



Efficient Use of Nitrogen Fertilizers: A Basic Necessity for Food and Environmental Security 11

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Abstract

Use of Fertilizer Nitrogen (N) to increase food production constituted one of the major factors in supporting population growth in the twentieth century. The trend continues in the twenty-first century, particularly in the developing countries of the world. Because a part of the N applied as fertilizer is prone to be lost from the soil–plant system to the environment and degrade its quality, increasing fertilizer N Use Efficiency (NUE) in agricultural farms can lead to achieving both food and environmental security. However, it is a challenging task because NUE is determined by a host of factors including nature of the crops grown, soil quality, and management of fertilizer N and other farm operations. In developing countries like India, China, and Egypt, NUE is rapidly falling since the Green Revolution era because consistently increasing fertilizer N consumption is accompanied by declining crop yield response to applied N. While in countries like the USA, crop yields continued to increase moderately even with a trend in the reduced increase in fertilizer N inputs, in most of the western European countries crop yields continued to improve without further increase or even decrease in fertilizer N consumption since the 1980s. These trends in crop yield and fertilizer N consumption in several developed countries have resulted in a regular increase in NUE for more than the last four decades. In line with the observed trends in NUE in countries like India and China, high N surpluses in agricultural soils are posing a threat to the environment. New knowledge-based N management strategies to improve NUE are becoming available, but significant new investments and partnerships between farmers, scientists, economists, citizens, and industries

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will be needed to improve NUE in current and future agricultural systems by the widespread adoption of both the existing and emerging technologies.

Keywords

Nitrogen use efficiency · Nitrogen input · Nitrogen output · Nitrogen surplus · Nitrogen balance · Partial factor productivity · Agronomic efficiency · Recovery efficiency · Soil nitrogen

Abbreviations

AE	Agronomic efficiency
DCD	Dicyandiamide
DMPP	3,4-Dimethylpyrazole phosphate
F	Fertilizer nitrogen level
N	Nitrogen
NBPT	N-(n-butyl) thiophosphorictriamide
NUE	Nitrogen use efficiency
PE	Physiological efficiency
PFP	Partial factor productivity
RE	Recovery efficiency
Rfc	Ratio of fertilizer to crop price
U	Total plant nitrogen uptake with nitrogen fertilizer
U ₀	Total plant nitrogen uptake without nitrogen fertilizer
Y	Crop yield with fertilizer nitrogen
Y ₀	Crop yield without fertilizer nitrogen
Y _F	Yield increase due to fertilizer nitrogen
Y _{max}	Yield at saturating fertilizer nitrogen levels

11.1 Introduction

Due to the increasing global population as well as improving standards of living, demand for food by 2050 should be 1.5–2 times as much as it is today. As per FAO's projection, there will be 60% higher agricultural production in 2050 than that recorded in 2005 to 2007 (Alexandratos and Bruinsma 2012). To achieve such food production levels without adding more farmed land, nitrogen (N) fertilizers produced by Haber–Bosch process are likely to continue playing a crucial role. According to Erisman et al. (2008), about 50% of the world population in 2008 was alive due to increased crop production achieved by applying fertilizer N. As depicted in Fig. 11.1, it is true even today and growth of the world population is more or less parallel to the rate of increase of fertilizer N consumption. Although production of enough fertilizer N and its reliable supply has allowed farmers to greatly increase

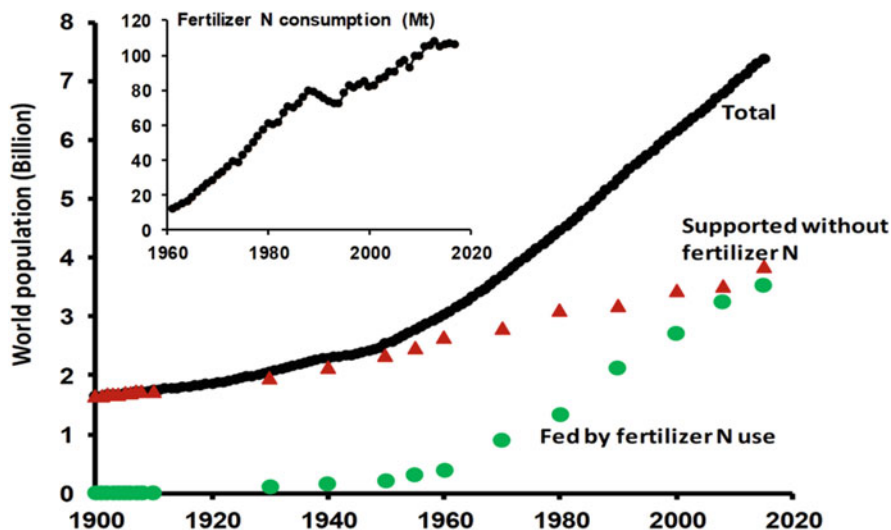


Fig. 11.1 Estimates of the share of the global population, which could be supported with and without the application of nitrogen fertilizers for food production on farms. Best estimates project that just over half of the global population could be sustained without applying nitrogen fertilizers on farms. Source: Erisman et al. (2008), Smil (2001), Stewart et al. (2005), IFADATA (2020)

crop production resulting in increased economic development as well as sparing forests from conversion to agricultural land (Foley et al. 2011), nearly one billion people all over the world still remain undernourished (Alexandratos and Bruinsma 2012; Kumar et al. 2018). It suggests that further improvement in fertilizer N management is needed to increase crop production per unit of applied fertilizer N.

Global fertilizer N consumption is increasing linearly (Fig. 11.1), but there exists wide variation in the extent of fertilizer N use in different countries of the world and in different regions within a country both in terms of total N consumption as well as consumption of N per ha of cropland. For example, until 1989 developed countries in the world consumed more fertilizer N than the developing countries, but later on, the consumption decreased in the developed countries but it is still increasing in developing countries (Bijay Singh and Ali 2020). Possibly, farmers in developed countries adopted improved fertilizer N management practices, which helped in producing high yield levels with less fertilizer N. Of the 107.7 Mt. fertilizer N consumed globally in 2017, 38.4% was used by farmers in China and India, the two developing countries where about 36% of the world population lives; North America and Western and Central Europe used only 25.4% of the fertilizer N consumed globally (<http://ifadata.fertilizer.org/ucSearch.aspx>, Accessed 8 August 2020). As fertilizer N is heavily subsidized in most of the developing countries, farmers often apply large N doses to avoid the risk of low crop yields but it leads to reduced N Use Efficiency (NUE). In Table 11.1 are listed data pertaining to fertilizer N use per unit area of arable land in different regions of the world in 2003 and 2018. In terms of agricultural intensification based on farm mechanization and the use of

Table 11.1 Fertilizer nitrogen use per ha of crop land in different regions of the world during 2003 to 2018

Region	Fertilizer N use (kg ha ⁻¹)			Relative change (%)
	In 2003	In 2018	Absolute change	
Middle Africa	0.89	2.44	+1.56	+176
Northern Africa	33.26	38.81	+5.56	+17
North America	61.65	72.32	+10.67	+17
Western Europe	136.27	118.52	-17.74	-13
Southern Asia	65.13	97.34	+32.21	+49
Eastern Asia	183.96	198.82	+14.86	+8
World	57.84	69.43	+11.59	+20

Fertilizer N use in kg ha⁻¹ was calculated by dividing the fertilizer N consumption with area under arable land and permanent crops

Data source: FAOSTAT (2020)

fertilizers and chemicals, there exist large disproportions between different countries of the world (Mueller et al. 2012; Bouwman et al. 2013; Nierdscheider et al. 2016). In countries like China, Egypt, or in some parts of Europe, the application of heavy fertilizer N doses is resulting in a large amount of surplus N in the soil–plant system. But on the other hand, soils in many African countries are getting depleted of their N reserves due to the application of fertilizer N than less than the removal by crops (Sutton et al. 2013; Lassaletta et al. 2014; Kumar et al. 2020). Fertilizer N use per ha almost did not pick up in Middle Africa but it increased substantially in South Asia. In Western Europe and eastern Asia, fertilizer N use per ha was already very high in 2003 so that during 2003 and 2018, there was a relative increase of only 8% in Eastern Asia while a decrease of 13% was recorded in Western Europe. In 2018, China, Egypt, and India were applying 186, 276, and 97 kg N ha⁻¹. Thus, there are regions in the world where fertilizer N application rates are not even enough to achieve the full production potential of crops and in several countries, fertilizer N is being applied in farms at levels that may well exceed the N needs of crops.

While in natural ecosystems N present in the soil meets the N requirement of the growing plants, in the modern agro-ecosystems fertilizer has to be applied to supplement soil N to achieve N uptake levels of the crops needed to produce optimum yields. But fertilizers besides supplying N can also disturb microbial and other functions of the soil and different ecosystem services it performs. When fertilizer N is not efficiently utilized by crops due to excessive application levels and/or mismanagement, a portion of applied N may leave the soil–plant system and adversely impact the environment including groundwater contamination with nitrate-N, eutrophication of surface water bodies, and production of nitrous oxide—a greenhouse gas (Galloway et al. 2003, 2008; Reay et al. 2012). When applied in doses more than the requirement of the crops, fertilizer N leads to increased residual inorganic N in the soil, which accelerates the loss of soil organic matter through its mineralization leading to the deterioration of soil health (Bijay Singh 2018). Thus, too little N in the soil leads to reduced crop productivity, soil degradation, reduced protein intake by humans, and overall food insecurity but an

excessive supply of N can result in environmental insecurity along with concomitant threats to human health, ecosystem health, and economic prosperity. Under these circumstances, the best solution is to apply only enough fertilizer N that the crop does not suffer due to N deficiency but ensure that a large portion of the applied N is used by crop plants and minimal amount escapes from the farms. It can be achieved by ensuring high fertilizer NUE, which represents the percentage of applied fertilizer N recovered in the farm produce, and it is the most effective means for achieving food security through increased crop productivity on the one hand and environmental security through reduced losses of N from the soil–plant system on the other (Cassman et al. 2003; Davidson et al. 2015). According to Zhang et al. (2015a), improvements in NUE in crop production, although conditional on the farm-scale adoption of innovative technologies and improved fertilizer management practices as well as on socio-economic factors, are critical for achieving food and environmental security, and resist climate change. In the fourth session of the United Nations Environment Assembly (UNEA 4) held in March 2019, a resolution passed on sustainable N management calls upon improving NUE for achieving the Sustainable Development Goals (UNEA 2019). This chapter is an attempt to discuss NUE in terms of the fertilizer N transformations in the soil and ways and means based on advances in technological capacity for knowledge-based N management in agriculture to improve NUE for achieving food security with minimal environmental degradation.

11.2 The Fate of Fertilizer Nitrogen in the Soil-Plant System

In all the soils, whether in unmanaged natural ecosystems to which no fertilizer N is applied or in agricultural ecosystems to which N is applied through fertilizers, N retention in organic combinations is a characteristic feature. As shown in Fig. 11.2, mineral N released through mineralization-immobilization turnover from the huge soil N pool remains available in a mineral N pool from which N is used by plant roots or it can be lost via leaching and/or in gaseous forms. At any time, soil N pool is huge in comparison to mineral N pool which continuously gets replenished at rates defined by moisture and temperature conditions (Fig. 11.2). In natural ecosystems, N released from the soil and its removal by roots of plant communities are synchronized both temporally and spatially to a very large extent so that losses of N from the soil–plant system are minimal. It represents a case of a relatively tight N cycle (Christensen 2004; Kumar et al. 2021). When fertilizer N is applied to agricultural soils, only a portion of it directly contributes to the mineral N pool, from where roots of crop plants absorb N or it can be lost to the environment via different mechanisms. The remaining portion of the fertilizer N becomes a part of the large pool of organically bound N in the soil. Chien et al. (2009) collected data from 800 experiments and found that recovery of applied N by cereal crops was only 51% and that fertilizer N recoveries were even lower when fertilizer N was applied at high rates.

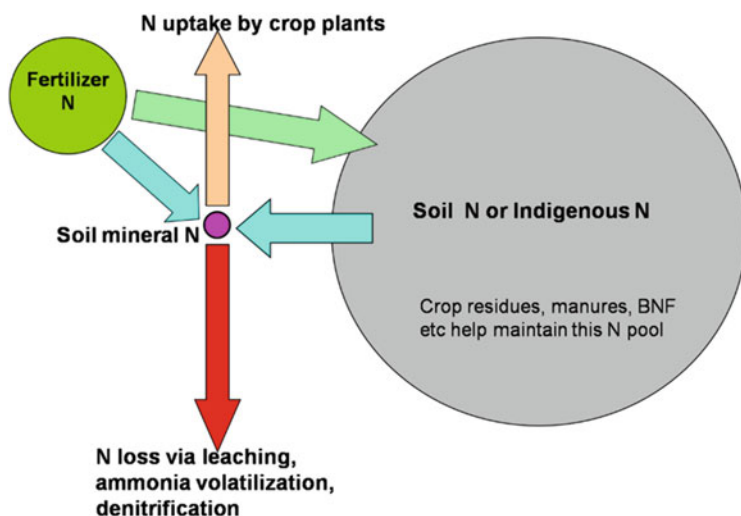


Fig. 11.2 Schematic diagram of the fate of fertilizer N applied to agricultural soils

Table 11.2 Typical range of grain yield and total amount of N removed by wheat, maize and rice

Crop	Yield per crop (t ha^{-1}) ^a	Annual N removed (kg N ha^{-1})
Wheat (<i>Triticum aestivum</i>)	2–8	40–160
Maize (<i>Zea mays</i>)	3–8	45–120
Rice (<i>Oryza sativa</i>)	3–8	70–190 ^b

^aLægheid et al. (1999)

^bFor two crops of rice grown in a year

In contrast to the natural ecosystems, N cycling in the agro-ecosystems is relatively open with other ecosystems. The yield and amount of N typically harvested in agricultural systems based on the three most important cereal crops are shown in Table 11.2. To maintain the productivity of these systems, N has to be applied as fertilizers, manures, or N_2 -fixation to compensate for the removal of N to the extent of 300 kg N ha^{-1} each year in the form of harvested crops (Cassman et al. 2002). When enough fertilizer N is not applied in agro-ecosystems, soil N gets depleted. According to broad estimates, 20 to 80% of the N taken up by crop plants originates from soil N (Broadbent 1984). Although the rest of the N in crop plants is supplied by fertilizers, several studies prove that annual fertilizer N inputs are still more than the quantity of N removed in crop harvest by 40% to more than 100%, leading to loss of N to the environment (Galloway and Cowling 2002).

Despite some limitations (Stark 2000), ^{15}N -labeled fertilizers when applied to agricultural crops permit quantification of applied N in crop and different soil N pools. Based on data from 93 published studies (572 data points) from all over the world that used ^{15}N -labeled fertilizer, Ladha et al. (2005) revealed that the overall recovery of fertilizer N in the above-ground portions of maize, rice, and wheat was

Table 11.3 Percentage of soil N and fertilizer N in total N uptake by above-ground portions of different crops grown in different countries as determined by applying ^{15}N labeled fertilizers

Crop	Countries	Fertilizer N applied (kg N ha ⁻¹)	Total N uptake by the crop (kg N ha ⁻¹)	N in the crop derived from fertilizer (%)	N in the crop derived from soil (%)
Wheat	Bangladesh, Chile, Egypt, Morocco	42–160	60–161	16–43	57–84
Maize	Chile, Malaysia, Sri Lanka, Vietnam	60–300	53–178	18–58	42–92
Rice	China	60	292	7	93
Sugarcane	Brazil	63	251	16	84
Sunflower	Morocco	35	129	7	93
Bean	Morocco	85	225	7	93
Mean			147 ± 6	21 ± 1	79 ± 1

Modified from Dourado-Neto et al. (2010)

44%. A limited number of studies also exists in which recovery of ^{15}N -labeled fertilizer N has been studied even after the first crop (Hart et al. 1993; IAEA 2003; Kumar and Goh 2002). Mean recoveries of applied fertilizer N in first to fifth subsequent crops in different cropping systems were found to be 3.3%, 1.3%, 1.0%, 0.4%, and 0.5%, respectively so that in the six continuous crops only about 50% of the applied fertilizer N was recovered by crop plants. Thus as shown in Fig. 11.2, most of the remaining 50% of the remaining N applied through fertilizer was converted into organic N in the large soil N pool. Depending upon the closeness of the fertilizer N dose to the optimum for a crop, a part of the applied N should be directly susceptible to losses from the soil–plant system to the environment. In ^{15}N -recovery experiments conducted by Dourado-Neto et al. (2010) in diverse tropical locations, the average total contribution of ^{15}N -labeled fertilizer N by different crops was found to be 21% (7–58%) of the average crop N uptake of 147 ± 6 kg N ha⁻¹ (Table 11.3). Thus, on an average 79% N in the above-ground crop plants was contributed by soil N. Based on data generated from 217 field studies in temperate grain agro-ecosystems in which ^{15}N -labeled fertilizer was applied, Gardner and Drinkwater (2009) also revealed that even with the application of high fertilizer N application rates, about 60% plant N came from soil N. That contribution of N released through mineralization of soil N is very crucial in supplying N to the growing plant even when the optimum amount of fertilizer N is applied, is an important finding and it has implications for both N nutrition of crop plants and environmental degradation. Sebilo et al. (2013) made a one-time application of ^{15}N -labeled fertilizer N at 120 kg N ha⁻¹ to wheat and 150 kg N ha⁻¹ to sugar beet grown under rotating cultivation in two intact lysimeters. Later on for three decades annual N fertilization rate for both crops was 120 kg N ha⁻¹. All the crops grown for three decades used only 61–65% of the applied fertilizer N. Substantial portion of the applied fertilizer N rapidly became a part of the soil N pool. While

32 to 37% of the applied N was incorporated in the soil organic matter after 3 years, 12–15% of the fertilizer N was still recovered in the soil N pool even after 28 years.

11.3 Measuring Fertilizer Nitrogen Use Efficiency

Nitrogen use efficiency is commonly used as a generic term and can be defined based on different components as in the specific indices listed in Table 11.4. Different indices of fertilizer NUE are essentially the ratios between crop output (economic yield or N uptake) and N inputs in the form of fertilizer (Crop Science Society of America 1992). Keeping in view that NUE is governed by efficiency in uptake and utilization of N for production of grains (Moll et al. 1982), indices of NUE have been classified as agronomic efficiency (AE), physiological efficiency (PE), recovery efficiency (RE) and partial factor productivity of applied N (PFP). Some other indices have also been used, but they have no additional advantage in studying the fate of fertilizer N in improving the N nutrition of crops (Huggins and Pan 1993). Recovery efficiency measured using ^{15}N -labeled fertilizer N can provide detailed information on the fate of applied N in terms of utilization by crop plants, losses from the soil–plant system, immobilization, and mineralization of soil N.

In field studies, the three NUE measures—RE, PE, and AE are computed from the increase in crop yield and/or N uptake by applying fertilizer N. These NUE measures are commonly referred to as computed by following the “difference method”. When using ^{15}N -labeled fertilizers, uptake of fertilizer N by the crop also provides a measure of NUE. Time scale for estimating RE, PE, and AE is usually one cropping season and these are based on a spatial scale mostly of a field or plot. When comparing different cropping practices in which crop yield in plots receiving no fertilizer N (Y_0) differs greatly due to following these practices, AE and RE are not appropriate indices of NUE (Dobermann 2007). In such scenarios, partial factor productivity (PFP) of fertilizer N (the ratio of grain yield and amount of fertilizer N applied) serves as the proper index of NUE as it allows making comparisons across agronomic practices since measurements of grain yield or N uptake in no-N control plots are not required in calculating PFP. In Table 11.4 are described the calculations, interpretation, and optimum range of different fertilizer NUE indices in cereal crops.

11.4 Fertilizer Nitrogen Use Efficiency and Crop Production

As discussed in the previous sections, all N applied as fertilizer is not available to the crop and the N applied through fertilizer constitutes only one of the several N sources in the soil. Therefore, NUE expressed as PFP provides a measure of the total economic output as a result of N utilization from all sources of N including fertilizer. Farmers also prefer to measure NUE as PFP as it provides a measure of the return from the application of fertilizer N, regardless of the indigenous soil supply. As yield (Y) recorded by applying fertilizer N at a given rate (F) represents the sum

Table 11.4 Definition, calculation, range and interpretation of different fertilizer nitrogen (N) use efficiency indices in cereals

Nitrogen use efficiency index	Formula ^a	Explanation	Range
RE, Apparent recovery efficiency of fertilizer N (kg increase in N uptake per kg fertilizer N). It can also be expressed as percentage of applied fertilizer N	$RE = (U - U_0)/F$ or $RE = (U - U_0)/F \times 100$	<ul style="list-style-type: none"> • Defined by congruence between plant N demand and N supplied by fertilizer. • Affected by the amount, time of application, placement, and form of fertilizer N, and factors controlling the size of the crop nutrient sink 	0.30–0.50 kg/kg In well-managed crops, at low fertilizer N levels, or at low soil N supply, RE can be 0.50–0.80 kg/kg
PE, Physiological efficiency of fertilizer N (kg yield increase per kg increase in N uptake from fertilizer)	$PE = (Y - Y_0)/(U - U_0)$	<ul style="list-style-type: none"> • Capability of a plant to translate N utilized from fertilizer into grain yield. It depends on genotype, environment and management. • Low PE suggests sub-optimal growth due to N deficiency, drought stress, heat stress, mineral toxicities and pests 	40–60 kg/kg In well-managed crops, at low fertilizer N levels, or at low soil N supply, PE can be >50 kg/kg
AE, Agronomic efficiency of fertilizer N (kg yield increase per kg fertilizer N)	$AE = (Y - Y_0)/F$ or $AE = RE \times PE$	<ul style="list-style-type: none"> • As AE is the product of RE and PE, it depends on management practices that affect RE and PE 	10–30 kg/kg In well-managed crops, at low fertilizer N levels, or at low soil N supply, AE can be >25 kg/kg
PFP, Partial factor productivity of applied N (kg harvest product per kg N applied)	$PFP = Y/F$	<ul style="list-style-type: none"> • It represents combined use efficiency of indigenous and applied N • Both high indigenous soil N supply and high AE determine PFP 	40–80 kg/kg In well-managed crops, at low fertilizer N levels, or at low soil N supply, PFP can be >60 kg/kg

Modified from: Dobermann (2007)

^aSymbols used in equations: F: fertilizer N applied (kg N ha⁻¹), Y: yield of the crop with application of fertilizer N (kg ha⁻¹), Y₀: yield of the crop (kg ha⁻¹) without fertilizer N, U: total N uptake by above-ground crop biomass at maturity (kg N ha⁻¹) with application of fertilizer N, U₀: total N uptake by above-ground crop biomass at maturity (kg ha⁻¹) without fertilizer N

of the yield without fertilizer N (Y_0) and the yield increase because of fertilizer (Y_F), the PFP can be expressed as:

$$\text{PFP} = Y/F = (Y_0 + Y_F)/F = Y_0/F + Y_F/F \quad (11.1)$$

As Y_F/F is the ratio of net increase in grain yield due to application of fertilizer N and the amount of fertilizer N applied, it is equivalent to AE, which is the product of recovery efficiency (RE) and physiological efficiency (PE) (Table 11.4), PFP can be written as:

$$\text{PFP} = Y_0/F + \text{AE} = Y_0/F + \text{RE} \times \text{PE} \quad (11.2)$$

Thus, PFP represents an efficiency index, which is based on the yield of the crop due to N derived from the soil, RE, and PE. The term “ Y_0/F ” in the above equation suggests that PFP in farmers’ fields can be improved by increasing uptake of soil N as well as by enhancing AE and PE (Cassman et al. 1998). It suggests that the buildup of soil N or soil organic pool due to the application of fertilizer N (Fig. 11.2) can contribute to an increase in NUE in subsequent years. And to achieve high NUE in a given season, it is important to adjust the dose and time of fertilizer N application as per the availability of soil N.

Reports already exist that sustained increases in organic matter, particularly in aerated soils (not under irrigated rice), lead to increased N supply from the soil due to mineralization of organic N pools and reduced fertilizer N applications can maintain both high yield levels and PFP (Bell 1993; Kolberg et al. 1999). If due to some kind of soil mismanagement, organic matter in the soil is declining over time, it can lead to loss of N from the soil N pool over and above that from the fertilizer N. It will lead to a reduction in PFP and fertilizer N doses will have to be increased to maintain optimum yield levels. In soil in South Asia containing more than 2500 kg N ha⁻¹ in the 0–0.3 m depth, a crop of irrigated wheat will typically remove 110 kg N ha⁻¹ at a fertilizer N application rate of 120 kg N ha⁻¹. With RE of 0.40, only 48 kg N ha⁻¹ comes from fertilizer, and rest 62 kg N ha⁻¹ is the contribution of soil N. But at the same time, a substantial portion of the 72 kg N ha⁻¹ applied as fertilizer but not used by the crop, becomes a part of the soil N. It may become available for N uptake by crops in subsequent years. If in the above example, soil is able to supply only 50 kg N ha⁻¹ rather than 62 kg N ha⁻¹, to achieve the same yield and N uptake levels by wheat crop, fertilizer N rate will have to be increased to 150 kg N ha⁻¹ at RE of 0.40, although RE always decreases at higher fertilizer N application levels. At high fertilizer N application rates, fertilizer substitution value of indigenous N increases substantially. Buildup of soil N through fertilizer N substitution contributes to high RE. A decrease in soil N supply reduces the overall productivity of the soil. Improved crop varieties and application of high fertilizer N rates may sustain or increase crop yields for some years, but eventually, soil health degradation due to loss of soil N reserves will result in stagnation or even decline in yield. It is an emerging challenge for intensive agriculture based on high fertilizer N inputs in most parts of the world. Fifty-year (1961–2010) global N budget based on data generated

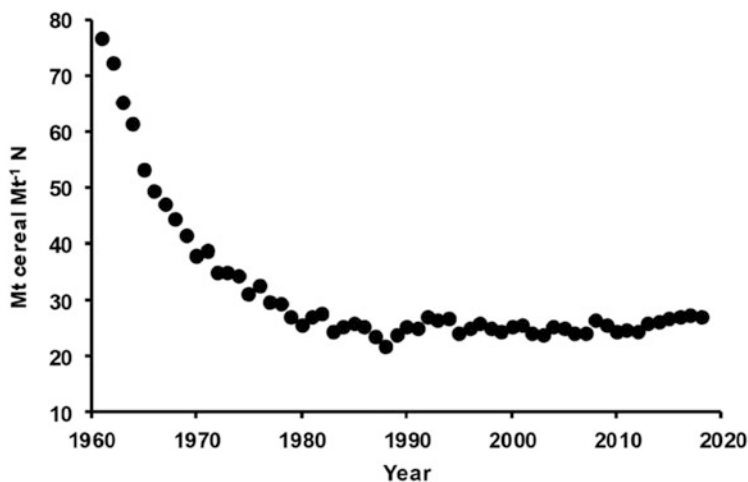


Fig. 11.3 Partial factor productivity of fertilizer N for global production of cereal grains. Data source: FAOSTAT, <http://www.fao.org/faostat/en/#data/QC> (Accessed 17 September, 2020)

in 114 long-term experiments being conducted in different parts of the world, revealed that soil N reserves have declined by 8% in maize and wheat production systems, but increased by 4% in rice (Ladha et al. 2016). According to Yan et al. (2014), due to continuous high fertilizer N input for the last 30 years (1980–2010) in China, RE has declined to less than 0.30 but a large portion of applied N became a part of soil N every year so that 40–68% of applied fertilizer N was utilized by the crops eventually.

As PFP is a ratio of grain yield and amount of fertilizer N applied, its large values observed at small N application rates decline with increase in fertilizer N application rates. Of course, PFP is also defined by the nature of cereal crops and achievable yield potential, soil quality, and fertilizer and crop management operations. As global fertilizer N consumption increased from 11.39 Mt. in 1961 to 108.66 Mt. in 2018, PFP in cereal grain production decreased from 77.0 kg grain kg⁻¹ N in 1961 to 27.3 kg kg⁻¹ in 2018 (Fig. 11.3). Until and unless the response curve for yield as a function of the amount of applied N is shifted up by removing constraints on yield through improved management, a decrease in PFP is expected when high yields are recorded following a fixed N response function. Thus, decline in PFP soon after the introduction of N fertilizers in a region was observed due to the application of increasing amounts of fertilizer N by farmers. In many developed countries in North America, Western Europe, and countries like Japan and South Korea in Asia, a steady increase in PFP has been observed since the mid-1980s because cereal yields in these countries have been increasing even though fertilizer N use has been small or even declined in some regions (Dobermann and Cassman 2005). High yields along with high PFP in these countries have been observed due to improved management practices, fertile soils, favorable climate, high yielding and stress-tolerant cultivars, and improved fertilizer recommendations (IFA 2007). In contrast

Table 11.5 Different fertilizer nitrogen use efficiency indices for rice, wheat and maize. Average values as reported by Ladha et al. (2005) are based on data obtained from 93 published studies conducted all over the world

Crop	Fertilizer N rate (kg N ha ⁻¹)	AE ^a	RE ^b	RE (¹⁵ N) ^c	PE ^d	PFP ^e
Maize	123	24.2	65	40	36.7	72.0
Rice	115	22.0	46	44	52.8	62.4
Wheat	112	18.1	57	45	28.9	44.5
Average		20.6	55	44	40.6	51.6

Source: Modified from Ladha et al. (2005)

^aAE = agronomic N use efficiency (kg grain increase kg⁻¹ N applied)

^bRE = recovery efficiency of fertilizer N (% of N applied)

^cRE (¹⁵N) = recovery of ¹⁵N-labeled fertilizer N (% of N applied)

^dPE = physiological N use efficiency (kg grain increase kg⁻¹ N taken up)

^ePFP = partial factor productivity of N (kg grain yield kg⁻¹ N applied)

to developed countries, fertilizer N use in the 1960s was very low in developing countries but after the Green Revolution fertilizer N application rates increased rather exponentially. This resulted in a sharp decrease in PFP; at rates of almost -1 to -2% year⁻¹ (Dobermann and Cassman 2005). However, Africa is an exception with very high PFP values indicative of unsustainable soil N mining. No reports are yet available which document country-scale increase in PFP due to the adoption of improved N management strategies in developing countries.

Ladha et al. (2005) carried out a worldwide evaluation of NUE in cereal-based systems and based on data generated in 93 published studies, reported average values of RE, PE, AE, and PFP for fertilizer N in rice, wheat, and maize. As shown in Table 11.5, both AE and PFP were the smallest in wheat and the largest in maize. The differences in PFP are ascribed to large economic outputs of maize and rice as compared to that of wheat as well as inherent N concentration in grains of the three crops: 9–12 g N kg⁻¹ rice, 13–14 g N kg⁻¹ maize, and 16–18 g N kg⁻¹ wheat (Ladha et al. 2005). The average RE values were 0.65, 0.46, and 0.57 for maize, rice, and wheat, and these were higher by 25%, 2%, and 12% than the RE values measured by using ¹⁵N-labeled fertilizer, respectively. The smallest RE values for rice among the three crops were caused by anaerobic conditions in which rice is grown as well as due to application of reduced forms of N in rice, which favors loss of applied N via ammonia volatilization and denitrification (Cassman et al. 1998). For cereal grain production, Raun and Johnson (1999) gave a worldwide average RE of 0.33. According to Ladha et al. (2005), it is likely that for rice, wheat, and maize, RE under rainfed conditions ranged from 0.20 to 0.30, and for crops grown with assured irrigation the range was from 0.30 to 0.40. The largest average values of PE for rice are due to low grain N concentration as compared to that of maize and wheat. Also with its large harvest index, rice can efficiently mobilize N from other plant parts to grains (Ladha et al. 1998). Maize shows higher PE than wheat as it is a C₄ crop and has relatively less inherent N concentration in grains (Cassman et al. 2002) (Table 11.5).

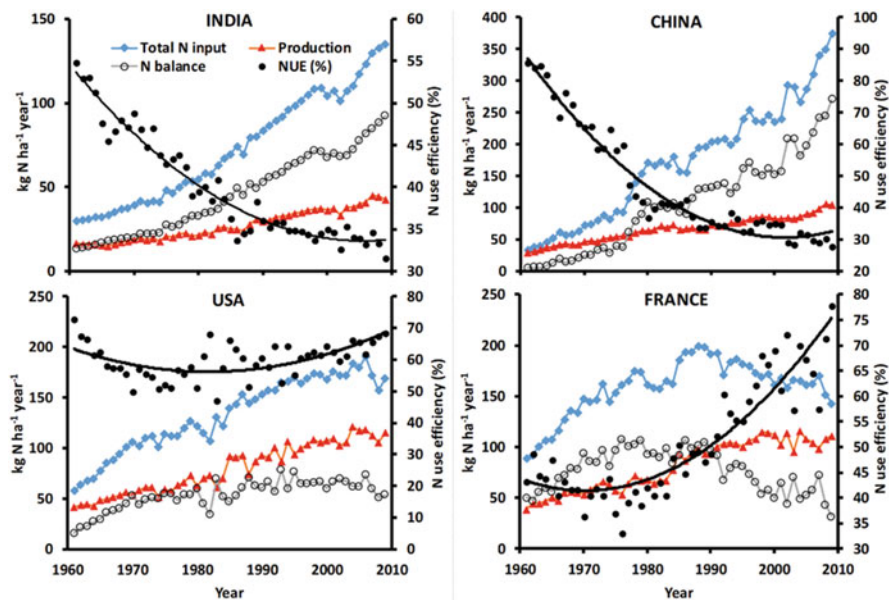


Fig. 11.4 Total N input through all sources including fertilizer, N output in economic yield of crops, N balance (difference of N input and N output), and N use efficiency (N output expressed as percentage of N input) in cropping systems in India, China, USA and France during 1961 to 2009. Data source: Lassaletta et al. (2014)

Lassaletta et al. (2014) used FAO databases to estimate total annual inputs of N to arable land through fertilizers, manures, symbiotic fixation, and atmospheric deposition, and total N output through crop yield for 124 countries of the world for the period 1961 to 2009. As both input and output of N were expressed as kg N ha⁻¹ year⁻¹, these data allowed to estimate N balance as the difference between N input and N output, and NUE as the N output expressed as a percentage of total N input. Time trends for 50 years in annual N input, N output, N balance, and NUE for India, China, USA, and France are plotted in Fig. 11.4. In both India and China, total N consumption has been continuously increasing since 1961, but the rate of increase in N output in terms of yield is very low. As a result, NUE in India has fallen from 54.8% in 1961 to 31.6% in 2009 and in China from 85.6% in 1961 to 27.7% in 2009. Several developing countries like India, China, and Egypt are following the trajectories of regularly increasing fertilizer N consumption with a continuously declining crop yield response to N and rapidly falling NUE. In the case of countries like USA, fertilizer N inputs did not increase rapidly from the 1980s onwards but yields of important crops (N output) kept on increasing, though moderately. It is reflected in a consistent trend in NUE over the time achieved through improved agronomical practices even for production factors other than fertilizer N (Howarth et al. 2002; Alston et al. 2010). Time trends in NUE for France, Netherlands, and most of the West European countries are unique in terms of increase in both fertilizer

N use (N input) and yield (N output) from 1960 to 1975. However, after 1975, while yields kept on increasing, fertilizer N consumption did not increase further; N input even exhibited a decreasing trend from the 1980s onwards. These trends are clearly translated into a rapid increase in NUE of about 40% in the early 1980s to 78% in 2009 as shown for France in Fig. 11.4.

By fitting a plot of N output (yield) versus total N input to a single parameter hyperbolic function, Lassaletta et al. (2014) computed Y_{max} , the yield obtainable at saturating N fertilization. The Y_{max} values for India based on yield trends during 1961–2009 and 1995–2009 were 51 and 59 kg N ha⁻¹ year⁻¹, respectively. Similarly for China, the values based on the periods 1961–2004 and 2005–2009 were 118 and 139 kg N ha⁻¹ year⁻¹, respectively. Almost similar Y_{max} values for the two periods for both India and China suggest that fertilizer management practices in the two countries did not improve substantially since the fertilizers were introduced so that NUE is rapidly falling due to continuously increasing fertilizer N consumption (Fig. 11.4). In sharp contrast, Y_{max} values for USA based on the periods 1961–1979 and 1985–2009 were 130 and 269 kg N ha⁻¹ year⁻¹, respectively, and for France the values were 103 kg N ha⁻¹ year⁻¹ based on the period 1961–1975 and 297 kg N ha⁻¹ year⁻¹ based on the period 1994–2009. The huge increase in Y_{max} values for USA and France when these were based on recent period convincingly suggest that fertilizer NUE has greatly increased by following improved management practices in these countries. In some countries such as in Africa, there are always very low N inputs as well as yields; sometimes even higher N output in terms of yields than fertilizer N input are observed. Such negative N balances constitute the signatures of unsustainable N mining scenarios in agricultural soils (Lassaletta et al. 2014).

11.5 Fertilizer Nitrogen Use Efficiency in Relation to Environmental Security

Surplus N in agricultural soils designated as N balance in Fig. 11.4 (Lassaletta et al. 2014) and defined as total N input minus N outputs, is an indicator of the potential losses of N from agro-ecosystems to different components of the environment (van Beek et al. 2003; Van Groenigen et al. 2010). When N input, N output, and N balance are expressed in units of kg N ha⁻¹ year⁻¹, and NUE is expressed as the ratio of N output and N input, N balance is related to NUE as:

$$\text{N balance} = \text{N output} \times (1/\text{NUE} - 1) \quad (11.3)$$

Thus in the well documented (Lassaletta et al. 2014; Conant et al. 2013) first phase of agricultural expansion in different countries of the world, rapid increase in fertilizer use or N input, a moderate increase in N output or yield, and a substantial increase in N balance or surplus N was accompanied with a concomitant decrease in NUE. In Fig. 11.4, this phase is visible up to 1980s in USA and France which represent North America and Europe, respectively. India, China, and most of the

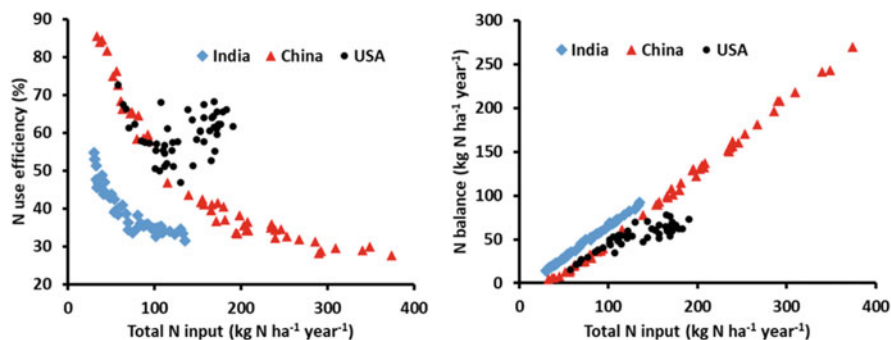


Fig. 11.5 Nitrogen use efficiency (N output expressed as percentage of N input) and N balance (difference of N input and N output) as functions of total N input during 1961 to 2009 in India, China and USA. Data source: Lasaletta et al. (2014)

developing regions of the world are still in the initial phases of agricultural intensification and with falling NUE showing increasing surplus N in the form of N balance, which is posing a potential threat to environmental security. Developed countries such as USA and France are already in the second phase of agricultural expansion which consists of sustainable intensification of agriculture being achieved by growing high yielding crop cultivars, improved water management, balanced application of different plant nutrients, adopting tools for precision and need-based application and site-specific management of fertilizers, and using enhanced-efficiency fertilizers (Houlton et al. 2019). In the second phase of agricultural expansion, while N output in the form of yield kept on increasing, applied N and surplus N, either declined (as in the case of France in Fig. 11.4) or did not increase appreciably (as in the USA) while NUE showed an increasing trend. Countries like India and China and most of the developing countries are yet to enter the phase of sustainable intensification of agriculture.

In Fig. 11.5, NUE and N balance are plotted as a function of N input for India, China, and the USA. Although total N input did not exceed $150 \text{ kg N ha}^{-1} \text{ year}^{-1}$ in India, NUE was conspicuously less than both USA and China. As explained in the previous section, it is because of soil and climate constraints as well as inadequate fertilizer management that the potential for obtaining high yields (Y_{\max}) in India ($59 \text{ kg N ha}^{-1} \text{ year}^{-1}$) is lower than both China ($139 \text{ kg N ha}^{-1} \text{ year}^{-1}$) and USA ($269 \text{ kg N ha}^{-1} \text{ year}^{-1}$). In accordance with trends in NUE values, the highest N balance or potential for loss of N from agricultural soils to the environment was observed in India, followed by China, and the least in the USA (Fig. 11.5). These data convincingly show that achieving high NUE values in agro-ecosystems is a must for controlling environmental degradation due to increasing fertilizer N use in crop production.

Modern agriculture strives to achieve food security on a sustainable basis both at country and global scales but not at the cost of environmental security (Foley et al. 2011). According to Dobermann and Cassman (2005) and Ladha et al. (2016), until

and unless NUE is substantially increased in farms all over the world, fertilizer N consumption will have to be increased by about 60% to produce enough cereal grains to meet the global demand but it will lead to major environmental issues. Recently, Lu et al. (2019) studied the role of fertilizer N use in the USA in defining state-level NUE for maize and wheat and reported that in recent decades it was due to an increase in NUE for the production of the two crops which resulted in reduced losses of N from agriculture. They further observed that N surplus in agro-ecosystems was reduced due increase in N uptake and productivity of maize and wheat. While discussing strategic options for policy coordination on a global scale, Houlton et al. (2019) emphasized that by rapidly improving NUE of food production there will be an economic benefit to farmers as well as reduced N-based global warming, air, and water pollution.

11.6 Economic Aspects of Fertilizer Nitrogen Use Efficiency

Economic models dealing with carbon issues on a global scale (Rockström et al. 2017; Meena et al. 2020) have not yet been perfected to optimize N solutions although excess N has already caused substantial economic damage. Clear public policies are still lacking in several countries leading to a reduced appetite for technological breakthroughs. According to Houlton et al. (2019), policies and pricing mechanisms on N-related social costs can spur appropriate innovations to use N for producing enough food for the masses but with minimal environmental costs.

The ratios of fertilizer to crop prices (R_{fc}) are useful not only in guiding farmers regarding the application of fertilizer at levels that give them optimal economic returns but also in making decisions about technologies and nutrient management practices, which influence NUE and surplus N in agro-ecosystems (Zhang et al. 2015b). Since adequate amount of data were available for maize, Zhang et al. (2015a) studied the role of the cost of fertilizer and selling price of the farm produce (effect of government subsidies included) in influencing management decisions on the farm. They found that R_{fc} for maize is positively correlated with NUE. As maize prices in the USA follow the same trend as the price of other major crops, historical values of R_{fc} for maize were also found to be significantly correlated with NUE aggregated for all other crops. Van Grinsven et al. (2015) reported that in both France and USA, increases in R_{fc} since 1990 are closely related to increase in NUE. On the other hand, in both India and China, R_{fc} has been continuously declining due to heavy subsidies on fertilizer prices (Singh and Narayanan 2015; Li et al. 2013). In fact, globally the largest amount of surplus N in agro-ecosystems and the lowest national average NUE values have been reported from China. India also is showing similar NUE levels and accordingly high proportion of N input as surplus N (Fig. 11.4). Due to low R_{fc} values in countries like India and China, farmers have developed the tendency to sustain high crop yields by keeping increasing fertilizer N application levels instead of exploring and adopting efficient fertilizer N management strategies. In most of the countries in Africa, where fertilizers are very

expensive for smallholder farmers, fertilizer subsidies can play a positive role in boosting the low yield levels and reversing the small or negative N surplus (soil mining) in agricultural soils (Zhang et al. 2015a). In African countries, significant increases in fertilizer N inputs will hugely increase crop yields with little risk of much N leaving the soil–plant system and polluting the environment.

11.7 Improving Fertilizer Nitrogen Use Efficiency

Analysis carried out by Zhang et al. (2015a) shows that if global food security and environmental stewardship are to be achieved by 2050, the average RE in agricultural production systems will have to be increased from 0.40 to 0.70. Awareness is already growing to achieve the target although technological and socio-economic opportunities to improve different indices of NUE vary among regions and countries. To effectively reduce losses of reactive N from agro-ecosystems while maintaining an adequate rate of increase of cereal grain production to meet the food demand of the burgeoning global population, increases in both PFP and RE are to be ensured through innovative crop and soil management practices. Adequate emphasis is also being laid on improving PE because of its impact on grain yield through translocation of N into grains in relation to fertilizer N input (Cassman et al. 2002). Knowledge-based N management plays an important role but only the generation of appropriate technologies and strategies is not enough. Socio-economic incentives, as well as removal of obstructions for adoption of proven technologies and management options are equally crucial to help farmers achieve high levels of different indices of NUE (Davidson et al. 2015).

The rooting system of vigorous crop plants efficiently uses both indigenous and fertilizer N to produce optimum yields, which contribute to improvement in NUE. In this context, efficient uptake and utilization of applied N (improved RE and PFP) and efficient translation of N to grain yield (improved PE) can be achieved by ensuring adequate crop health, appropriate climate and soil moisture conditions, balanced application of N with other nutrients, use of improved cultivars and hybrids, and management of insects, pests and weeds. Thus, in a well-managed crop, optimum RE and profits can be recorded when the soil mineral N pool is maintained at the optimum size to meet the N requirements of the crop throughout the season (Fig. 11.2). While too little N in the mineral N pool leads to reduced profits, too much N in the pool results in losses of N from the soil–plant system (Cassman et al. 2002).

Several reviews including those by Ladha et al. (2005), Fageria (2014), Davidson et al. (2015), Prasad and Hobbs (2018), and Houlton et al. (2019) have emphasized that improvement in NUE can be achieved by adopting a mix of technologies and strategies managing fertilizers, soils and crops. The efficient N management strategies revolve around fertilizer N rates which are optimum for the crop, appropriate methods and timings of fertilizer N application, and correct placement of N in the soil. In recent decades, the use of enhanced-efficiency fertilizers which include controlled-release fertilizers as well as the use of urease and nitrification inhibitors

with conventional N fertilizers, integration of different sources of N (fertilizers, manures, and/or crop residues), and site-specific management of fertilizer N to achieve improved synchronization of N supply with N uptake by crops are being used to achieve high NUE in different crop production systems. The “four rights” or simply the 4Rs of fertilizer N management: *right rate, right type, right placement, and right timing* (Johnston and Bruulsema 2014; Zhang et al. 2015a) constitute the most important strategy to improve NUE, but the 4Rs best management practices are not simply a universal set of recommendations. Considering the variability that generally exists in agricultural farms, defining 4Rs for a crop in a given field, location or region is not easy. Ideally, 4Rs for fertilizer N is very site-specific because N supply to crop plants is governed by soil N to a great extent even when optimum levels of fertilizer N are applied (Chien et al., 2009; Yadav et al. 2020). Further, it is essential to achieve a balance among the 4Rs because these are interconnected and are also governed by the overall management practices followed in the agro-ecosystem. If any one of the 4Rs is not correct, the remaining ones also cannot be right. Many times farmers overemphasize the fertilizer N rate because it is directly linked with cost. Therefore, source, time of application, and placement of fertilizer N in the soil offer opportunity for improving NUE. There can be several right combinations of 4Rs for fertilizer N at a given location and crop. However, when one of the 4Rs is changed, the others need to be adjusted accordingly.

Enhanced-efficiency N fertilizers constitute promising management options to improve NUE. These products include slow-release and controlled-release fertilizers and fertigation technologies, which precisely deliver nutrients as per need of the crop, and amendments, which alter microbial transformations in favor of increased N availability to crop plants (urease and nitrification inhibitors and N stabilizers). In a meta-analysis based on studies carried out in China during 2000 and 2016, Ding et al. (2018) reported that by applying slow-release fertilizers in rice average increases in RE, AE and PFP were 34.8%, 29.5%, and 6.3%, respectively, over the values recorded for water-soluble fertilizers like urea. Zhang et al. (2019) conducted a meta-analysis using 866 observations from 120 studies and found that application of controlled-release urea to maize increased average yield by 5.3% and NUE by 24.1% as compared to when urea was applied to supply the same level of N. Using controlled-release fertilizer rather than ordinary urea also resulted in a significant reduction in nitrous oxide emission, N leaching, and ammonia volatilization by 23.8%, 27.1%, and 39.4%, respectively. Greater improvement in NUE and higher reduction of nitrous oxide emissions by applying N through controlled-release urea fertilizer were observed at medium ($150 < N < 200 \text{ kg N ha}^{-1}$) and high N rates ($N > 200 \text{ kg N ha}^{-1}$) than at low fertilizer N application rates. Abalos et al. (2014) conducted a meta-analysis of 27 studies (21 for NUE) to evaluate the effect of applying nitrification and urease inhibitors (DCD, DMPP, and NBPT) yield and NUE of different crops. It was observed that grand mean effects were 7.5% and 12.9% increase in crop yield and NUE, respectively.

During the last two decades, improvement in NUE in crop production systems has been recorded by achieving greater synchrony between N supply from all sources including fertilizer and N demand by the crop throughout the growing

season (Cassman et al. 2002). The site-specific management of fertilizer N revolves around the utilization of both fertilizer N and soil N but takes into account the spatial and temporal variability in crop responsiveness to fertilizer N. Losses of N from the soil are also taken care of by the site-specific N management. It is emerging as an important strategy for improving NUE in different cereal crops (Diacono et al. 2013; Witt et al. 2007; Franzen et al. 2016; Peng et al. 2010; Bijay Singh et al. 2020). Bijay Singh and Singh (2017a, b) have reported significant increases in different indices of NUE in rice in developing countries when rather than the general recommendations for the region, site-specific N management based on mid-season measurement of plant N status using chlorophyll meter or leaf color chart was practiced. In large fields in developed countries, variation in soil N supply is taken care of by using on-the-go variable rate N-fertilizer applicators (Inman et al. 2005). Delineation of soil management zones and soil mapping is also being used to improve NUE. Process-based, dynamic crop simulation models can also be used to achieve synchronization between plant N demand and N supply in the soil from different sources including fertilizer (Zhang et al. 2012).

Keeping in view the global fertilizer N consumption scenario, NUE can be significantly enhanced by using fertilizer N where it is needed the most (Houlton et al. 2019). While farmers in a large number of countries have affordable and easy access to N fertilizers, still several countries such as sub-Saharan Africa lack access to adequate amounts of fertilizer N (Wang et al. 2017). Improving the availability of fertilizer N in these countries through intergovernmental cooperation and policies and using efficient and technologically advanced approaches will not only ensure an increase in overall NUE but also reduce famines and promote resilience.

It is not that NUE improvements can be made only by adopting new technologies. It is possible to make large gains even by the widespread adoption of the existing technologies. Using less fertilizer N by improving NUE has two incentives—economic gains and reduced N pollution. When new technologies for improving NUE are offered, adoption by farmers is not likely if these will not be able to ensure adequate economic returns to the farmers. In many countries, complex socio-economic factors affect the decision-making by farmers for adopting strategies for improving NUE. In fact, it is only recently that farmers in most of the countries have started becoming knowledgeable about NUE and it is going to be critical in improving NUE (Davidson et al. 2015). Socio-economic impediments discouraging farmers from adopting improved nutrient management practices are not only related to cost and perceived risk but also to lack of trust in the advice being provided by agricultural extension agencies. According to Zhang et al. (2015b), due to the reasons that farmers primarily act to maximize their profits, and because incentives to adopt new technologies and management practices are limited, new technologies will not always result in reduced N pollution. Zhang et al. (2015b) developed an NUE economic and environmental impact analytical framework and by following it concluded that technologies that do not increase yield ceilings always lead to reduced N application rates as well as reduced N losses. But adoption of these strategies does not lead to land sparing and as a result, farmers do not get encouraged to follow these. In contrast, technologies such as planting hybrids, which increase

the yield levels, lead to environmental benefits in terms of sparing the land so that farmers readily adopt these due to high economic incentives. But such technologies and management practices generally result in the application of high N rates and more N losses to the environment.

11.8 Conclusions

Fertilizer N produced by Haber–Bosch process is a double-edged sword. It helped in the fight against hunger in the second half of twentieth century but created several environmental challenges for the twenty-first century. The solution lies in achieving high fertilizer NUE in agricultural systems. Although NUE simply represents the percentage of applied N, which is taken up by crop plants or economic produce that leaves the farm, it is not as simple because fertilizer N strongly interacts and mingles with a large pool of N already in the soil and only a small portion (up to ~45%) of applied N is directly used by crops plants. NUE can be expressed in the form of AE, RE, PE, and PFP, but PFP and RE are the most useful indices for fertilizer N applied to produce high yields with minimal loss of N to the environment. Improving NUE in agro-ecosystems is of enormous importance and represents a great research challenge because increasing demand for food and fiber cannot be fulfilled without applying fertilizer N and surplus N (applied N more than removed via economic yield) can become a potential threat to the environment.

India, China, and several other developing countries are yet in the initial phases of agricultural intensification characterized by a rapid increase in fertilizer N use, moderate increase in crop yield, and substantial increase in surplus N, and accompanied by a concomitant decrease in NUE. This phase lasted up to the 1980s in developed countries in North America and Europe. These countries are already in the second phase of agricultural expansion in which yields are increasing but N input through fertilizer and surplus N either declined (as in Western Europe) or did not increase appreciably (as in the USA) and NUE is showing an increasing trend. Ensuring high NUE values in agro-ecosystems is a must for controlling environmental degradation due to increasing fertilizer N use for crop production.

The ratio of fertilizer to crop prices constitutes an important factor in deciding fertilizer N application rates to produce crop yields that will give optimal economic returns and is also positively correlated with NUE. With the availability of heavily subsidized fertilizers in developing countries like India and China, the low fertilizer to crop price ratios are resulting in very low NUE values and large surplus N in the agricultural soils. Farmers in these countries prefer to increase crop yields by applying more fertilizer N rather than exploring and adopting efficient fertilizer N management strategies.

Knowledge-based N management is already playing an important role in improving NUE and reducing surplus N in developed countries in Europe and North America but cultural and socio-economic incentives and impediments are proving crucial for the adoption of technologies and fertilizer N management strategies by farmers for achieving high NUE in most of the developing countries. The efficient N

management strategies to improve NUE revolve around optimum N rates, appropriate methods and time of application, and correct placement in the soil of fertilizer N. These are increasingly being achieved through the development of enhanced-efficiency fertilizer materials, integrated use of fertilizers and organic N sources, and site-specific N management to achieve improved synchronization between the requirement of N by crops and supply of N from all sources. Nevertheless, it is also possible to make large gains in NUE by the widespread adoption of the existing technologies.

New technologies or strategies for improving NUE, which do not increase yield ceilings result in reduced N applications as well as reduced surplus N, are generally not welcomed by farmers because they cannot spare land. Technologies that increase yield levels are preferred by farmers but these require high N application rates and may lead to high N surplus as well. Significant new investments and partnerships between farmers, scientists, economists, citizens, and industries will be required to overcome technical, economic, and social impediments to improve NUE in current and future agricultural systems to meet society's food and environmental security.

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