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Review/Overview Article

Need for determining ecofriendly optimum fertilizer nitrogen level for better environment and for alleviating hunger and malnutrition

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ABSTRACT

Asia accounts for about two-thirds of hungry and malnourished people in the world and within Asia, South Asia, which includes India, Pakistan and Bangladesh accounts for about 34.3%, which in absolute numbers are 276.4 million people. Cereals are the staple food in Asia and alleviation of hunger aims at increasing the availability of cereals (rice, wheat, maize etc.) in these countries. It is estimated that without fertilizer nitrogen about half of the world population would have remained hungry and malnourished. However, excess fertilizer nitrogen is detrimental to the environment. Ammonia volatilized from surface applied fertilizer nitrogen reduces air quality, while nitrous oxide is a powerful greenhouse gas contributing to global warming and is also responsible for depletion of atmospheric ozone. Excessive nitrogen fertilizer is reported to increase nitrate concentration in drinking water leading to blue baby syndrome or methaemoglobinemia, while eutrophication of surface water is responsible to mortality of fish and other sea creatures. Therefore, efforts are underway to increase the efficiency of fertilizer nitrogen by using 4Rs, namely, right source applied at the right rate, time and depth. A number of studies have indicated that it is possible to obtain the desired production of cereals with much lesser nitrogen rates and it is suggested to shift from economic optimum rate ($Econ_{opt}$) to ecological optimum rate ($Ecol_{opt}$) rate of nitrogen application to cereals in making out fertilizer recommendations. This exercise has not yet been done by the agronomists in India and is strongly recommended.

Key words : Agronomic efficiency of N (AE_N), $Ecol_{opt}$ rate of nitrogen, $Econ_{opt}$ rate of nitrogen, Fertilizer nitrogen, Hunger, Malnutrition, Recovery efficiency of N (RE_N), $Yield_{opt}$ rate of nitrogen

With all the advances in agricultural technology millions of people even today go hungry to bed in the world and need our attention and help. Hunger is caused by the want or scarcity of food in a country or by lack of money to buy food by the poor people. In many countries both these occur simultaneously, because when food is in short supply, the prices also rise making it more difficult for the poor to procure it. Hunger leads to malnutrition and undernutrition and protein-energy malnutrition (PEM) are of foremost importance (Prasad, 2013). Protein is essential for the development and maintenance of body tissue and as enzymes is responsible for the key body functions and therefore for the life. PEM leads to wasting or loss of muscles (known as *marasmus*) in adults and if not corrected may lead to death. In children protein deficiency despite adequate energy leads to *kwashiorkor*, which is characterized by *edema*, irritability, anorexia, ulcerating dermatoses, and an enlarged liver with fatty infiltrates. Sufficient calorie intake, but with insufficient protein consumption, distinguishes *kwashiorkor* from *marasmus*. Both *marasmus* and *kwashiorkor* cases occur in areas of famine or poor food supply. Most (98.2%) of the world's undernourished people are in developing countries of the world in Asia, Africa, Latin America and the Carribbeans (Table 1). Asia accounts for about two-thirds (66.5%) of malnourished people in the world and within Asia, South Asia (Afghanistan, Bangladesh, Bhutan, India, Maldives, Nepal, Pakistan, and Sri Lanka) accounts for about 34.9%, which in absolute numbers are 276.4 million people.

Alleviating hunger with increased food production

The only way to alleviate hunger and PEM is by producing more and better quality food. Cereals rank number one in food and in South and East-Asia, rice and wheat supply and will continue to supply 50% or more of calorie needs of humans as compared to only 30–33% in in-

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Table 1. Spread of under-nourishment in the world (2012–14)

Region	Million	Percentage of total
World	805.3	100.0
Developed regions	14.6	1.8
Developing regions	790.7	98.2
Africa	226.7	28.7
Asia	525.6	66.5
East Asia	161.2	20.4
South-East Asia	63.5	8.0
South Asia	276.4	34.9
Latin America and Caribbean	37.0	4.7
Oceania	1.4	0.2

Source: FAO (2015).

Table 2. Population and food production in the world

Item	2005–07	2050
Population (million)	6,569	9,110
Developed countries	1,351	1,439
Developing countries	5,218	7,671
Arable land (million hectares)	1,592	1,661
Cereal production (million metric tonnes)	2,068	3,009
Cereal yield (metric tonnes/hectare)	3.32	4.30
Cereals as food (kg/capita/year)	158	160
Cereals all uses (kg/capita/year)	314	330
Meat production (million metric tonnes)	258	455
Meat as food (kg/capita/year)	38.7	49.4
Oil crops (oil equivalent) as food (kg/capita/year)	12.1	16.2
Oil crops (oil equivalent) for all uses (kg/capita/year)	21.9	30.5

Source: Alexandratos and Bruinsma (2012).

dustrialized countries. In mid Twentieth Century (1954), world cereal production (wheat, rice, maize) was only 446.8 million metric tonnes (Mt) (FAO, 1955) but increased about 4.5 times in the next 50 years to 2,068 Mt during triennium 2005–07 and is further estimated to increase to 3,009 Mt in 2050 (Alexandratos and Bruinsma, 2012) (Table 2). This is necessary to meet the increasing food demands by ever increasing human population, which was 6,569 million during the triennium 2005–07 and is estimated to reach 9,110 million by 2050. During the triennium 2005–07, developing countries accounted for 79.4% population and it is estimated to further increase to 84.2% in 2050. If these food production targets are reached, there will be adequate available food for everyone in the world; its availability will, however, depend upon several factors including, regional availability, purchasing power of the people and government support to the poor. Thus, poverty will continue to be a major barrier to the access of food, especially in developing countries.

With the increasing urbanization and industrialization and the extra-land needed for housing, schools, hospitals, roads, railways, airports etc., the cultivable land is going to decrease in future; the tragedy is that these amenities take away some very fertile land. It is estimated that at best the cultivable land in world will increase from 1,592 million hectares (Mha) during the triennium 2005–07 to 1,661 Mha in 2050, a mere 4.3% increase. Thus, most increase in food production has to come by increase in productivity (yield/ha). There have been and will continue to be 2 major ways to achieve this.

High yielding hybrids and varieties of cereals

The first and foremost is better and higher crop hybrids/varieties including genetically modified (GM) plants. Development of corn hybrids in US during early 20th century paved the way for increased maize yield in the world (Crow, 1998; Smith *et al.*, 2004). Similarly the development and promotion of semi-dwarf rice hybrid and varieties by the International Rice Research Institute, Philippines (Dalrymple, 1978) increased rice production in the world. Again Green Revolution in India was brought about by the introduction of high yielding wheat varieties from CIMMYT, Mexico (Swaminathan, 2013).

Role of fertilizer nitrogen in augmenting cereal production

The second most important factor responsible for increased food/cereal production has been the fertilizer nitrogen (Prasad and Shivay, 2015). Synthesis of ammonia using nitrogen and hydrogen gases was first achieved by a German Chemist Fritz Haber in 1908, for which he received the Nobel Prize in Chemistry in 1908. However, he used Osmium as a catalyst, which was expensive and not readily available. Carl Bosch, another German Chemist later discovered that oxides of iron along with some other chemical could be substituted for Osmium as a catalyst, and this made synthesis of ammonia industrially possible. The process is now known as Haber-Bosch process. Bosch received Nobel Prize in Chemistry in 1930. Synthetic ammonia is the basic material for all nitrogen fertilizers. The most popular solid fertilizer urea is made by reacting anhydrous ammonia with carbon di-oxide (Prasad, 1998). In USA, anhydrous ammonia is directly injected in the soil and is a major nitrogen fertilizer.

Discovery of synthetic ammonia coupled with hybrid corn led to phenomenal increase in corn production in USA and for the production of cereals in general throughout the world. The importance of this discovery in increasing cereal production is well recognized and Erisman *et al.* (2008) observed that without this discovery about half of the world population would have remained malnourished.

Similarly, Synder (2010) observed that 40% of the population on earth owes its existence due to increased food production made possible by fertilizer nitrogen. Yet another estimate suggested that about half of the protein in human beings is made of nitrogen that was originally fixed by Haber-Bosch process (BBC-Discovery: Can Chemistry serve the world? Fixing the nitrogen fix. Via Wikipedia). However, Conant *et al.* (2013) observed that during 1961 and 2007, worldwide fertilizer nitrogen input has increased faster (+134%) than crop yields (+120%) and among the cereals wheat yields have increased most (+143%), followed by maize (+140%) and rice (+103%). Based on thousands of on-farm trials in India Tandon (1994) reported that increase in yield due to fertilizer nitrogen was 59% in wheat, 64% in *kharif* (rainy season) maize, 68% in *kharif* sorghum, 58% in *kharif* pearl millet and 27–28% in rice.

During 2010–11, fertilizer nitrogen consumption in the world was about 104 million metric tonnes (Mt), while the cereal production was 2,475 Mt. Heffer (2013) reported that during 2010–11 globally, fertilizer nitrogen consumption by cereals was 55.2% (wheat 18.1%, rice 16.8%, maize 15.4%, and other coarse cereals 4.8%) of the total N consumption. Thus, during 2010–11 about 57.5 Mt nitrogen was applied to cereal. Taking the average Agronomic Efficiency of fertilizer nitrogen (AE_N) (kg grain produced per kg N) at 20.6 (Ladha *et al.*, 2005) 1,030 Mt of cereal grain was produced by nitrogen alone, which works out to 49.8% (nearly 50%) of total cereal production of 2,068 Mt in 2007. Continuing these calculations further, additional production of 941 Mt cereals per annum by 2050 over that in 2007 (Table 2) would need an application of 45.7 Mt in cereals alone. However, it should be kept in mind that since area under cereals is not going to increase much and most of the additional increase in yield has to come from fertilizer nitrogen alone, obviously at much higher rates, when agronomic efficiency of applied nitrogen is likely to go down. Thus, additional fertilizer nitrogen for increased cereal production alone may be 15–20% higher than the value of 45.7 Mt. Tilman *et al.* (2011) predicted the need for a 100–110% increase in global food production from 2005 to 2050 and predicted a fertilizer nitrogen consumption of 250 Mt. However, it may be pointed out that the benefits of fertilizer nitrogen just discussed assume balanced NPK fertilization and site-specific application of secondary (Ca, Mg, S) and micronutrients (Fe, Mn, Zn, Cu, B, Mo, Ni) deficient in soil (Srivastava, 2006; Prasad, 2007; Singh, 2008).

Environmental impact of fertilizer nitrogen

Fertilizer nitrogen is not all boon. The global average recovery efficiency ($RE_{N)}$ of fertilizer nitrogen by cereals is 55% (Ladha *et al.*, 2005), although it could be as low as 21% for rice in some cases (Katyal *et al.*, 1985). As reviewed by Ladha *et al.* (2005), average recovery efficiency of ^{15}N for cereal crops was 44% in the first growing season and total recovery of ^{15}N fertilizer in the first and five subsequent crops was only around 50%. Assuming that amount of ^{15}N in the roots becomes negligible in the sixth growing season, the remaining 50% of the ^{15}N fertilizer would have either become part of the soil organic matter pool or was lost from the cropping system. Recently Ladha *et al*. (2016) constructed a top-down global N budget for maize, rice, and wheat for a 50-year period (1961 to 2010). Cereal grains and above-ground straw contained a total of 1,551 Mt of N, of which 48% was supplied through fertilizer-N. The N output was estimated to be 3,306 Mt, of which the crop harvested 47%, whereas the remaining 53% or 1,755 Mt of N input was lost. In addition, soil-N declined by about 68 Mt.

Most of the remaining nitrogen is lost to the environment or leached down the profile to groundwater or through surface runoff to the inland waters, rivers and sea. There have been a large number of reports on ammonia volatilization losses and emissions as nitrous oxide (Davidson, 2009; Reay *et al.*, 2012) to the atmosphere. Ammonia volatilized from surface applied fertilizer nitrogen reduces air quality, while nitrous oxide is a powerful greenhouse gas contributing to global warming and is also responsible for depletion of atmospheric ozone (Schlesinger, 2009; Pinder *et al.*, 2012). Excessive nitrogen fertilizer is reported to increase nitrate concentration in drinking water (Prasad and Power, 1995; Zhang *et al.*, 1996; Yin *et al.*, 2007; Kundu *et al.*, 2008; Burrow *et al.*, 2010) leading to blue baby syndrome or methaemoglobinemia (Knobeloch *et al.*, 2000), while eutrophication of surface water is responsible to mortality of fish and other sea creatures (Elser *et al.*, 2007; Diaz and Rosenberg, 2008; Keeler *et al.,* 2012) (Table 3). Fertilizer nitrogen has also global warming effects (Zhang *et al.,* 2012) and leads even to acidification of soils (Guo *et al.*, 2010). Nitrogen has direct and indirect effects towards global warming and cooling. The warming effects of N include: (1) N_2O emissions, which is a greenhouse gas with long atmospheric lifetime; (2) NO_x emission, which contributes to formation of tropospheric O_3, a short-lived green house gas (GHG) lasting several weeks; and (3) detrimental effects of ozone on plant C sequestration (Pathak, 2013). The cooling effects include: (1) C sequestration due to application of N, which increases plant CO_2 fixation; (2) losses of N to water bodies, where freshwater and marine eutrophication can increase CO_2 removal from the atmosphere; (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 N supply also affects CH_4 production and consumption in soils and albedo of the land surface by affecting vegetative cover and increasing chlorophyll content of vegetation.

In 2013, global consumption of fertilizer N was only 110.4 Mt and consumption of fertilizer N in India was 16.7 Mt. Global estimates of nitrogen losses as ammonia volatilization, denitrification (nitrous oxide) and leaching/ run-off (nitrate) from all sources of N including manure BNF, crop residues and deposition etc. are at 37, 25 and 95 Mt of N, respectively, while the values for India are at 4.1, 3.1 and 3.1, respectively (Prasad *et al.*, 2014). Such heavy losses of fertilizer nitrogen therefore call for reducing rates of nitrogen application to crops and if possible to improve methods and timings of application and if available use more efficient nitrogen fertilizers.

Efficient use of fertilizer nitrogen

While talking about 4R nutrient stewardship, emphasis should also be given on site-specific N management (SSNM) in cereals. The blanket recommendations for a region may be based on best fertilizer management practice, but they can not take care of field-to-field and temporal variability in the availability of soil N. We believe the role of SSNM needs to be emphatically mentioned in this review paper. Although a passing reference to the use of leaf colour chart (LCC) and chlorophyll meters for managing N has been made in the section on rate of N application. Plant based SSNM takes care of both rate and time of application of split doses of N to achieve synchronization between N available in the soil and fertilizer N being applied. Fertilizer N management is bound to change in India as well. Agronomists including soil scientists in India and elsewhere have done considerable research in the line of 4R nutrient stewardship concept mooted by the International Plant Nutrient Institute (IPNI), which focuses on the use of right source at the right rate, time and place (Bruulsema *et al.*, 2012; Majumdar *et al.,* 2014). Nitrogen management systems appropriately incorporating these techniques can substantially increase agronomic and recovery efficiency of applied fertilizer nitrogen (Zhang *et al.*, 2011, 2013; Robertson *et al.*, 2012).

Sources of nitrogen

Indian farmers do not have much choice for sources of nitrogen, since urea meets about 80% of all fertilizer nitrogen needs in the country. However, research at the Division of Agronomy, IARI under the leadership of Rajendra Prasad (Prasad *et al.,* 1993; 1999; 2002; 2007; Shivay *et al.,* 2001) led to the development of neem coated urea (NCU), its on-farm confirmation by others (Thind *et al.*, 2010) and feedback by the famers has led to its manufacture of NCU in India on a large scale. Recently, Government of India has allowed the urea manufacturers to convert their entire urea production as neem coated urea (GOI, 2015). In addition to increasing efficiency of fertilizer nitrogen, the farmers have also conveyed the reduction of termite incidence in wheat and the incidence of

Table 3. Environmental problems associated with fertilizer use and the mitigation strategies

Environmental problem	Causative mechanism	Mitigation strategies
Ground water contamination	Nitrate leaching	Judicious use of fertilizers, increasing efficiencies, nitrification inhibitors, coated fertilizer use
Eutrophication	Erosion, surface run-off or ground water discharge	Reduce run-off, water harvesting, controlled irrigation, control erosion
Methaemoglobinemia	Consumption of high nitrate through drinking water and food	Reduce leaching loss of N
Acid rain and ammonia re-deposition	Nitric acid originating from reaction of N oxides with moisture in atmosphere, ammonia volatilization	Reduce ammonia volatilization loss, decrease the *p*H of soil, increase CEC, use fertilizer formulations and inhibitors
Stratospheric ozone depletion and	Nitrous oxide emission from soil global warming	Use of nitrification inhibitor, urease inhibitor, increase N use efficiency
Minamata disease	Ingestion of fish contaminated with methyl mercury (Hg) compounds	Controlled use of mercury (Hg) pesticides
Itai-Itai (ouch-ouch) disease	Eating rice and drinking water contaminated with cadmium (Cd)	Soil management such as liming or water control in rice fields

Source: Pathak (2016).

nematode attack in some vegetables and fruits; these properties of neem are already known (Prasad *et al.*, 2007). Thus, India has taken a lead in the world towards producing more efficient nitrogen fertilizers. However, this is just a beginning and it is a long journey to have really controlled release nitrogen fertilizers. A number of slow release nitrogen fertilizers have been developed and evaluated (Prasad *et al.*, 1971; Trenkel, 1997), but among them two deserve special mention. These are urea-formaldehyde condensates (Alexander and Helm, 1990) and polymer coated urea (Zhang *et al.,* 1994). By varying the proportion of formaldehyde and urea in urea-formaldehyde condensates and by changing the polymer and the thickness of its coating in polymer coated ureas, nitrogen release rate can be tailored to crop needs. It may be mentioned that under Indian growing seasons and conditions most cereals need only 1 to 1.5 kg N/ha/day. To reduce nitrogen losses from the agricultural crops controlled release nitrogen fertilizers have to be used in the future, especially in tropical and sub-tropical countries, where heavy and incessant rains during few months makes nitrogen management an uphill task in crops like rice (Prasad, 2005; 2011). The departments of Chemical Engineering in Indian Institutes of Technology can largely help in developing cost effective more efficient nitrogen fertilizer, if they work in collaboration with agricultural institutes/universities of India. In evaluating these new and more efficient nitrogen fertilizers, the amount of environmental benefits should also be taken into account and not just the additional yield. Controlled- and slow-release fertilizers have been shown to be more efficacious than conventional fertilizers and their consumption grew at an average annual rate of about 30% during 2009 to 2014. But their use is relatively limited as these are very expensive (2 to 10 times) than the conventional fertilizers. China is the largest producer and consumer of controlled- and slow-release fertilizers. Chinese consumption has been increasing significantly in recent years and is projected to grow at 12.8% annually during 2014 to 2019. It also includes application on large areas under rice.

Timing of nitrogen application

In irrigated cereal production, split application of nitrogen is the thumb rule and its advantages are well established; the number of splits and the proportion of nitrogen applied in different splits vary with crop and soil (Tandon, 1989; Katsura *et al.*, 2008; Sahu *et al.*, 2015; Angel, 2015). Sometimes split application of nitrogen can do wonders. For example, Chen *et al.* (2011b) were able to double maize yield in Republic of China, while completely eliminating nitrogen losses by applying nitrogen in five split doses with soil test guided application rates.

Placement of nitrogen

As compared to phosphorus, deep placement of nitrogen has not received that much attention. Excepting the seed drill sown cereals, such as wheat and maize, where basal nitrogen is placed a few centimeters below the seed, most nitrogen is broadcast. Application of fertilizer N before or after an irrigation even can also lead to different kinds of fertilizer N placement in the soil. Of course soil texture and permeability of the soil also play a big role. Further, about half to two-thirds of nitrogen applied to cereal is top-dressed and there is no other way but to side-dress or broadcast it. This leads to nitrogen losses due to ammonia volatilization (Mohanty *et al.*, 1999) and nitrous oxide emission (Ventera and Coulter, 2015). Even in dryland agriculture, where most nitrogen is applied at seeding, it is not deep placed, because the farmers apply it only after rains are received. Nitrogen solutions would be ideal for dryland agriculture, but no serious efforts have yet been made in India in this direction.

Rate of nitrogen application

A number of approaches have been suggested for determining the rate of nitrogen application to cereals and other crops. These include biological soil tests, which determine the amount of soil nitrogen mineralized on incubation for 2 or more weeks (Stanford and Smith, 1972), chemical soil tests determining soil N hydrolyzed by alkaline permanganate (Subbiah and Asija, 1956) or calcium hydroxide (Prasad, 1965), pre-plant nitrogen nitrate N in 60-120 cm soil profile (PPNT) (Fox and Piekiekek, 1983) or nitrate-N in top 30 cm soil before top-dressing (PSNT) (Fox *et al.*, 1992) and determining chlorophyll concentration in leaves using leaf color chart or chlorophyll meter (Maiti *et al.*, 2004; Varinderpal-Singh *et al.,* 2010). Nevertheless, whichever method is used to determine the nitrogen rate, most well-off farmers intend to over-fertilize the cereal crops.

Agronomists are familiar with two optima on a response curve of a crop to nitrogen application. These are: yield optimum ($\text{Yield}_{\text{opt}}$) and economic optimum ($\text{Econ}_{\text{opt}}$). $\text{Yield}_{\text{opt}}$ refers to the nitrogen rate at which maximum yield is attained, while Econ_{opt} refers to the rate at which economic returns are the most and is the point on the response curve, when the cost of the yield increase due to an unit increment in nitrogen is equivalent to the price of that input. Most fertilizer recommendations are based on Econ_{opt} rate. However, in recent years a number of researchers have pointed out that Econ_{opt} rates of nitrogen in cereals are fairly high and lead to large amount of nitrogen losses to the environment and have therefore suggested the need for an ecological optimum (Ecol_{opt}) rate of nitrogen application to cereals (Ju *et al.*, 2009; Chen *et al.*, 2011a, Gao *et al.,* 2012; Grassini and Cassman, 2012; Xia and Yan, 2011). The environmental impacts of agricultural practices are the costs that are typically unmeasured and often do not influence farmer or societal choices about production methods (Tilman *et al.,* 2002). In a recent study 91 on-farm trials were conducted on response of maize to nitrogen in 12 counties of Henan province in China (Wang *et al.*, 2014). Based on the results from these trials, $\text{Yield}_{\text{opt,}}$ Econ_{opt} and Ecol_{opt} were found to be 289, 237 and 171 kg N/ha, respectively. Thus, the ecological optimum rate was 66 kg N/ha lesser than the economic optimum rate and this reduced nitrous oxide emission, ammonia volatilization and nitrate leaching losses by 47%, 65% and 38%, respectively. The ecological optimum rates of nitrogen reduced maize yield by 0.3 Mg/ha only and maintained a high level of return on investment on fertilizer nitrogen.

In a study on global scale, Mueller *et al.* (2014) concluded that 2000 AD level of cereal production could be achieved with about 50% less fertilizer nitrogen and about 60% lesser nitrogen losses. Doing crop-wise analysis for the three major cereals (maize, wheat, rice) they reported that maize received 16.6 Mt of N (12 Mt fertilizer N, 4 Mt manure N and 0.6 Mt atmospheric N deposit) of which 8.6 Mt (51%) was lost to the environment. Similarly wheat received 20.1 Mt N (14.7 Mt fertilizer N, 4.6 Mt manure N and 0.8 Mt atmospheric N deposit) of which 10.4 Mt N (52%) was lost. Again, rice received 18.8 Mt N (12.8 Mt fertilizer N, 5.4 Mt manure N and 0.6 Mt atmospheric N deposit) of which 12 Mt N (64%) was lost. Thus, nitrogen losses were most from the rice fields.

Although average nitrogen fertilization consumption (kg N/ha of arable and) in India during 2013 was only 157.5 as compared to 364.4 in China, 361.3 in Republic of Korea, 256.7 in Japan, 246.6 in UK, 231.1 in Netherland and 203.5 in Germany (world Bank, via internet), it is fairly high in rice–wheat cropping (2 crops a year) belt of north India (Prasad, 2005) and rice-rice cropping (2 crops a year) regions in south and east India and deserves serious reconsideration from the ecological viewpoint.

Nitrogen is the pre-requisite of modern agriculture. It is required in large quantities in plant for higher productivity and ensuring food and nutritional security. In view of the emerging trends in modern agriculture there is a need for optimization of fertilizer N use for nutritional security and environmental sustainability. Despite intensive research on mechanism of N losses from fertilizers, average N use efficiency in farmers' fields has remained unchanged over the past 30 years. Because of the lack of congruence between fertilizer, soil N supply and crop demand, recovery efficiency of applied N is low. Other nutritional disorders such as micronutrient deficiencies have become more important management factors. Therefore, there is a need to change to securing short-term farming gains and maintenance of soil quality and profitability in the long-run. Recent studies suggest that we need to take a serious look on our fertilizer nitrogen recommendations for cereals and other crops and try to determine Ecol_{opt} rates for different regions in India so that nitrogen losses and consequent environmental damage is the least, without a serious reduction in production. This would require a joint exercise by the agronomists, economists and environment scientists.

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