nitrous oxide (N_2O), nitrate (NO_3^-), urea, amines, proteins and nucleic acids. However, efficient management of N offers opportunities for climate change adaptation and GHGs mitigation.

Emission of gaseous N

Agricultural activities have greatly altered the global N cycle and produced nitrogenous gases of environmental significance. There are a variety of sources of N in agricultural systems that are anthropogenic. These include (a) synthetic fertilizers, (b) animal manures, (c) N derived from enhanced biological N-fixation through N_2-fixing organisms, (d) crop residue returned to the field after harvest and (e) human sewage sludge application. Although some part of the N from animal manures, crop residue and sewage may have come from previous application of synthetic fertilizer, the reentry of this N into soil system again renders it susceptible to microbial processes of transformation. A major consequence of this human-driven change in global N cycle is the increased emission of N-based trace gases, such as nitrous oxide (N_2O), NO_x ($NO + NO_2$) and ammonia (NH_3) that impacted regional and global atmospheric chemistry. Figure 1 shows the contribution of different sources to nitrous oxide emission from Indian agricultural soils in 2010 (Bhatia *et al*., 2013).

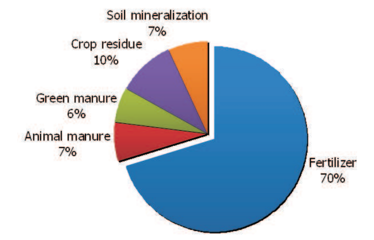

Fig. 1.Contribution of different sources to nitrous oxide emission from Indian agriculture in 2010

The N_2O is emitted into the atmosphere from both natural (like water bodies and soils) as well as from anthropogenic activities like agriculture, transport, industries and waste management practices. Nitrous oxide is produced naturally in soils through the processes of nitrification and denitrification. Nitrification is the aerobic microbial oxidation of ammonium to nitrate, and denitrification is the anaerobic microbial reduction of nitrate to nitrogen gas (N_2). Nitrous oxide is a gaseous intermediate in the reaction sequence of denitrification and a by-product of nitrification that leaks from microbial cells into the soil and ultimately into the atmosphere. The emissions of N_2O that result from anthropogenic N inputs or N mineralization occur through both a direct pathway i.e., directly from the soils to which the N is added/released, and through two indirect pathways following (i) volatilization of NH_3 and NO_x from managed soils and from fossil fuel combustion and biomass burning, and the subsequent re-deposition of these gases and their products NH_4^+ and NO_3^- to soil and water; and (ii) after leaching and runoff of N, mainly as NO_3^- from managed soils.

The release of nitrogen oxides ($NO_x = NO + NO_2$) has accelerated during the last few decades primarily through the increase in fossil fuel combustion. The NO_x emission is predominantly contributed by sources such as vehicular exhaust, coal combustion and biomass burning. The higher temperatures in the flame during combustion are generally responsible for the formation of NO_x as it helps in breaking down the molecular N_2 and O_2 of the air which recombines to form NO_x which includes both nitric oxides (NO) and nitrogen dioxide (NO_2). The vehicular exhaust is the largest contributor of NO_x. The NO_x emission from the soil is primarily a result of NO production by the microbial oxidation of ammonium, the process known as nitrification. The NO production in the soil also occurs through the microbial reduction of nitrate (denitrification). This reaction only occurs in water saturated soils where little NO is released from the soil to the atmosphere.

Use of fertilizers in the agricultural sector and rearing of livestock are mainly responsible for NH_3 emission. The emission estimates of NH_3 are highly uncertain in India and the loss of ammonia varied from 0.98 to 25.8 kg N ha^{-1} depending upon soil type, crop and fertilizer material. Some studies have shown that the leaching loss of N from soils in the IGP is 10-15 kg N ha^{-1} while the ammonia volatilization loss is 20-30 kg N ha^{-1} with application of 120 kg N ha^{-1} in rice and wheat (Banerjee *et al*., 2002; Aulakh and Bijay-Singh, 1997)

Nitrogen and climate change

Nitrogen has direct, indirect and also short- as well as long-term effects towards global warming and cooling and thereby climate change. The warming effects of N include (1) N_2O emissions, which is a greenhouse gas with long atmospheric lifetime (IPCC 2007); (2) NO_x emission, which contributes to formation of tropospheric O_3, a short-lived GHG lasting several weeks; and (3) detrimental effects of ozone on plant C sequestration. The cooling effects include (1) C sequestration due to application of N, which increases plant CO_2 fixation (de Vries *et al.,* 2011); (2) losses of N to water bodies, where freshwater and marine eutrophication can increase CO_2 removal from the atmosphere (Boyd *et al*., 2010); (3) increasing oxidation potential of the atmosphere by O_3, which decreases the atmospheric lifetime of CH_4 and increases rates of aerosol formation; and (4) NO_x and NH_3 emissions, which contribute to formation of ammonium and nitrate aerosols. In addition, tropospheric O_3 and NH_3 both accelerate the oxidation of sulphur dioxide (SO_2) to sulphate aerosols. The Nr supply also affects CH_4 production and consumption in soils (De Vries *et al.,* 2011) and albedo of the land surface by affecting vegetative cover and increasing chlorophyll content of vegetation (Hollinger *et al*., 2010). There are strong feedback effects of climate change on Nr availability through the effects of temperature and rainfall patterns on the cycling of Nr (Erisman *et al*. 2012).

Nitrogen management for enhancing efficiency and climate change mitigation

Intensive agricultural systems, envisaging high productivity, high input use, high rainfall or irrigated systems, are widely recognized as major sources of gaseous N emissions. Currently farmers' decision on input use is based on 'field average' concept combined with visual observations**.** Rather than such blanket applications, there is an urgent need for fine-tuned N use based on season- and field-specific monitoring of crop and soil nutrient status. Appropriate crop management practices, which lead to increased N-use efficiency and higher yield by optimizing the crop's natural ability to compete with the N-loss processes, hold the key to mitigating gaseous N losses. Some approaches for increasing NUE are:

- Optimal time, rate and methods of application for matching N supply with crop demand
- Split fertilizers application, customized fertilizers at different sites
- Slow release fertilizers including those with urease and nitrification inhibitors
- Integrated use of fertilizers, manures and crop residues
- Demand-driven N supply using leaf colour chart and green seeker
- Water-use-efficient technologies such as fertigation, sprinkler, drip, etc.
- Other specially formulated fertilizers or methods of use
- Adoption of nitrogen use efficient crop cultivars

It has been shown that nutrient-use efficiency can be improved by adopting fertilizer, soil, water, and crop management practices that will synchronize N supply and demand, maximize crop N uptake, minimize losses, and optimize indigenous supply. There is a need to ensure informed choice of the available options and better implementation at the farm level, to achieve the optimal congruence between crop N demand and N supply. Using proper fertilizer formulation and right method of application, use of N-transformation inhibitors, optimizing tillage, irrigation and drainage and growing of suitable crop cultivars are some of the potential technologies. However, adoption at the farm level has been limited for various reasons in developing countries. Efficient use of N is absolutely essential for attaining the goal of sustainability in agriculture. Better management of N in agriculture by enhanced implementation of all the available tools and techniques could immensely help the farmers, consumers, and government. It could well be the driving force for climate change mitigation. Because of strong inter-relationship among N use, climate change and food security, future N management strategies should be developed with a target of climate change mitigation and adaptation.

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Manipulating plant roots in the soil environment: A key to yield sustainability

India had a phenomenal increase in foodgrain production (from 50 million tonnes in 1950-51 to about 250 million tonnes in 2014-15), ensuring the national food security. However,in recent years, the country is facing new challenges viz., yield plateauing of cereal crops, degradation of soil and land resources, diminishing water availability and climate aberrations. On top of that, India shares a quarter of the global hunger burden. Imbalance use of fertilizers, especially use of urea alone has caused a huge damage to the soil health. Concerns are, therefore, emerging on the sustainability of agriculture in the long run.

Success of agriculture largely depends on water, while the response of fertilizer to crops is primarily determined by the water-nutrient synergy. Limited availability of water and poor fertility of soils have been major constraints in low-input agriculture, and is prevalent in many parts of India. On the contrary, imbalance use of fertilizers, and indiscriminate pumping of ground water for irrigation have been two major issues related to high-input systems. Practices in improving water and nutrient use efficiencies in large numbers are being advocated, although a few of these pay attention on plant roots, the hidden half of the plant. Roots with better efficiency in water and nutrient capture will certainly reduce the impacts of intensive fertilization and irrigation, and make the system more sustainable. It is argued that the food demand of the 21st century can be met through the understanding and manipulation of the belowground roots (Bishopp and Lynch, 2015).

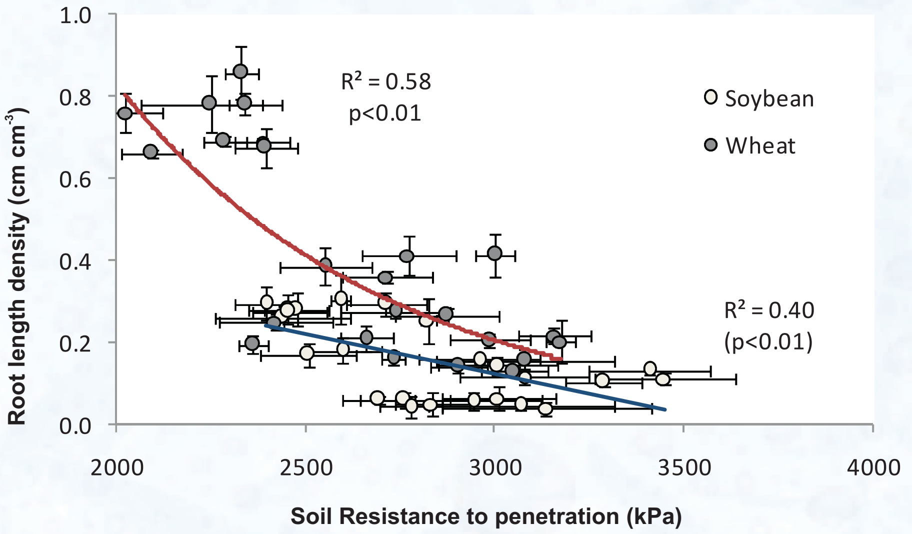

Fig.1. Root growth in soybean and wheat crops in rotation increased with reduction in soil strength at sub-surface layer through deep-chiselling

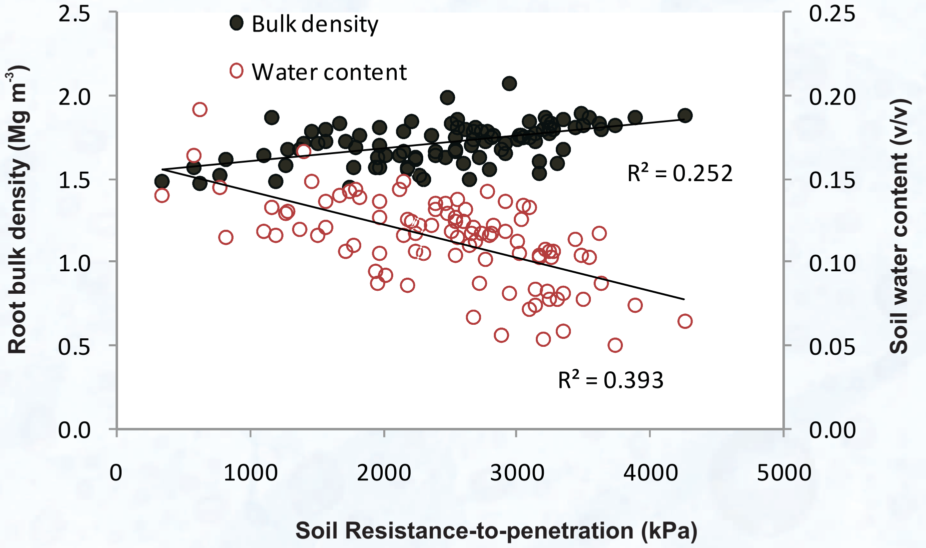

Fig.2. Soil resistance to penetration as a factor of bulk density and soil water content at different layers of soil

Considering the fact that huge gaps between yield-potential and actual yields often exist, and the yields of high-yielding varieties appears plateauing, there could be limitations by the plants in utilizing the available nutrients in soil. In intensive cropping systems, especially in rice-wheat rotation, the sub-surface compaction has been noticed (Kumar *et al.*, 2014). Drying of the soil makes the situation even worse. These conditions may restrict root growth, leaving a limited volume of soil for the roots to explore for water and nutrient acquisition. This may potentially reduce the yield (Whiteley and Dexter, 1982). In physical terms, penetrometer resistances >2 MPa, air-filled volume of 10% and a matric potential < -1.5MPa limit root elongation even to less than half of its normal, unrestricted elongation rate (Bengough*et al.*, 2011). Mechanical impedance often limits root elongation, even when the soil is relatively wet (Whalley*et al.*, 2008; Bengough*et al.,* 2011). It is imperative that soil becomes soft after irrigation and/or rainfall, allowing the roots to penetrate, but becomes hard on drying, restricting the root growth, even though the soil is sufficiently wet. Soil resistance to penetration is closely linked to root growth. Deep-chiselling to break the sub-surface compact layer increased root length in both soybean and wheat crop in rotation (Fig. 1; Ahmed, 2015). A major consequence of the effects of compaction lies in understanding the role of co-factors, including soil water status. For example, it may decrease the soil matric potential (Whalley*et al.*, 2006) and hydraulic conductivity, thus reducing water availability to plants, and can aggravate the effects of drought. However, water content may have larger effect than that of the bulk density in imparting soil strength (Fig, 2; Unpublished).

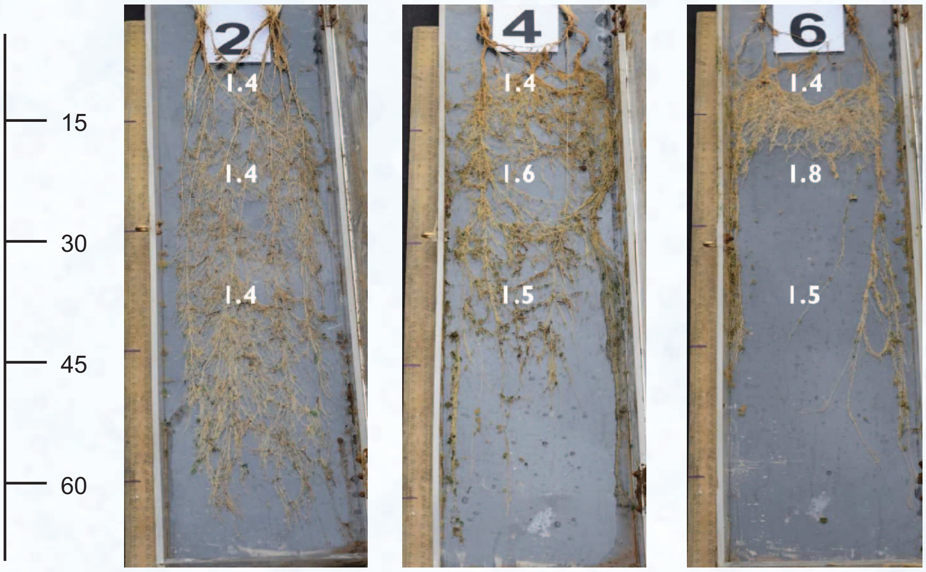

Fig.3. Distribution of roots in wheat in rhizobox as affected by the compact layer at 15-30 cm.

In a controlled experiment with compacted soil condition at 15-30 cm, an abrupt reduction in root length of wheat in this layer was recorded (Fig. 3, Unpublished). However, at surface layer (0-15 cm) roots became thick with larger surface area and volume (Fig. 4, Unpublished). Length, surface area and volume of roots were significantly ($p<0.01$) lower at compacted sub-surface layers (BD 1.6 and 1.8 Mgm^{-3}). On the contrary, average diameter of roots became higher at surface, indicating thicker roots at surface when the soil strength was higher at sub-surface. Soil texture has strong influence in modifying the root response to compaction. In the clay loam soil, roots experienced less adversity of compaction, even when the soil was dry (limited water), compared to sandy loam soil in otherwise identical situation. Depending on the soil properties, little drying may increase the strength of soil sufficiently to reduce root elongation. Thus, in moderately dry soil, mechanical impedance is likely to be a major factor limiting root growth. Soil with higher clay content (clay loam) facilitates more water retention and could negate the effect of sub-surface compaction on the root growth, even in limited water condition.

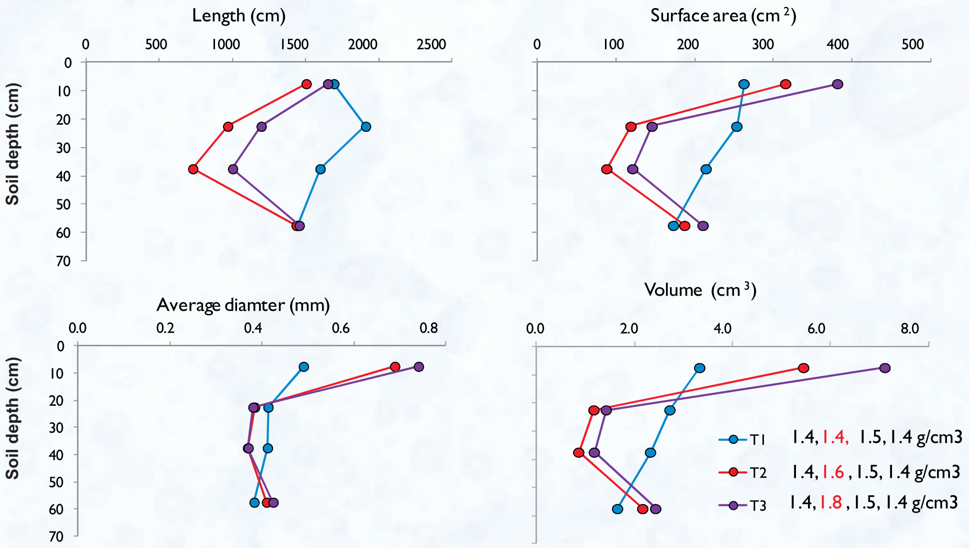

Fig.4. Root morphological changes in wheat under sub-surface (15-30 cm) compaction

Sustainability in rice-wheat cropping system is of paramount importance for ensuring national and global food security. Conventional system of tillage in rice-wheat system has developed a compact layer just below the plough pan, which adversely affect the yield of the crops, especially in wheat (Dwivedi*et al.*, 2012; Singh *et al.*, 2014). In a quest to sustaining yields, and address the issues related to the conventional system, conservation agriculture practices have been introduced. Conservation tillage can improve soil physical condition, although the impact varies widely with soil types. However, due to absence (or reduction) of tillage, soil bulk density and the soil resistance-to-penetration are likely to be different under alternate tillage and crop establishment practices. The bulk density at sub-surface (15-30 cm) layer was marginally lower (2-8% less in conservation plots) after 5 years in a conservation agriculture (CA) experiment with rice-wheat rotation at IARI, New Delhi (Chakraborty, Unpublished) in a clay loam soil. Soil pores which drain water at 100 cm suction constituted of 27-34% of total pores in 0-60 cm profile, and were extremely variable across the soil layers. Pores that retained water (i.e., small meso- and micro-pores) corresponding to a suction >100 cm, were higher in conservation agriculture (CA), ensuring a higher plant-available water content. Zero-tillageresulted in marginally higher root length and root surface area of wheat at 0-15 cm while at 15-30 cm, significantly higher total root length was recorded, compared to conventional system.

Alternate tillage practices bring modifications in soil physical environment, and the root behaviour. Engineering root architecture through breeding or by other means also leads to manipulation of the soil environment, where roots play a major role in improving nutrient and water use efficiency to the benefit of plant growth. These will aid in better input management decisions for ensuring higher productivity and use efficiency.Manipulation of root anatomy and architecture is recently being given due attention e.g., the introduction of allelic variation in the *DRO1* gene into rice lines for deeper rooting and improvement of drought avoidance in the crop (Uga*et al*., 2013). With the availability of advanced tools for study of root anatomy and architecture, scope of manipulating the roots for greater efficiency under adverse condition seems possible. Physical understanding of the soil system must also be accompanied.

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**Editors: H. S. Sen, Biswapati Mandal, Dipankar Ghorai,
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