Nitrogen and cereal production: Opportunities for enhanced efficiency and reduced N losses

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Abstract
Presently, 50 percent of the human population relies on synthetic nitrogen (N) fertilizer for food production. In agriculture of subsistence during pre-chemical era, biological N_2 fixation (BNF) was the primary source of reactive N but, in recent decades, chemical N fixation (synthetic N) has become more important in global agriculture. Today, synthetic N fertilizer introduces reactive N of over 100 Tg N year^{-1} into the global environment to increase food production. Although this has sustained the large human population in meeting dietary needs, a large agriculture area in the world still lacks available N to sustain the crop production. This together with a larger growing population obviously means that the future global demand for synthetic N is bound to grow markedly. However, since a substantial amount of N applied for food production is lost to the environment, this has also caused a web of problems causing air and water pollution and contributing to climate change. Unlike nonreactive gaseous N_2, reactive N has magnified the adverse effects because the same atom of N can cause multiple effects in the atmosphere, in terrestrial ecosystems, in freshwater and marine systems, and on human health. This paper, while focusing three major cereals (maize, rice and wheat) of global importance, (i) analyses the global consumption and demand for fertilizer N, (ii) evaluates synthetic fertilizer N recovery efficiency and losses, (iii) examines long-term effects of continuous N fertilization on changes in soil N reserves, (iv) constructs global N budgets, and (v) analyses various strategies available to improve the overall use efficiency of N.

Key Words
Cereals, N fertilizer, N recovery efficiency, biological N_2 fixation, N use efficiency, N loss

Global N Consumption and Demand for Major Cereals
During and after the Green Revolution in the 1960s, synthetic N fertilizer has played a crucial role in increasing crop productivity to alleviate the growing food insecurity caused by a worldwide increase in population. Since then, the application of synthetic N on fertilizer-responsive and lodging-resistant short-stature cultivars of cereals boosted the food production by about 260 percent (an average growth of 6.4 percent per year). Today, fertilizer N supplies approximately 45 percent of the N input for global food production with the global use of around 100 million metric tons (Mt) (FAO, 2010). Nearly half of this N is consumed by three most important cereals (rice, wheat and maize) with 50-year (2010-2010) average application rates (kg ha crop^{-1}) of 77, 69 and 51 in maize, rice and wheat, respectively (Ladha et al 2016). In 2010, maize and rice approached similar N application rates (114 kg ha^{-1}) followed by wheat (99 kg ha^{-1}). It is projected that to meet the global cereal demand of three billion tons by 2050 and with projected increase of 7 percent in harvested area, fertilizer application rates to the three cereals must increase by about 65 percent, assuming no change in N use efficiency of the crop. In terms of global quantity of synthetic N, the increase would be from 51.8 Tg in 2010 to 85.4 Tg in 2050.

Fertilizer N Recovery Efficiency and N Losses
Nitrogen fertilizers are expensive inputs, costing agriculture more than US$50 billion per year. Most agricultural crops use fertilizer N inefficiently. Trials conducted globally in a wide diversity of maize, rice and wheat agro-ecosystems show fertilizer N recoveries (RE_N; fertilizer N recovery efficiency defined as kg crop N uptake derived from kg^{-1} fertilizer N applied) ranged between 0.2 and 0.9 kg N taken up kg^{-1}fertilizer N applied (20–90%) (Ladha et al 2005). As expected, many of the studies that obtained large values of RE_N used relatively lower N rates in a cropping season. The review of globally published data during last decades showed that the average RE_N across all regions and crops was 7 % lower when estimated by the nitrogen-15 (^{15}N) dilution method than by the N-difference method (Krupnik et al 2004; Ladha et al 2005). Additionally, 6.5% of applied N (residual N) was made available to subsequent crops during five growing seasons as determined by ^{15}N fertilizer recovery ($RE^{15}N$) (IAEA 2003). With an average $RE^{15}N$ of 44 % in the first

growing season (Ladha et al 2005), the total crop recovery of ^{15}N fertilizer, including the recovery by the five subsequent crops, is approximately 47 %. Since many soils cultivated with cereals have reached a near-steady state, it is likely that much of surplus fertilizer N of 53% would be lost to the environment (Krupnik et al 2004; Ladha et al 2005).

Role of Synthetic N Fertilizer in Sustaining Soil Organic Nitrogen in Cereal Cultivated Soils

Soil organic nitrogen (SON) is a key indicator of soil fertility representing an energy source for heterotrophs. It is an important source of plant nutrients, particularly but not exclusively for N. However, SON changes with cultivation and fertilizer-N inputs; normally, it decreases with cultivation without N fertilization and may increase with N-fertilizer amendment (Brye et al 2003). To test the hypothesis that long-term use of synthetic fertilizer-N results in a decrease in SON, Ladha et al (2011) analyzed peer-reviewed data from 100 long-term field experiments with N fertilizer treatments, representing a wide range of climatic zones, soil types, crops, and management practices. Results of their meta-analysis showed an average decline of 4 % of SON with the application of synthetic fertilizer N. Results indicated that synthetic N fertilization helped to maintain SON at near-steady state (Ladha et al 2011).

Global N Budgets in Maize, Rice and Wheat Cropping Systems

Since there is a continual loss of reactive N in an agroecosystem, an important question arises as to whether the system is reaching N disequilibrium. An agroecosystem would be in N equilibrium if the sum of N inputs equaled the sum of N outputs. Among various inputs and outputs of N, inputs from synthetic N sources and from manure/crop residue recycling, BNF and deposition, and outputs through crop harvest and losses in various forms are the most important. 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) by integrating global quantities of various sources and sinks of N, which were easier to estimate, rather than assessing N losses, which are highly location and management specific. A total of 1551 Tg of N were harvested by these cereals during the period, of which 48% was derived from fertilizer-N source and 4% was contributed through net soil depletion (Figure 1). The remaining 48% (737 Tg) of crop N harvest had sources other than fertilizer- or soil-N, corresponding to 29, 38, and 25 kg ha^{-1} yr^{-1} for maize, rice, and wheat, respectively. The major source of this N is apparently the non-symbiotic N_2 fixation, contributing 25% of total N in the crop, which is equal to 13, 22, and 13 kg ha^{-1} yr^{-1} for maize, rice, and wheat, respectively (Ladha et al 2016). Other non-fertilizer and non-soil sources include manure (14%) and atmospheric deposition (6%), while crop residues and seed contribute marginally (2 and 1%, respectively) to the crop N. This finding highlights the need to consider all the sources of N (synthetic, SON, manure/residue, deposition and non-symbiotic BNF) when designing strategies to improve N use efficiency.

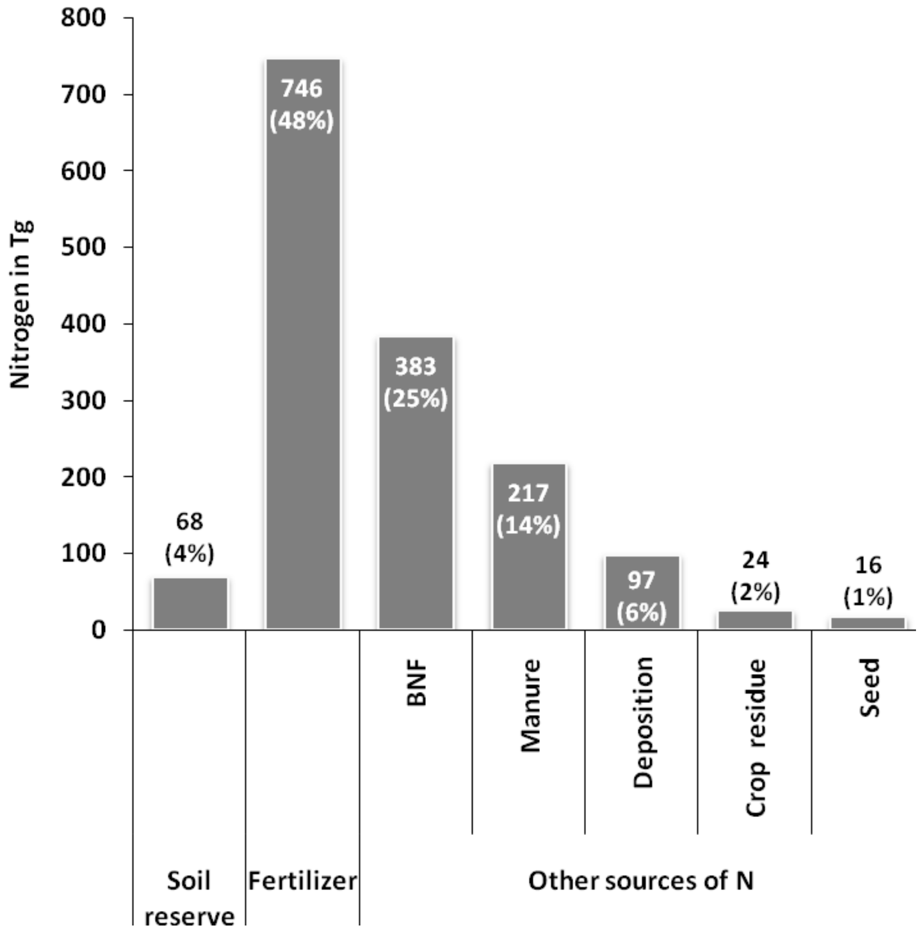

Figure 1. Global estimates of sources of N in crop harvest of maize, rice, and wheat production systems: total (Tg) for 50 years (1961-2010). Source Ladha et al (2016).

N Input-Output Framework to Assess Nitrogen-use efficiency

Nitrogen-use efficiency (NUE) is a complex term involving more than one component and there are several methods of expression. It is commonly regarded as a ratio that considers an output variable (biological or economic yield as dry biomass or their N content) as the numerator, and an input variable (N supply from SON and/or synthetic fertilizer) as the denominator (Ladha et al 2005). The recovery efficiency **[**RE_N], defined as the ratio of plant N to N supply is most commonly used to express NUE. Recently, the EU N Expert Panel (2015) and Zhang et al (2015) proposed a N input/N output based framework to assess the NUE. An emphasis is placed to include all the N inputs (i.e. manure/residue, deposition and non-symbiotic BNF) and not just synthetic fertilizer N as the sole N input. In addition, the term of N surplus which is the difference of N input and N output is used to estimate N loss to the environment. We used 50-year global N budget datasets developed for maize, rice and wheat to examine the NUE framework proposed by EU N expert panel. Our results show large differences in the input/output analysis when considered fertilizer N vis-à-vis all the sources of N. When considered only fertilizer N, the outputs were close to 90% NUE whereas when considered all the sources of N (fertilizer, manure, BNF, deposition, residue, SON), the outputs remained close to 50% NUE. In addition, the thresholds of N output target and the surplus N were different for three cereals.

Strategies to Improve the N Fertilizer Use Efficiency

Our goal should be to synchronize crop N demand with supply to ensure maximal NUE and thereby minimal N losses. High crop N demand linked to maximal genetic yield potential and harvest index (HI) of a crop will ensure high NUE which can be achieved through sound agronomic management practices and genetic crop improvements (Table). A full account of these strategies can be found elsewhere (e.g. Cassman et al 1998; Giller et al 2004; Dobermann and Cassman 2004; Drinkwater 2004; Ladha et al 1998, 2005; Shanahan et al

2008; Chalk et al 2015). From the N supply side, it is essential to adopt more efficient fertilizer, soil, water and crop management including conservation agriculture practices, which help to increase higher crop demand of N by creating a better and favourable production condition. Holistic management approaches will maximize crop N uptake, minimize N losses and optimize indigenous soil N supply including non-symbiotic N fixation by maintaining soil health. Management approaches suggested for increasing NUE include optimal time, rate, and methods of application for matching N supply with crop demand; the use of more efficient forms of fertilizer including slow and controlled release; urease and nitrification inhibitors; the integrated use of fertilizer, manures, and/or crop residues; and optimizing irrigation management (Table 1). In addition, some modern tools such as precision farming technologies, simulation modeling, and decision support systems, also help to improve NUE.

Genetic improvement of NUE through plant selection, breeding and genetic engineering has also been explored. Broadly, two plant traits related to NUE are involved: (a) N acquisition from soil and fertilizer N, and (b) internal efficiency with which N is used to produce plant biomass and grain (Ladha et al 1998). Differences in the efficiency of N acquisition may arise from differences in (a) the efficiency of absorption and assimilation of NH_4^+ and other N species; (b) root-induced changes in the rhizosphere affecting N mineralization, transformation and transport; and (c) root-and rhizosphere-associated BNF. Variations in the efficiency of internal use may arise from variances in (a) internal N requirements for growth, biomass production, and organ formation, (b) ability to translocate, distribute and remobilize absorbed N in various organs, (c) flag leaf N import/export and leaf senescence patterns, and (d) the efficiency of N use in converting CO_2 to carbohydrates. The N acquisition trait of NUE appears to be important when N supply is limiting which may exist in unfavorable environments (Moll et al 1982; Ortiz-Monasterio et al 1997). However, both N acquisition and internal N efficiency traits in favorable environments with non-limiting N supply appears to have already been taken care of in high yielding varieties with high HIs (Peng and Cassman 1998). Crop varieties with similar HIs may have slightly improved NUE through lower N concentrations in grain and straw. which However, lower N concentration in grain may not be acceptable to food processors and consumers because it would reduce the protein content and production quality (Singh et al 1998; Ladha et al 1998).

Improving the NUE of crop through gene manipulation has also been investigated. Numerous genes involved in N uptake, translocation, and remobilization; amino acid biosynthesis; C and N storage and metabolism; signaling targets; and regulatory elements are being explored (McAllister et al 2012). Some of the genes linked to ammonium assimilation are believed to improve NUE even though they are yet to show any positive effect in engineered plants. On the other hand, over expressing alanine aminotransferase (AlaAT), a gene not related to N metabolism, has resulted in improved biomass, yield and N content in rice grown under N limiting condition (Shrawat et al 2008). It will be interesting to investigate if AlaAT or other genes hypothesized to affect NUE would result in additional gains in improved crop genotypes which breeders have already developed for high yield potential, HI and RE_N (Peng and Cassman 1998).

In conclusion, the primary function of synthetic fertilizer N is to provide the crop with an immediately available source of N, often the most limiting nutrient for plant growth. The secondary function is to reduce the decline in SON content, a function which has long-term consequences on the sustainability of the systems as SON plays multiple roles in maintaining soil quality and ecosystem services. Recent N budgeting suggests that in maize, rice and wheat, 48% of their N requirement is met from synthetic fertilizer-N, and an equal portion of crop N comes from other sources including non-symbiotic BNF. This finding, therefore, highlights the need to consider all the sources of N, and not just synthetic fertilizer N, when designing strategies to improve N use efficiency. While synthetic fertilizer-N has played an immense role in meeting the growing food demand, it has also contributed adversely to the environment, causing water pollution, climate forcing, and loss of biodiversity. Globally, about 50% of applied synthetic fertilizer-N amounting to a several fold increase during the last 50 year is unaccounted for at the cropping system level. Fortunately, there is a great potential to improve the efficiency of fertilizer through improved management together with good agronomy/crop management and reduce the negative impact of reactive N on the environment (Grassin and Cassman 2012; Chen et al 2011; Ladha et al 2016).

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Table. Assessment of various strategies/tools and recommended actions to improve nitrogen use efficiency.

Approach/tools/tactics	Benefit	Potential	Constraint	Recommended action
Through improved resource management				
Best management (soil, water and crop) and conservation agricultural practices	Increased crop N demand	Very high	Inadequate documentation and dissemination	Proper documentation and active extension for dissemination
Improved crop variety	Increased crop N demand	Very high	Poor seed supply	Assured seed supply of improved crop varieties
Site specific N management - optimal N rate, source, timing (tools i.e. Chlorophyll meter, LCC)	Better N synchrony	High	None except high cost of SPAD (chlorophyll) meter	Active extension for awareness and effective dissemination of LCC
Controlled and slow release fertilizers	Better N synchrony with reduced N loss	High	High cost	R&D with greater involvement of private sector
Fertilizer placement	Better N synchrony with reduced N loss	High	Unavailability of suitable applicators for all ecologies	R&D with greater involvement of private sector
Nitrification inhibitors	Reduce N loss	Low	Variable response and high cost	R&D with greater involvement of private sector
Manure and organic amendments including crop residue cycling and green manuring	Non fertilizer/supplemental organic N inputs and Improved soil health ;	High	Availability and handling of bulky material, other competitive uses of organic sources and labor shortage	Development of efficient machines for handling of organics
Bio-fertilizers (inoculations of N_2 fixers)	Non fertilizer/supplemental biologically fixed N	Low	Variable response of inoculation	R&D with greater involvement of private sector
Through crop improvement				
Crop screening/breeding	Superior N acquisition and utilization; and rhizosphere N_2 fixation	High	Potential of further improvements in crop yield potential and harvest index;	Concerted research effort

			and rhizospheric N_2 fixation seem to have biological limits	
Genetic engineering	Efficient N metabolism	High	Evidence/proof of concept lacking	Concerted research effort
	Crop's ability to fix its own N thru BNF	High	Complicated and a long-term project	