

Nitrogen in Cereal Systems : Opportunities for Sustainable Agricultural Growth

Anupam Das¹ and Debashis Chakraborty²

(Received : January 11, 2024; Revised : January 14, 2024; Accepted : January 15, 2024)

ABSTRACT

Nitrogen is the most important nutrient in plant production. Nitrogen management is also essential to ensure global food security while reducing environmental degradation and stabilize disequilibrium. To maintain N balance in an agricultural ecosystem, the value of N inputs must equal N. Soil organic matter (SOM) is an important indicator of soil fertility, a source of energy for heterotrophic organisms, and an important source of plant nutrients, particularly nitrogen in the form of soil organic matter (SON). Progress has been made in developing effective nitrogen management techniques as well as good agricultural practices to increase yields and efficient nitrogen use while reducing nitrogen loads. There are many technologies that farmers can use, such as sowing at higher plant densities, soil test-based fertilizer N application, split N fertilizer applications, fertigation, site-specific N management, new fertilizer formulations such as controlled release nitrification inhibitors and nano-fertilizer formulations in order to encourage the adoption by farmers. Finally, for sustainable agricultural growth, campaign against the misuse of nitrogen fertilizer and policies to improve soil quality need to be promoted.

Key words : Nitrogen budget, Nitrogen use indicators, N Use Efficiency, Sustainable development goals.

Introduction

Nitrogen (N) is essential for maintaining the health of the biosphere. About 99% of N is present in the atmosphere as inert molecular N₂ gas, while approximately 425 Tg of reactive forms of N (N_R) is produced every year through natural processes and human activities (Bodirsky *et al.*, 2014). The Haber-Bosch process, invented in early 1900 to convert inert gaseous N₂ to reactive forms for manufacturing synthetic

fertilizers, contributes an additional 120 Tg N year⁻¹ (IFA, 2016). Another 30 to 51 Tg of reactive N is added to the atmosphere through biological N fixation (BNF) by leguminous and non-leguminous crops adds (Ladha and Chakraborty, 2016b). Nitrogen is the most essential nutrient in crop production. Despite the fact that N_R has mostly contributed to human dietary needs, there are still a vast areas in the

¹Assistant Professor-cum-Junior scientist, Department of Soil Science and Agricultural Chemistry, Bihar Agricultural University, Sabour, Bhagalpur (Email: anusoil22@gmail.com); ²Senior Cropping System Agronomist (CWANA Region), International Maize and Wheat Improvement Center (CIMMYT), NASC Complex, Dev Prakash Shastri Marg New Delhi, 110012 (Email: D.CHAKRABORTY@cgiar.org)

world where there is not enough available N to ensure food and nutritional security (Ciceri and Allanore, 2019). The future demand for N_R will substantially grow to meet the anticipated population of 9.7 billion people by the middle of the century (FAO, 2018; Rivas and Nonhebel, 2017)

Nitrogen management is essential to meet global food security while minimizing environmental losses. Fertilizer N is blamed for a 20% increase in atmospheric nitrous oxide since the industrial revolution (Park *et al.*, 2012). In recent decades, N emissions to the atmosphere have exceeded carbon dioxide emissions, raised a concern about its impact on human health and environment. To achieve this, we need to improve nitrogen use efficiency (NUE) through careful agronomic management. The General Assembly of the UN Environment Programme has passed a resolution towards developing a globally coherent approach to sustainable N management. NUE is the ratio of N output to inputs, and N surplus estimates N losses to the environment. Nitrogen management is a crucial topic in contemporary agronomy. Sustainable N management is necessary to achieve most of the Sustainable Development Goals (SDGs).

N Budget in Global Agriculture

Agroecosystems are prone to huge loss of reactive N, which raises the question of N disequilibrium. To achieve N equilibrium in agro-ecosystem, the sum of N inputs must equal the sum of N outputs. Major sources of N inputs include fertilizers, manures, recycling, BNF, and deposition, whereas N outputs are crop harvest and losses. Constructing N budgets improves the understanding of N transformation and

quantifies various N reservoirs. Efforts to construct N budgets are often limited to small-scale studies. Few studies attempt to estimate N budgets at the landscape, food production system, or global scale.

More than 50 years ago, Allison (1955) highlighted the lack of data to construct accurate budgets and referred to “*the failure of a N budget to balance*” as an enigma. Greenland and Watanabe (1982) identified three difficulties associated with the origin of the enigma: (1) difficulty in measuring the change in total N content of a given mass of soil, (2) the amount of N added to the soil-plant system by BNF, and (3) losses of N from a soil-plant system. After that, significant progress have been made in all three areas identified by Greenland and Watanabe (1982), and relatively substantial numbers of various components of N gains and losses have been generated to construct N budgets in agricultural systems. N budget estimations was summarized for (a) all arable crops (Liu *et al.*, 2010; Smil, 1999; Zhang *et al.*, 2015), and (b) three globally important cereals (maize, rice, and wheat) (Ladha *et al.*, 2011). Except for synthetic N as an input and crop harvest as an output, both of which have relatively more accurate estimations, uncertainties remain in the estimations of other N flows. Because different approaches to N budgeting were used by various studies, a useful comparison of absolute amounts of inputs and outputs among studies is not appropriate. Nevertheless, the trends are reasonably similar.

Worldwide, synthetic N is used to supply approximately 50-57% of the total N requirement by croplands and grazing

pastures (Table 1). While the remaining requirement (43-50%) was contributed by BNF (~43-44%) and other sources *viz.* deposition, manure, and crop residue (Ladha *et al.*, 2020). If we talk about N removal, crop harvest accounted for 36-42% of the total nitrogen output, whereas losses accounted for 57-64%. A global N budget for maize, rice, and wheat constructed by Ladha *et al.* (2016a) showed that out of the 100 Tg of synthetic nitrogen, 50% is being used in the cultivation of these three major cereals. The N budget sheet for these cereals was developed by estimating global quantities of various sources and sinks of N over a 50-year period (1961 to 2010). During this period, these cereals harvested a total of 1,551 Tg of N, of which 48% was derived from fertilizer-N. The rest of the N was contributed through net soil depletion or non-fertilizer and non-soil sources, including manure and atmospheric deposition. Non-symbiotic BNF by free-living bacteria and cyanobacteria was found to be the major source of N, contributing 25% of the total N in the crop (Fig. 1). Other non-fertilizer and non-soil sources, such as manure and atmospheric deposition, contributed 14% and 6%, respectively. Crop residues and seeds contributed marginally to crop nitrogen supply. These findings highlight the importance of considering all sources of nitrogen, including synthetic, manure/residue, deposition, symbiotic, and non-symbiotic BNF and indigenous soil organic nitrogen (SON), when developing strategies to improve the NUE.

Role of Fertilizer N in Maintaining N Balance in Cultivated Soils

Soil organic matter (SOM) is a crucial indicator of soil fertility. It's an energy

source for heterotrophs and an important source of plant nutrients, particularly for N in the form of SON constituted 90-98% of the total soil nitrogen. However, cultivation and fertilizer N inputs affect SON. N fertilizer may augment SON or lead to enhanced loss of SON. It's important to determine whether long-term use of synthetic fertilizer N leads to a decline in SON. An ecosystem-based approach to nutrient management is suggested to build-up and maintain both organic nutrients and mineral reserves over time.

A study conducted by Ladha *et al.* in 2011 analyzed data from 135 studies of 114 cereal-based long-term experiments, located at 100 sites throughout the world over time scales of decades under a range of land-management and climate regimes. A total of 580 observations for soil N, from control (unfertilized or zero-N) and synthetic N-fertilized treatments were analyzed. The study quantified changes in total soil nitrogen (N) with continuous cultivation and fertilization. Soil N declined by 11% under zero-N input conditions, but when synthetic N was applied, soil N decreased by only 4%. The study also enumerated that the long-term use of synthetic fertilizer N leads to a slower rate of decline in SON content compared to no use of synthetic N. Based on the overall average, SON was 10% higher with synthetic fertilizer N than with zero N, however SON declined over time with cultivation with or without the application of synthetic N. This also emphasized that the use of synthetic N leads to an increase in crop growth, which in turn increases C and N input in the soil and is a key driver for increased SOM and SON. These findings are consistent with the

conclusions of Powlson *et al.* (2010) who argued that the long-term use of synthetic fertilizer N led to a slower decrease, and possible increase, in SOM content compared with zero input of synthetic fertilizer N.

At a global level, there have been several estimates of changes in soil nitrogen (N) due to continuous cultivation and N fertilization. Smil (1999) estimated a global N accumulation of 4 Tg in arable soils during the mid-1990s. But Liu *et al.* (2010) reported a negative soil N balance of 11.53 Tg ($\sim 11 \text{ kg of N ha}^{-1} \text{ yr}^{-1}$) in the year 2000. It is important to note that there is significant variability in soil N changes (depletion or accumulation) across different regions, as reported by Liu *et al.* (2010) (Fig. 2). On the other hand, meta-analysis of global long-term experiments estimated a negative N balance of 32 and 62 Tg in maize and wheat, respectively, over a 50-year period (1960-2010). In contrast, a positive N balance of 26 Tg was found in rice during the same period (Ladha *et al.*, 2016a). The annual variation of soil N in N-balance studies were relatively meager; thus, the major cereal production agroecosystems seem to be either near-steady or at N-equilibrium.

Nitrogen Use Indicators and Framework to Assess N Use Efficiency and N Surplus

Nitrogen budgeting is a crucial exercise for reflecting and quantifying N cycling in a crop/soil system. However, nutrient use efficiency (NUE) is commonly used to compare agronomic, physiological and environmental consequences of N use in an agro-ecosystem. Most widely used three efficiency ratios to quantify NUE are agronomic efficiency, recovery efficiency,

and physiological efficiency (Cassman *et al.*, 2002; Craswell and Godwin, 1984; Dobermann, 2007; Fixen *et al.*, 2015; Hirel *et al.*, 2007; Novoa and Loomis, 1981). Recently, an additional index referred to as system NUE (sNUE) has been proposed to link crop and soil-based efficiencies (Martinez-Feria *et al.*, 2018). The sNUE is a ratio of NUE_{crop} to NUE_{soil} . The sNUE is essentially constructed using the basics of N budgeting. N surplus is a robust indicator of potential environmental N losses associated with N inputs applied in crop production.

The EU N Expert Panel introduced a NUE framework based on an N output-to-input ratio, which can help policymakers compare NUE between farms, systems, and countries (Fig. 3). They proposed a two-dimensional input and output diagram to show system performance in relation to NUE, N output in harvested produce, and N surplus or loss, alongside possible target, and reference values. However, direct measurements of some of the sources of N inputs, such as BNF and deposition, are often omitted from NUE estimates due to methodological constraints.

The NUE framework proposed by the EU N Expert Panel was examined for maize, rice, and wheat using the 50-year global N budget datasets by Ladha *et al.* (2016a). There were significant differences between input and output of N-budget when all potential sources of N were considered including synthetic fertilizer N input. NUE reaches to 90% when synthetic fertilizer N input considered alone, whereas NUE declined to 50% when all potential sources of N (synthetic fertilizer, manure, residue, deposition, BNF, SON) were being

considered. Moreover, surplus N was also different for major cereals. N-surplus for maize, rice and wheat were 51, 73 and 49 kg N ha⁻¹ when only synthetic N was considered, and 98, 111 and 81 kg N ha⁻¹ for maize, rice, and wheat, respectively, when all sources of N were considered. This suggests that specific crop-wise NUE targets and reference values should be considered to avoid ambiguity in planning.

The major uncertainty of N budget-based indices are the precise measurement of changes in total soil N to ensure the soil N equilibrium and a net sink or source. Other difficulties are accurate measurement of N losses, BNF and other natural depositions. Although simulation models have been found useful to estimate some of the inputs and N losses, they are likely to have errors. Another problem often overlooked is the multiplication of errors associated with the summation of the N inputs and outputs in an estimated N balance when analyzed using parametric statistics.

Global N Recovery Efficiencies and Releases of Surplus N to the Environment

The average NUE for cereals globally is 0.55 based on the N-difference method and 0.50 based on the ¹⁵N-dilution method. This is consistent with other published NUE values for food crops, ranging from 0.43 to 0.59 (Smil, 1999; Sheldrick *et al.*, 2002; Liu *et al.*, 2010; Howarth *et al.*, 2002; Janzen *et al.*, 2003; Bouwman *et al.*, 2005). Studies conducted globally on maize, rice and wheat agroecosystems show that the NUE ranges from 0.20 to 0.90 (Ladha *et al.*, 2005). The average recovery efficiency (RE_N) across all regions and crops was 7% lower when estimated by the ¹⁵N dilution

method (0.50) as compared to the N-difference method (0.55). Additionally, 6.5% of applied N would be available as residual N to subsequent crops during five growing seasons. There are a wide deviation exists in recovery efficiency between researchers' trials and farmers' fields due to economic constraints and sub-optimal crop management. On-farm assessments have shown lower REN estimates of 0.31 kg N harvest derived from kg⁻¹ fertilizer N applied, which were 25% lower than the average REN of 0.41 determined in researcher-managed plots (Dobermann *et al.*, 2004).

Ladha *et al.* (2016a) estimated N surplus in maize, rice and wheat crops of 848 Tg of fertilizer N in 50 years (1961-2010) and 7.7, 10.0 and 9.8 Tg, respectively for 2010 only. Average N surplus rate for maize, rice and wheat were 1.37, 1.72 and 1.0 kg ha⁻¹ year⁻¹ respectively, in 1990 and were reduced to 0.5, 1.0 and 0.9 kg ha⁻¹ year⁻¹ respectively, in the last two decades (Fig. 4). This could be due to adoption of better N management resulting in improvements in crop NUE. Zhang *et al.* (2015) estimated the global NUE averages of 0.46 for maize, 0.38 for rice and 0.43 for wheat. Their estimates of N surplus were 15, 18 and 17 Tg yr⁻¹ considering the sum of all N removed in harvest crop biomass as outputs and the sum of all N sources as inputs.

Regional Differences in N Use and the Sustainable Development Goals

The use of N has both positive and negative effects on agriculture and the environment, impacting most of the Sustainable Development Goals (SDGs) (Fig. 5). While nitrogen plays a beneficial role in food production and industrial

applications, its detrimental effects can cause environmental changes that adversely affect both people and the planet. Achieving some of the SDGs can help optimize N application, which in turn will contribute to sustainable agricultural growth. Improving agricultural production through sustainable intensification practices and better access to fertilizers can help reduce poverty and inequality, while promoting health and soil productivity. Small farmers are often most affected by the lack of N, leading to declining yields, reduced income, and exacerbating inequality within the food system. In extreme cases, farmers may resort to clearing new land, affecting biodiversity and GHG emissions.

A key connection between N and the SDGs lies in the efficient and responsible use of N, which aligns closely with SDG 12, “responsible consumption and production”. By promoting sustainable management of N, which contributes to SDG 12, we can establish a positive feedback loop that will impact other SDGs that are currently suffering due to insufficient or uneven use of N.

Globally, there is a wide variation in fertilizer N use. In Sub-Saharan Africa, fertilizer consumption is low, resulting in poor yield and human nutrition. On the other hand, China consumes a significant amount of fertilizer at a high rate. Improving access to fertilizer N and managing crops and soil resources can help end poverty, eliminate hunger, improve health and well-being, foster economic growth and reduce land degradation.

Excessive use of fertilizers in some countries leads to loss of nitrogen through

leaching, denitrification, and volatilization, contributing to various environmental problems. This not only affects public health, but also undermines the efficient use of energy consumed during production of fertilizers. Fertilizer N contributes to over 30% of agriculturally related N₂O emissions, which is a potent greenhouse gas with a global warming potential much higher than CO₂ (IPCC, 2014). Agriculture is responsible for around 60% of global N₂O emissions (Foley *et al.*, 2011), with 70% of fertilizer related N₂O emissions coming from developing economies like China and India (Foley *et al.*, 2011; Lassaletta *et al.*, 2014).

Targeted policies have helped decrease the growth of fertilizer N use in Europe and North America. This has led to an increase in NUE and lower N surpluses. The Netherlands has implemented well-targeted policies to improve N management practices, resulting in decreased fertilizer use and increased yields (Lassaletta *et al.*, 2014). Efficient use of N can be achieved through education, particularly through non-formal education and vocational training, as well as women empowerment (Farnworth *et al.*, 2017; Waddington *et al.*, 2014). Adequate infrastructure, clean energy, and addressing social equity and justice in development efforts can also contribute to efficient use of N (Ciceri and Allanore, 2019; Pradhan *et al.*, 2015). Overall, partnerships for the goals are essential to address unbalanced N management. Efforts to popularize the best agronomic management practices and use of appropriate technologies can contribute to knowledge and technology transfer (Kanter *et al.*, 2006).

A Case of Imbalance : India

Between 1970 and 2010, the use of fertilizer in India increased by around 11 times, but the amount of crops harvested only increased by three times. This means that the efficiency of the fertilizer decreased significantly, and the amount of N lost to the environment increased by four times. Most of the fertilizer is used on cereal crops (57%) in India, but the yields have not improved much for rice and wheat, which make up 36% and 70% of the land area, respectively (Ray *et al.*, 2012).

The use of fertilizer increased rapidly after the introduction of high-yielding varieties of rice and wheat that were responsive to fertilizers in the mid-1960s. This was followed by favourable fertilizer policies in the 1970s and 1980s, which led to a nearly five-fold increase in the use of nitrogen fertilizers from 8.9 to 43.1 kg ha⁻¹ over the same period. Today, the total use of nitrogen fertilizer in India is 17.4 million tons, with an average application of 89.7 kg per hectare (FAO, 2015). This accounts for around 16% of global production and 17% of global consumption.

Although India's use of nitrogen fertilizers has increased by an average of 6% per year over the last five decades, the associated losses and emissions of NO_x, NH₃, and N₂O have also increased. Nitrogen oxide emissions from sources such as industries, vehicles, cooking, and residue burning are another source of N loss in India. It is estimated that India loses N worth US\$10 billion per year as fertilizer value, while the costs of N loss to health, ecosystems, and climate are estimated at US\$75 (US\$38-151) billion per year (Ladha *et al.*, 2020).

There is a wide variation in the use of fertilizer N between Indian states. The highest application rates are in the Northwestern states of Punjab (171.8 kg ha⁻¹), Haryana (158.9 kg ha⁻¹) and the southern state of Telangana (145.39 kg ha⁻¹). However, many states use little fertilizer N, which means that India's overall fertilizer N consumption is not significantly different from the recommended rates (Chand and Pavithra, 2015). The main challenge in India is to increase the NUE of agriculture in high-use regions, rather than reducing the total fertilizer N use, especially considering that India needs to increase food production by 25% by 2050.

The crop NUE in India has decreased from around 55% in 1960 to 30-35% in 2010 (Singh, 2017). During the same period, the N balance, which is calculated as the difference between N input and output in crop yield, has increased from 3.7 to 92.5 kg N ha⁻¹ yr⁻¹. It is possible that a small part of this surplus N might have contributed to SON, given the generally low SOM status of Indian soils. However, since SOM does not increase indefinitely and reaches equilibrium, it could be assumed that at least 50% of the total N applied is lost to the environment. This level of nitrogen loss not only harms human and ecosystem health (with associated hidden costs), but also represents a significant waste of subsidies by the Government of India. Overuse or imbalanced use of fertilizers is largely due to the low cost of urea compared to other nutrients, such as phosphorus and potassium.

Imbalance to balance

India, with its diverse agro-ecologies, provides examples of varying N use,

ranging from low to high. Some of the N management approaches that are applicable to Sub-Saharan Africa are also relevant to India. These approaches include optimizing the time, rate, and methods of application for matching N supply with crop demand, using more efficient forms of fertilizer such as slow and controlled release fertilizers, employing urease and nitrification inhibitors, integrating synthetic N, manures, and/or crop residues, and optimizing irrigation management. Best management practices, such as the appropriate use of conservation agriculture (CA)-based techniques of zero tillage, residue and/or manure retention, and crop rotation, can improve soil health, thereby maximizing the benefits of precision N management tools (Sapkota *et al.*, 2014). Other interventions, such as coating urea with neem oil, can also help to improve NUE and reduce N₂O emissions (Singh, 2016). However, significant improvements can only be achieved by the balanced use of all nutrients. Additionally, modern tools such as precision farming technologies and simulation modelling-supported decision support systems can also help improve NUE.

Precision nutrient management tools and techniques are now available to support the best in-season fertilizer N management on farms in India. These tools include the GreenSeeker, Nutrient Expert decision support software, Chlorophyll Meters, and Leaf Colour Charts (Singh, 2017) (Fig. 6). Techniques such as drilling/banding of fertilizer, split application and fertigation are also available. They provide a means of fine-tuning N management decisions. Moreover, computer/android

phone-based decision support software like Nutrient Expert and Crop Manager are being used to refine N management practices in farmers' fields in India. Such tools are becoming increasingly important in smallholder-dominated geographies where blanket fertilizer recommendations are the norm.

Although some techniques will continue to be useful for improving NUE in Indian agriculture, holistic approaches that maintain soil health will help maximize the crop N uptake, minimize surplus N and optimize indigenous soil N supply, including non-symbiotic N fixation. High crop N demand linked to maximal genetic yield potential and harvest index of a crop will ensure high NUE, provided they are supported by sound agronomic management practices (Ladha *et al.*, 2005, 2016c). The principles of CA are becoming attractive due to their potential to increase NUE and recycle crop residue, which is otherwise burnt. Crop residue burning adversely affects soil fertility, results in substantial air pollution with serious human health consequences, and releases greenhouse gases. Recently, CIMMYT with the Borlaug Institute for South Asia (BISA) has developed a novel technique of sub-surface irrigation with fertigation for conservation agriculture-based wheat-rice system and wheat-maize system resulting in high NUE and substantial water savings and a small increase in crop yields (Sidhu *et al.*, 2019). Further refinement of sub-surface irrigation with crop residue cover on soil surface provides exciting future opportunities to address multiple goals of SDGs (Fig. 7). In addition, the use of innovative agricultural machinery, such as the so-called 'Happy Seeder' designed to

drill seed without tillage into fields with very high residue loads, could also help to arrest the problem of residue burning in South Asia's rice-wheat cropping systems (Sidhu *et al.*, 2015).

Institution and Policies

The Government of India provides significant subsidies on fertilizers, particularly on urea, where it amounts to 75% of the total cost with a cash subsidy of approximately US\$7 billion per year (Ministry of Chemicals and Fertilizers, 2016). However, smaller subsidies of 34% and 37% are provided on phosphorus- and potassium-based fertilizers, respectively, which are relatively expensive due to their prices being pegged to international markets. This pricing difference leads farmers to use more urea, resulting in an imbalance in the N:P:K ratio. This ratio has widened from 4.7:2.3:1.0 in 2010-11 to 7.3:2.9:1.0 in 2015-16, which negatively impacts crop yields, soil health, and the environment (Tewatia *et al.*, 2017). The neem-coating of imported and domestically manufactured urea is mandatory, which may improve NUE to some extent. However, balanced use of all nutrients is necessary for optimal fertilizer use efficiency, and this requires incentivizing through pricing policy corrections (Singh, 2016).

It is worth noting that the Government of India recently launched the ambitious Soil Health Card Scheme (<https://soilhealth.dac.gov.in/>). As part of this scheme, nearly 110 million health cards were supplied to farmers, providing them with information about the status of their soil with respect to 12 parameters. The cards also include crop-wise recommendations for

soil amendment and fertilizer, which includes N fertilizer to improve productivity through the judicious use of inputs. By linking this 'Soil Health Card' initiative with N management tools, we can further help to meet the N challenge. India has a great opportunity to improve the low NUE of its agriculture sector, which will have a positive impact on several SDGs including 3, 6, 7, 11, 13, 14, and 15. By implementing current technologies at scale and with the support of enabling government policies, it is possible to avoid around 30% of the emission of N_2O compared to business-as-usual by 2030 (Sapkota *et al.*, 2019). This will result in a significant reduction of emissions, about 17.5 Mt CO_2 e yr^{-1} , without compromising the yield. However, to achieve this, supportive policies and well-equipped extension systems are required to ensure the large-scale use of these knowledge-intensive practices.

Conclusions

Nitrogen is a crucial nutrient for food production, required to meet human dietary needs. However, the dual role of N can be both positive and negative, creating challenges in achieving national food and nutritional security while meeting India's global commitments on climate and sustainable development. Fortunately, there has been progress in developing technologies for efficient N management, along with good agronomy practices to enhance crop yields and N use efficiency while reducing excess N. Achieving these goals, we have to trade off two challenges. Firstly, we must encourage farming practices that promote soil health through balanced use of organic matter and support ecosystem services such as

biological N fixation and intelligent use of fertilizer N in areas where poverty, hunger and malnutrition are prevalent. Secondly, we need to optimize N use and minimize negative impacts in areas where crop productivity has peaked, and there is excess or misuse of N. Currently, the average recovery efficiency of N in India is only 46% (globally, 44%), whereas we need an efficiency of 67% to meet global food demand in 2050 while maintaining acceptable air and water quality to meet the Sustainable Development Goals.

Despite these challenges, there have been successes and active efforts to improve NUE and soil organic matter management. With advances in digital soil mapping and new tools to enable rapid diagnostics of nutrient variability at large spatial scales, appropriate recommendations can be generated to assist farmers in making balanced use of nutrients. There are many technologies available for farmers to use like sowing at higher plant densities, soil test-based fertilizer N application, split N fertilizer applications, fertigation, site-specific N management, new fertilizer formulations such as controlled release nitrification inhibitors and nano-fertilizer formulations etc. our effort should be to encourage the farmers to adopt these technologies. We also need to educate officials, policymakers, extension personnel, and farmers about the benefits of appropriate soil management and intelligent use of nitrogen fertilizer. We need to campaign against the misuse of nitrogen fertilizer and promote policies that improve soil quality in areas where nitrogen use is low. Finally, we need to do more research to understand the link between sustainable nitrogen management and food and nutritional security.

Reference

- Allison, F.E. 1955. The enigma of soil nitrogen balance sheets. *Advances in Agronomy* **7**: 213–250. [https://doi.org/10.1016/S0065-2113\(08\)60339-9](https://doi.org/10.1016/S0065-2113(08)60339-9).
- Bijay-Singh 2016. Agronomic Benefits of Neem Coated Urea—A Review. International Fertilizer Association. <https://www.researchgate.net/publication/309384701>.
- Bodirsky, B.L., Popp, A., Lotze-Campen, H., Dietrich, J.P., Rolinski, S., Weindl, I., Schmitz, C., Müller, C., Bonsch, M., Humpenöder, F., Biewald, A. and Stevanovic, M. 2014. Reactive nitrogen requirements to feed the world in 2050 and potential to mitigate nitrogen pollution. *Nature Communications* **5**: 3858. <https://www.nature.com/articles/ncomms4858>.
- Bouwman, A.F., Van Drecht, G., Van der Hoek, K.W., 2005. Global and regional nitrogen balances in intensive agricultural production systems for the period 1970–2030. *Pedosphere* **15**: 137–155. https://www.pbl.nl/sites/default/files/cms/publicaties/bouwman_pedosphere.pdf.
- Campbell, B.M., Hansen, J., Rioux, J., Stirling, C.M., Twomlow, S. and Wollenberg, E. 2018. Urgent action to combat climate change and its impacts (SDG 13): Transforming agriculture and food systems. *Current Opinion in Environmental Sustainability* **34**: 13–20. <https://doi.org/10.1016/j.cosust.2018.06.005>.
- Chand, R., Pavithra, S. 2015. Fertiliser use and imbalance in India. Analysis of States. *Economic and Political Weekly*

- 44:** 98–104. Available at: http://www.im4change.org/siteadmin/tiny_mce/uploaded/Fertiliser_Use_and_Imbalance_in_India.pdf.
- Ciceri, D. and Allanore, A. 2019. Local fertilizers to achieve food self-sufficiency in Africa. *Science of the Total Environment* **648**: 669–680. <https://doi.org/10.1016/j.scitotenv.08.154>.
- FAO, 2015. World Fertilizer Trends and Outlook to 2018. Food and Agriculture organization of the United Nations (FAO), Rome, pp. 53. <http://www.fao.org/3/a-i4324e.pdf>.
- FAO, 2018. The Future of Food and Agriculture—Alternative Pathways to 2050. Summary version FAO, Rome, p. 60. <http://www.fao.org/3/CA1553EN/ca1553en.pdf>.
- Farnworth, C.R., Stirling, C., Sapkota, T.B., Jat, M., Misiko, M. and Attwood, S. 2017. Gender and inorganic nitrogen: what are the implications of moving towards a more balanced use of nitrogen fertilizer in the tropics? *International Journal of Agricultural Sustainability* **15**: 136–152. <https://doi.org/10.1080/14735903.2017.1295343>.
- Foley, J.A., Ramankutty, N., Brauman, K.A., Cassidy, E.S., Gerber, J.S., Johnston, M., Mueller, N.D., O'Connell, C., Ray, D.K., West, P.C., Balzer, C., Bennett, E.M., Carpenter, S.R., Hill, J., Monfreda, C., Polasky, S., Rockstrom, J., Sheehan, J., Siebert, S., Tilman, D. and Zaks, D.P. 2011. Solutions for a cultivated planet. *Nature* **478**: 337–342. <https://doi.org/10.1038/nature10452>.
- Greenland, D.J. and Watanabe, I. 1982. The continuing nitrogen enigma. (in) *Managing Soil Resources to Meet the Challenges to Mankind*: Transactions of the 12th International Congress Soil Science, New Delhi, India, 8–16 February 1982.
- Howarth, R.W., Boyer, E.W., Pabich, W.J. and Galloway, J.N., 2002. Nitrogen use in the United States from 1961–2000 and potential future trends. *AMBIO Journal of Human Environmental Studies* **31**: 88–96. <https://doi.org/10.1579/0044-7447-31.2.88>.
- IFA, 2016. Nitrogen Fertilizer Consumption Data. *International Fertilizer Industry Association*, Paris, France. 12 Mar. International Fertilizer Industry Association (IFA), Paris, France.
- IPCC, 2014. Intergovernmental panel on climate change. Anthropogenic and natural radiative forcing. (in) *Climate Change 2013—The Physical Science Basis: Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, pp. 659–740. <https://doi.org/10.1017/CBO9781107415324.018>.
- Janzen, H.H., Beauchemin, K.A., Bruinsma, Y., Campbell, C.A., Desjardins, R.L., Ellert, B.H. and Smith, E.G. 2003. The fate of nitrogen in agroecosystems: an illustration using Canadian estimates. *Nutrient Cycling in Agroecosystems* **67**: 85–102. <https://doi.org/10.1023/A:1025195826663>.
- Kanter, D.R., Zhang, X., Howard, C.M., 2006. Nitrogen and the sustainable

- development goals. (in) *Proceedings of the 2016 International Nitrogen Initiative Conference, 'Solutions to Improve Nitrogen Use Efficiency for the World'*, December 4–8, 2016, Melbourne, Australia. <http://www.ini2016.com>.
- Ladha, J.K., Tirol-Padre, A., Reddy, C. K., Cassman, K. G., Verma, Sudhir, Powlson, D. S., van Kessel, C., Richter, Daniel de B., Chakraborty, D. and Pathak, H. 2016a Global nitrogen budgets in cereals: A 50-year assessment for maize, rice, and wheat production systems. *Scientific Reports* **6**:19355 | DOI: 10.1038/srep19355.
- Ladha, J.K. and Chakraborty, D. 2016b. Nitrogen and cereal production: opportunities for enhanced efficiency and reduced N losses. (in) *Proceedings of the 2016 International Nitrogen Initiative Conference, 'Solutions to Improve Nitrogen Use Efficiency for the World'* December 4–8, 2016. Melbourne, Australia. Available at: http://www.ini2016.com/pdf-papers/INI2016_Ladha_Jagdish.pdf.
- Ladha, J.K., Rao, A.N., Raman, A., Padre, A.-T., Dobermann, A., Gathala, M., Kumar, V., Sharawat, Y.S., Sharma, S., Piepho, H.P., Alam, M.M., Liak, R., Rajendran, R., Reddy, C.K., Parsad, R., Sharma, P.C., Singh, S.S., Saha, A. and Noor, S. 2016c. Agronomic improvements can make future cereal systems in South Asia far more productive and result in a lower environmental footprint. *Global Change Biology* **22**: 1054–1074. <https://doi.org/10.1111/gcb.13143>.
- Ladha, J.K., Reddy, C.K., Padre, A.T. and Van Kessel, C. 2011. Role of nitrogen fertilization in sustaining organic matter in cultivated soils. *Journal of Environmental Quality* **40**: 1756–1766. <https://doi.org/10.2134/jeq2011.0064>.
- Ladha, J.K., Jat, M.L., Stirling, C.M., Chakraborty, Debashis, Pradhan, Prajal, Krupnik, T. J., Sapkota, T.B., Pathak H., Rana D.S., Tesfaye, K. and Gerard, B. 2020. Achieving the sustainable development goals in agriculture: The crucial role of nitrogen in cereal-based systems. *Advances in Agronomy* **163**: 39–116. <https://doi.org/10.1016/bs.agron.2020.05.006>.
- Lassaletta, L., Billen, G., Grizzetti, B., Anglade, J. and Garnier, J. 2014. 50 year trends in nitrogen use efficiency of world cropping systems: the relationship between yield and nitrogen input to cropland. *Environmental Research Letters* **9**: 105011. <https://doi.org/10.1088/1748-9326/9/10/105011>.
- Liu, J., You, L., Amini, M., Obersteiner, M., Herrero, M., Zehnder, A.J., Yang, H., 2010. A high-resolution assessment on global nitrogen flows in cropland. *Proceedings of the National Academy of Sciences of the United States of America* **107**: 8035–8040. <https://doi.org/10.1073/pnas.0913658107>.
- Ministry of Chemicals and Fertilizers, 2016. Annual Report, 2016–17. Department of Fertilizers, Govt. of India, p. 190. Available at: <http://fert.nic.in/page/publication-reports>.
- Omara, Peter, Aula, Lawrence, Oyebiyi, Fikayo, Raun and William R. 2019. World Cereal Nitrogen Use Efficiency

- Trends : Review and Current Knowledge. *Agrosystems, Geosciences & Environment* **2**:180045. <https://doi.org/10.2134/age2018.10.0045>.
- Park, S., Croteau, P., Boering, K.A., Etheridge, D.M., Ferretti, D., Fraser, P., Kim, K.-R., Krummel, P.B., Langenfelds, R.L. and Ommen, T.D.V. 2012. Trends and seasonal cycles in the isotopic composition of nitrous oxide since 1940. *Nature Geosciences* **5**: 261–265. <https://doi.org/10.1038/ngeo1421>.
- Powlson, D., Jenkinson, D., Johnston, A., Poulton, P., Glendining, M., Goulding, K., Mulvaney, R., Khan, S. and Ellsworth, T. 2010. Comments on “Synthetic nitrogen fertilizers deplete soil nitrogen: a global dilemma for sustainable cereal production” by Mulvaney, R.L., Khan, S.A., Ellsworth, T.R., *Journal of Environmental Quality* **38**: 2295–2314. 39, 749–752. <https://doi.org/10.2134/jeq2010.0001le>.
- Pradhan, P., Fischer, G., van Velthuisen, H., Reusser, D.E. and Kropp, J.P. 2015. Closing yield gaps: how sustainable can we be? *PLoS One* **10**: e0129487. <https://doi.org/10.1371/journal.pone.0129487>.
- Ray, D.K., Ramankutty, N., Mueller, N.D., West, P.C. and Foley, J.A. 2012. Recent patterns of crop yield growth and stagnation. *Nature Communications* **3**: 1293. <https://doi.org/10.1038/ncomms2296>.
- Rivas, M.J.I. and Nonhebel, S. 2017. Estimating future global needs for nitrogen based on regional changes of food demand. **8**: 555635. <https://doi.org/10.19080/ARTOAJ.2017.08.555735>.
- Sapkota, T.B., Majumdar, K., Jat, M.L., Kumar, A., Bishnoi, D.K., McDonald, A.J. and Pampolino, M. 2014. Precision nutrient management in conservation agriculture based wheat production of Northwest India: profitability, nutrient use efficiency and environmental footprint. *Field Crop Research* **155**: 233–244. <https://doi.org/10.1016/j.fcr.2013.09.001>.
- Sapkota, T.B., Vetter, S.H., Jat, M.L., Sirohi, S., Shirsath, P.B., Singh, R., Jat, H.S., Smith, P., Hillier, J., Stirling, C.M., 2019. Cost-effective opportunities for climate change mitigation in Indian agriculture. *Science of the Total Environment* **655**: 1342–1354. <https://doi.org/10.1016/j.scitotenv.2018.11.225>.
- Sheldrick, W.F., Syers, J.K., Lingard, J., 2002. A conceptual model for conducting nutrient audits at national, regional, and global scales. *Nutrient Cycling in Agroecosystems* **62**: 61–72. <https://doi.org/10.1023/A:1015124930280>.
- Sidhu, H.S., Jat, M.L., Singh, Y., Sidhu, R.K., Gupta, N., Singh, P., Singh, P., Jat, H.S. and Gerard, B. 2019. Sub-surface drip fertigation with conservation agriculture in a rice-wheat system: a breakthrough for addressing water and nitrogen use efficiency. *Agricultural Water Management* **216**: 273–283. <https://doi.org/10.1016/j.agwat.2019.02.019>.
- Sidhu, H.S., Singh, M., Singh, Y., Blackwell, J., Lohan, S.K., Humphreys, E., Jat, M.L., Singh, V. and Singh, S. 2015. Development and evaluation of

- the Turbo HappySeeder for sowing wheat into heavy rice residues in NW India. *Field Crop Research* **184**: 201–212. <https://doi.org/10.1016/j.fcr.2015.07.025>.
- Singh, B. 2017. Management and use efficiency of fertilizer nitrogen in production of cereals in India—issues and strategies. (in) *The Indian Nitrogen Assessment: Sources of Reactive Nitrogen, Environmental and Climate Effects, Management Options and Policies* (Lal, R. et al., eds.). Woodhead Publishing, Duxford, U.K, pp. 149–162. <https://doi.org/10.1016/B978-0-12-811836-8.00010-0>.
- Smil, V. 1999. Nitrogen in crop production: an account of global flows. *Global Biogeochemical Cycles* **13**: 647–662. <https://doi.org/10.1029/1999GB900015>.
- Tewatia, R.K., Rattan, R.K., Bhende, S. and Kumar, L. 2017. Nutrient use and balances in India with special reference to phosphorus and potassium. *Indian Journal of Fertilizers* **13**:20–31.
- Waddington, H., Snilstveit, B., Hombrados, J.G., Vojtkova, M., Anderson, J., White, H., 2014. Farmer field schools for improving farming practices and farmer outcomes in low and middle-income countries: a systematic review. *Campbell Systematic Reviews* **10** (6):1–335. <https://doi.org/10.4073/csr.2014.6>.
- Zhang, X., Davidson, E.A., Mauzerall, D.L., Searchinger, T.D., Dumas, P. and Shen, Y. 2015. Managing nitrogen for sustainable development. *Nature* **528**: 51–59. <https://doi.org/10.1038/nature15743>.

Table 1 : Global N inputs and outputs (Tg yr⁻¹)

Nitrogen flows	Smil (1999)	Liu et al. (2010)	Zhang et al. (2015)	Ladha et al. (2011)
	Year mid-1990s	Year 2000	Year 2010	Year 2010
	All crops	All crops	All crops	Maize, rice and wheat
Inputs	169	137	174	94
Synthetic N	78	68	100	58
Biological N fixation	33	22		11
Manure N	18	17		14
Residue N	14	11		6
Deposition	20	14		5
Sedimentation	4	3		
Seed	2	-		
Output	165	148	174	
Crop harvest	85	81	74	49
N leaching	17	23	100	49
N gaseous	33	20		
N erosion	20	24		
Loss from crop canopy	10	-		
Change in soil N	4	-13	0	-1

Obtained from Ladha et al., 2020

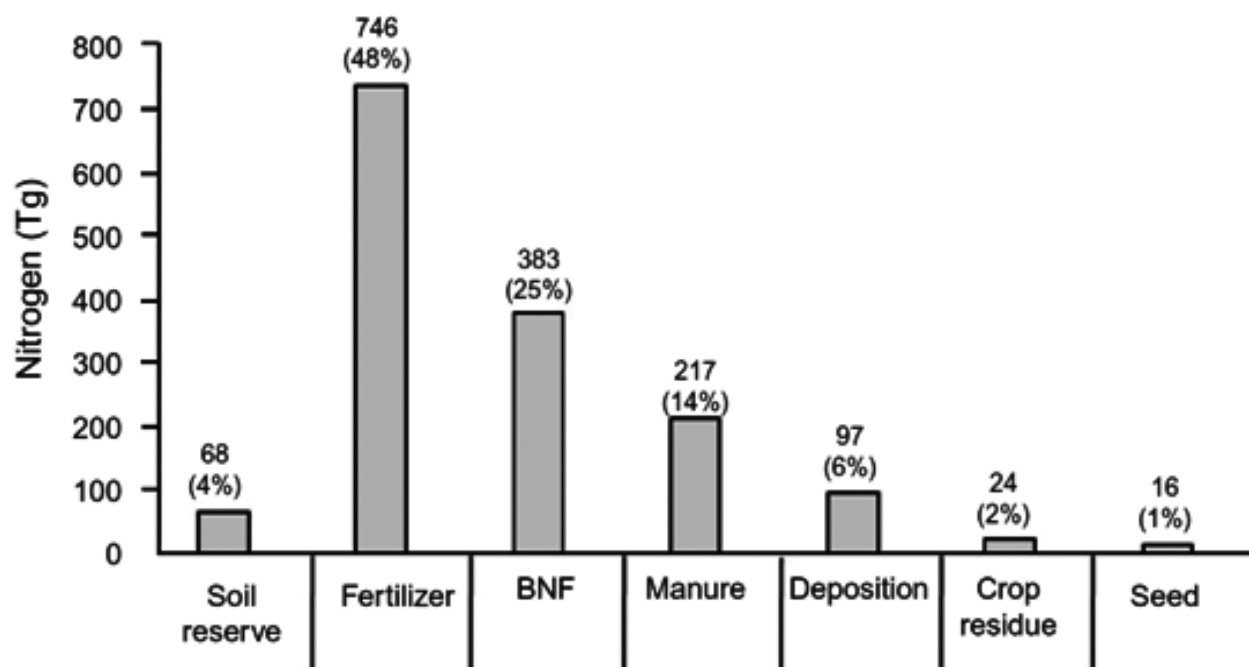


Fig. 1. Sources of N in major cereal crops (maize, rice, and wheat) [Values are global total (Tg) for 50 years (1961–2010); Source: Ladha *et al.* 2020

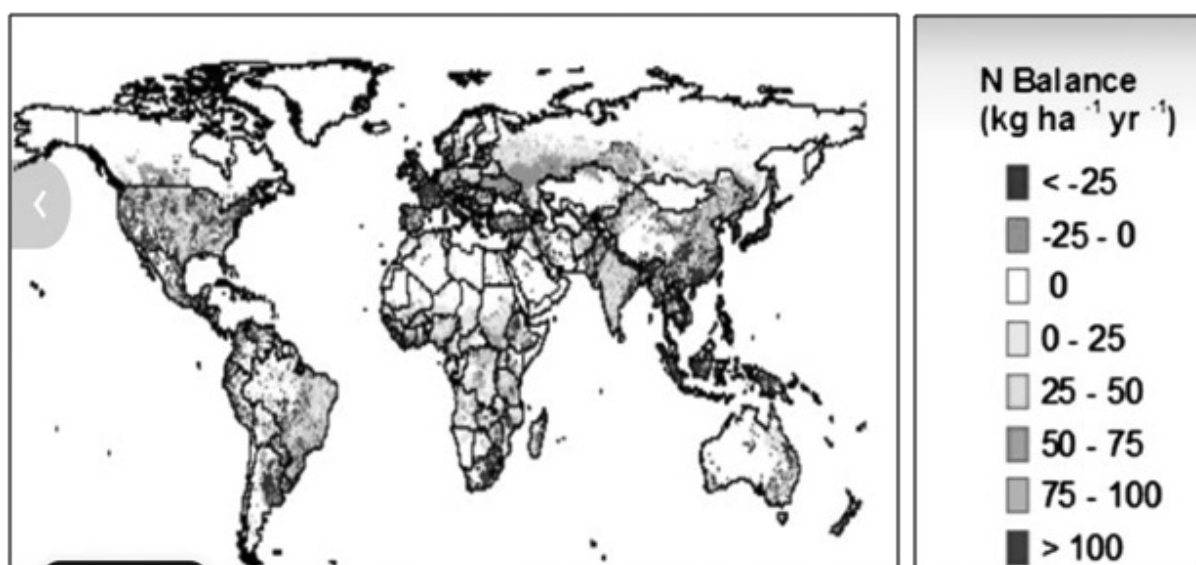


Fig. 2: Global map of soil N balance in cropland (Liu *et al.*, 2020)

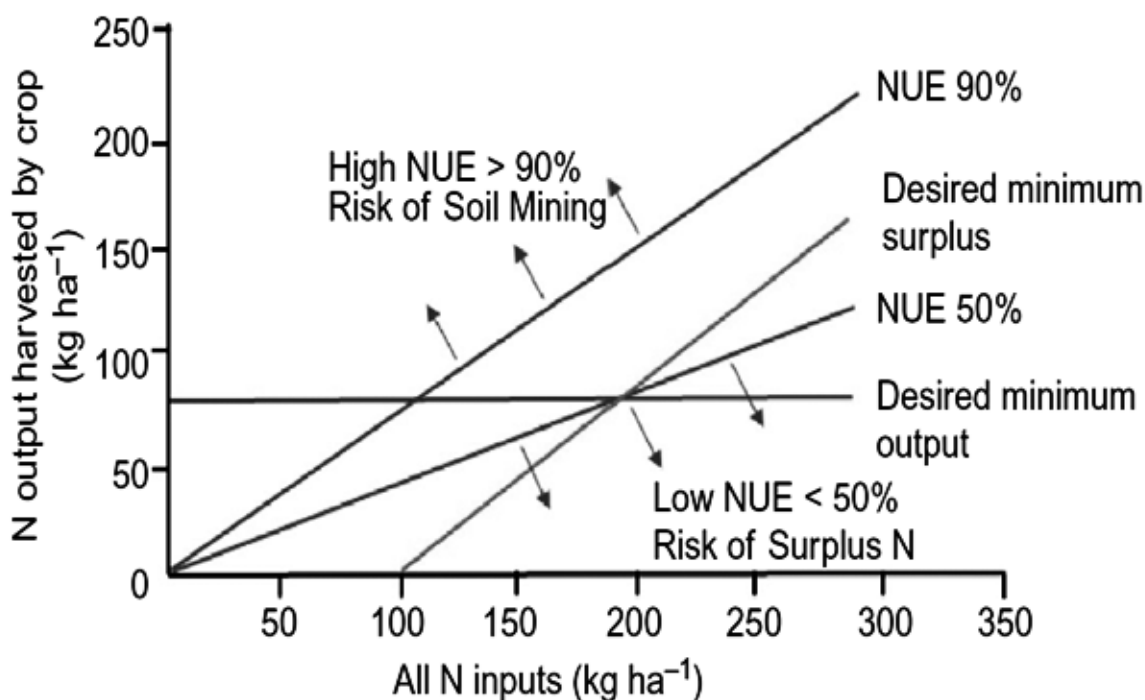


Fig. 3 : Conceptual framework of the Nitrogen Use Efficiency (NUE) indicator [EU Nitrogen Expert Panel, 2015].

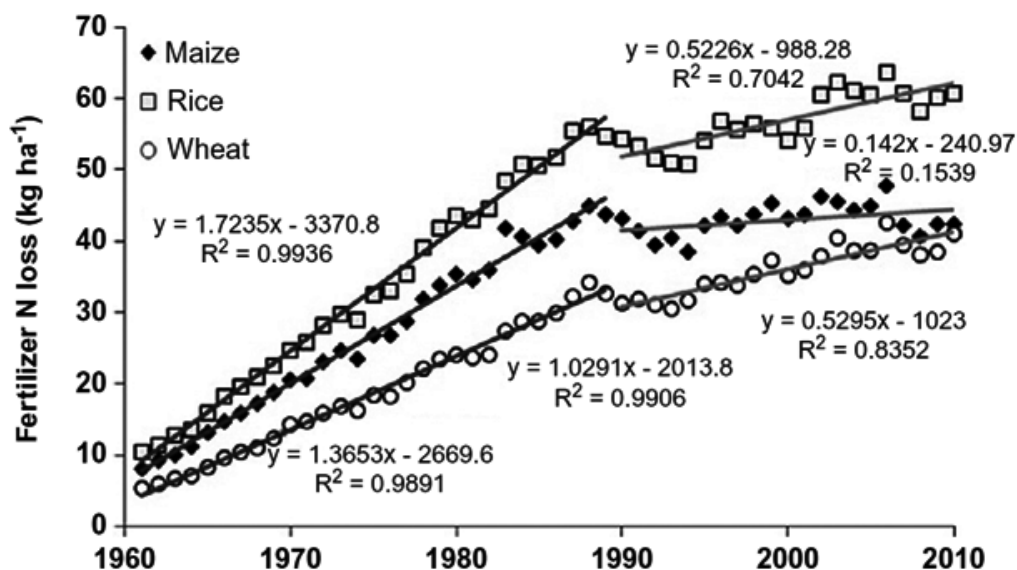


Fig. 4 : Fertilizer nitrogen surplus trends over 50 years in maize, rice and wheat [Source: Ladha *et al.*, 2020]

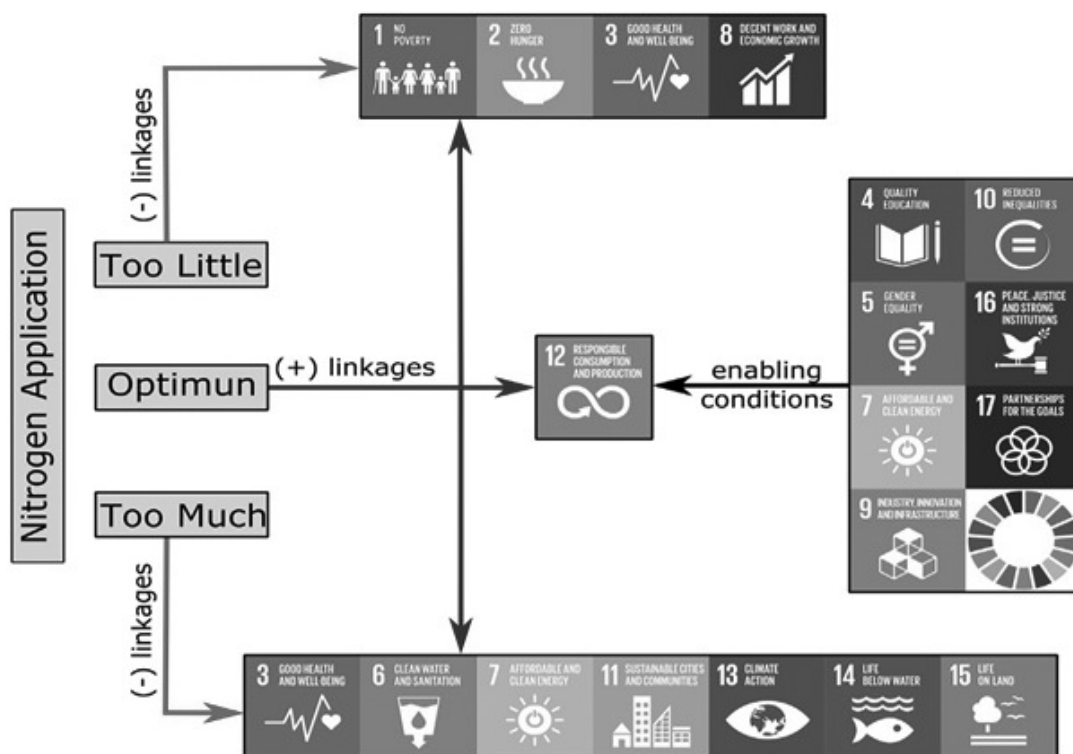


Fig. 5 : Impact of N use and the sustainable development goals [Source: Campbell et al., 2018]



Fig. 6 : Green-Seeker use in maize in a conservation agriculture experiment in Karnal, Haryana [Source: CIMMYT]

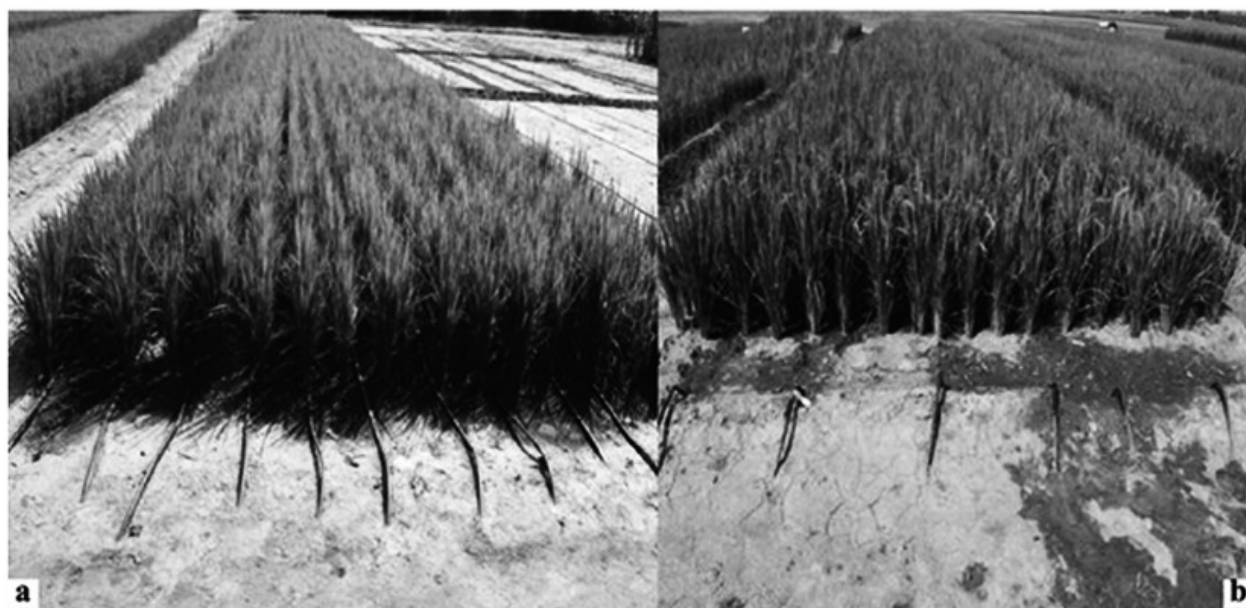


Fig. 7 Surface and sub-surface drip irrigation system in direct-seeded rice
[Source : CIMMYT-BISA]