Published June 20, 2019

World Cereal Nitrogen Use Efficiency Trends: Review and Current Knowledge

Peter Omara,* Lawrence Aula, Fikayo Oyebiyi, and William R. Raun

Core Ideas

- Cereal N use efficiency was estimated at 35, 41, 30, and 21% for the world, the United States, China, and India, respectively.
- There was a trend for increased N fertilizer consumption for agricultural use.
- Best N fertilizer management practices could improve N use efficiency.

P. Omara, Dep. of Plant and Soil Sciences, Oklahoma State Univ., Stillwater, OK 74078 and Dep. of Agronomy, Gulu Univ., Uganda; and L. Aula, F. Oyebiyi, and W.R. Raun, Dep. of Plant and Soil Sciences, Oklahoma State Univ., Stillwater, OK 74078.

Received 12 Oct. 2018.
Accepted 17 May 2019.
*Corresponding author (peter.omara@okstate.edu).

Agrosyst. Geosci. Environ. 2:180045 (2019)
doi:10.2134/age2018.10.0045

ABSTRACT

Two decades ago, world cereal nitrogen use efficiency (NUE) was documented at 33%. Since then, research addressing NUE has advanced. However, there are no current estimates to communicate whether or not research efforts and recent advances have contributed to improved NUE. With the apparent trends for increasing greenhouse gases, NUE values could be used as a management tool for agronomic and environmental sustainability. Our objective was to provide current estimates and trends of NUE for the world and selected countries for cereal crops cultivated in relatively large quantities. Data from the Food and Agriculture Organization (www.fao.org/faostat) website were used to compute NUE. The difference method was employed to derive NUE and trends. Results indicated that cereal NUE in 2015 was 35, 41, 30, and 21% for the world, the United States, China, and India, respectively. Compared with 33% reported in 1999, there was insignificant trend of increase ($r^2 = 0.01$) from 2002 to 2015 for cereal world NUE ($p > 0.05$). Low NUE for China and India was due to high N consumption. A slight improvement for the United States from 31% in 2002 to 41% in 2015 ($r^2 = 0.20$) could be a result of using improved cultivars and precision crop management. Increasing cereal NUE in the United States echoes the value of new technologies and the heightened importance of the environment. Recognizing year-to-year variability in N fertilizer requirement and implementing a systematic approach that combines agronomic recommendations with improved crop varieties could further improve NUE.

Abbreviations: CV, coefficient of variation; LDC, least developed countries; NUE, nitrogen use efficiency.

Nitrogen is an essential macro plant nutrient required in the largest quantity for growth and development (Fageria and Baligar, 2005). It is the largest by composition in the atmosphere and yet remains the most limiting in most plants. Aware of the fact that plants do not assimilate N in the form present in the atmosphere, its abundance therefore does not indicate availability to plants. Natural mechanisms for atmospheric–soil N input include non-symbiotic and symbiotic fixation, and addition in rainfall (Peoples et al., 1995; Sullivan et al., 2014). However, the natural mechanism of soil N input does not significantly support world food production, as the world population growth rate has outpaced this process (Crews and Peoples, 2004). Therefore, use of N from synthetic sources is inevitable in the face of increasing world population.

Because N principally determines crop yield, producers around the world have applied N in excess, thus leading to low nitrogen use efficiency (NUE). Cereal world NUE was estimated and reported by Raun and Johnson (1999) at 33%. This implies that 67% of all the applied N is unaccounted for and can be lost within the soil system through leaching and/or gaseous forms, potentially contributing to a decrease in air and water quality. The initial documentation for low cereal world N use efficiency sparked curiosity among researchers in many disciplines. Since the initial estimate, a number of research efforts have advanced from agronomic, environmental, and breeding perspectives in improving the low NUE (Raun et al., 2002; Presterl et al., 2003; Fageria and Baligar, 2005; Hirel et al., 2007; Garnett et al., 2009).

With increased concern for the environment and knowledge of excessive application of N fertilizers, increasing NUE has become the center of ecological/ecosystem research around the world. The biggest challenge to improving NUE is the ability to combine genetic, agronomic, and environment variables. Agronomic practices are responsible for low NUE due to excessive application of N fertilizers (Raun and Johnson, 1999; Zhu et al., 2005). However, improved N economy from reduced N fertilizer inputs must operate within acceptable crop yield levels (Hirel et al., 2007). This is in light of the fact that food production needs to be intensified on a fixed world land resource while embracing the challenges that comes with as much (Tilman et al., 2011).

The improvement in crop genetics over time has led to increases in cereal crop grain yields (Cassman, 1999; Hoisington et al., 1999). Unlike traditional crop selection methods, advancements in selection using faster methods like marker assisted selection and genetic engineering has shown promise in increasing grain yield amid ever-increasing environmental stresses. These methods accelerate crop breeding via improved genotyping and phenotyping processes, as well as increasing the availability of genetic diversity in the breeding program (Tester and Langridge, 2010). Since farmers still have to apply fertilizers to supplement increased yield potential for high-yielding crop cultivars, successes in breeding has not paralleled improved grain yields due to other external inputs (Dalrymple, 1986; Cassman, 1999).

Besides crop genetic improvements, advances in agronomy, and specifically research in precision agriculture, has contributed to improvement in nutrient use efficiency. Tester and Langridge (2010) noted that improvements in agronomy have resulted in a linear increase in global food production trends. In developed agricultural production systems, technologies have been established that allow for site specific management of agricultural fields. This includes nutrient, herbicide, and pesticide applications. Bongiovanni and Lowenberg-DeBoer (2004) noted that precision or site-specific management of agricultural inputs has resulted in both environmental and economic benefits. Because a significant portion of the N loss or inefficiencies in uptake are due to spatial variability in the landscape, management zones have been used to improve crop N uptake from the soil (Khosla et al., 2002). In experiments that were conducted in six different states/countries, Martin et al. (2005) demonstrated that the average plant-to-plant difference in by-plant-grain-yield was 2926 kg ha^{-1} or 47 bushels $acre^{-1}$. The variability in grain yield from fields that have been treated equally therefore imply different N fertilization needs, hence reducing waste and optimizing plant N uptake and utilization. Via variable rate technology, precision agriculture has helped to improve input use efficiency by providing information on spatial variability within a field (Torbett et al., 2007). This farming approach can optimize use of agricultural inputs for maximum economic output.

An important facet for improving NUE is via the application of in-season N fertilizer. The timing of N fertilizer application can improve synchronization of N availability to plants and maximize uptake and utilization (Blackmer and Schepers, 1994; Turner and Jund, 1994). Recent work has documented the value of "N Rich Strips" (Raun et al., 2010). This innovative approach entails applying relatively high N fertilizer rates in a narrow strip within the field and using sensor based fertilizer algorithms to visually discern in-season N application needs. Its main advantage in improving NUE is resolving the challenge of poor synchrony between fertilizer N and crop demand (Shanahan et al., 2008). This has helped counter spatial variability that leads to low NUE and reduced high N input when the season favored N availability. Because N response is independent of yield level and N availability is strongly dependent on the environment, optimum fertilizer N rates are often unpredictable (Dhital and Raun, 2016). Within-season N management is thus more appropriate to improve response to applied N fertilizer and improving NUE.

Developed vs. Developing Agriculture

Crop production requiring enhanced soil fertility management is a common practice for cereal production systems around the world. Fertilizer input rates, which have a significant influence on NUE, differ from one production system to another throughout the world (Drechsel et al., 2015). There are clear-cut differences between developed and developing agricultural production systems with the latter experiencing low crop yield. In most cases, developed agricultural systems experience high crop productivity as a result of mechanization and application of chemicals (Ruttan, 2002; Drechsel et al., 2015). Important to note is the high rate of fertilizer application, especially N fertilizer. Improved grain yields as a result of increased N fertilizer application come with a cost of degrading the environment through the various N loss pathways. Raun and Johnson (1999) reported world N use efficiency for selected cereal crops at 33%. The reason for this low NUE, in addition to having numerous loss pathways, is over-application of N fertilizer. In contrast, Edmonds et al. (2009) reported over 100% estimated NUE in Sub-Saharan Africa. The authors noted that mining of the already depleted soils as a result of low or no N application is the reason behind high estimates of NUE in this region.

Nitrogen Loss Pathways

Volatilization. Ammonia volatilization is one of the most important causes of N loss, especially in calcareous soils (Mandal et al., 2018). Whenever fertilizer N is applied to the soil, especially as urea, ammonia loss through volatilization occurs when pH exceeds 7.0 and this is therefore one of the major causes of low NUE. The rate at which volatilization losses occur depends on fertilizer management practices, and ecological conditions like wind, temperature, rainfall, and soil properties (Sommer et al., 2004). Brentrup et al. (2001) reported that the availability of N in soil after fertilization was dictated by ammonia volatilization in the applied fertilizer sources. Ammonia volatilization is mainly governed by the concentration of the entire ammonical N (Sommer et al., 2004). Proper application technique, straw incorporation, availability of soil moisture, and avoiding application at high wind speed are some of the techniques used to reduce the rate of volatilization of the applied fertilizer N (Cao et al., 2018; Sagoo et al., 2018; Woodley et al., 2018). For instance, Cao et al. (2018) reported that addition of wheat straw led to a 24% reduction in ammonia loss after the basal application. Reducing N loss from urea applied is the first and the most important step toward improving NUE in a cereal production system requiring application of urea fertilizer N sources.

Denitrification. This is a biological process involving the conversion of nitrate N to gaseous forms under anoxic soil environments. It is believed to be exclusively a bacterial trait and an important component of the N cycle, which reverses the N fixation process (Zumft, 1997). Denitrification is the loss of N in gaseous form as nitrous oxide, nitrogen monoxide, and nitrogen dioxide. It is probably considered the most important N loss pathway under oxygen limited agricultural systems that require heavy application of N fertilizer. Freney et al. (1990) reported that losses of the applied N fertilizer due to denitrification are extremely high in flooded or paddy rice. These losses can sometimes be as high as 50% of the applied fertilizer N (Houlton et al., 2006). Much as incorporating urea into the soil reduces N loss through volatilization; this is not always the case under anoxic soil conditions, as this would favor denitrification losses instead. Under flooded field conditions, the biggest challenge in the improvement of NUE is trying to control both loss processes at the same time (Freney et al., 1990). Therefore, it is difficult to improve NUE of the applied fertilizer N if both volatilization and denitrification are controlled simultaneously. Addiscott and Powlson (1992) reported that losses due to denitrification were on average, nearly twice that compared with N leaching losses when trying to partition N fertilizer losses due to the two processes. It is apparent that the magnitude of N loss due to denitrification depends on the prevailing environmental factors.

Nitrate Leaching. Occurs mostly in sandy permeable soils and also a result of soil having net negative charge, which does not retain the negatively charged nitrate ions (Stenberg et al., 1999; Di and Cameron, 2002). The amount of nitrate that is leached from soil depends on the concentration of nitrate present in soil solution, which in turn depends on the amount of N applied, the nitrification rate, and the denitrification rate (Cameron et al., 2013). The rate at which nitrate leaching occurs is also significantly influenced by the type of tillage practices such as conventional vs. no tillage. Some researchers have reported the influence of tillage practices on soil nitrate leaching. Hansen and Djurhuus (1997) concluded from a field experiment that cultivation practices increased soil nitrate leaching, although it was further influenced by soil type. For instance, cultivation increased soil nitrate leaching on a sandy loam soil but not on coarse sand. Stenberg et al. (1999) added that the timing of tillage is also very important in controlling nitrate leaching. In a study conducted in Sweden, the authors reported that delaying tillage can reduce nitrate leaching losses from 68 to 39 kg N ha^{-1} compared with early tillage. The increased level of nitrate N in groundwater is a direct result of leaching. High concentration of nitrate in drinking water is known to be harmful, especially to children below 1 yr of age, causing blue-baby syndrome (methemoglobinemia). If drained into surface water bodies such as lakes, rivers, or streams, nitrate can cause eutrophication with subsequent increased biological oxygen demand and greatly affect aquatic species (Di and Cameron, 2002).

Plant Losses. Plants are known to lose significant quantities of N after uptake and accumulation. Loss of N from the foliage as ammonia occurs during plant photorespiration. The accumulated gaseous N losses have been documented at 40 kg N ha^{-1}. This is a result of the imbalance between N accumulation and assimilation in plant systems (Xu et al., 2012). This loss is believed to increase with increased N rate applied and vary significantly with different crop species and varieties. Kanampiu et al. (1997) documented between 7.7 and 59.4% of post anthesis plant N loss in winter wheat. Although these losses were variety specific, they observed that there was a general increase with increased N rate applied. The two most important components of the N economy are comprised of the uptake and partitioning of N between the straw and grain (Desai and Bhatia, 1978). Efficient utilization of N in the production of grain also requires efficiency in the processes of uptake, translocation, assimilation, and redistribution. At favorable environmental conditions that reduce ammonia volatilization, leaching and denitrification, plant N loss can become the most important factor influencing low NUE. Wetselaar and Farquhar (1980) noted that the maximum amount of N in the aboveground plant parts are near anthesis, but losses occur continuously over the plant growth period with the peak loss occurring between anthesis and maturity. The objective of this article was to provide current estimates and trends of NUE for the world and selected countries for cereal crops cultivated in relatively large quantities.

MATERIALS AND METHODS

Various methods have been proposed to report fertilizer nutrient use efficiency including the difference method, mass balance, and isotopic discrimination. Of these, the difference method is probably the simplest and most commonly used for reporting nutrient use efficiency (Dhillon et al., 2017). For the difference method, percentage fertilizer recovery is calculated by dividing the difference between total N crop uptake from fertilized plots and total N crop uptake from unfertilized plots by rate of fertilizer N applied (Raun and Johnson, 1999). This is micro calculation of fertilizer nutrient use efficiency summarized by the equation below (Eq. [1]):

$$\text{NUE} = \frac{\text{Grain N from FP} - \text{Grain N from UP}}{\text{Total N applied}} \times 100 \qquad [1]$$

where FP is fertilized plot and UP is unfertilized plot.

For this work, macro analysis, adapted from the difference method was employed to compute NUE for selected cereal crops cultivated worldwide (all countries and territories of the world) using data obtained from the FAO Statistics database (FAO, 2019). This is summarized using the equation below (Eq. [2]):

$$\text{NUE} = \frac{\text{Aggregate CNF} - \text{Aggregate CNS}}{\text{Total cereal N consumption}} \times 100 \qquad [2]$$

where CNF is cereal N from fertilizer and CNS is cereal N from soil.

The cereal crops used in the computation of world NUE include maize (*Zea mays* L.), rice (*Oryza sativa* L.), wheat (*Triticum aestivum* L.), sorghum (*Sorghum bicolor* L.), barley (*Hordeum vulgare* L.), millet (*Pennisetum glaucum* L.), oat (*Avena sativa* L.), and rye (*Secale cereale* L.). In addition to the world, NUE was also computed for the United States, China, India, and least developed countries (LDC) to compare efficiency in production systems with low and high consumption of N fertilizer. In this estimate, three major assumptions were made. The first assumption was that cereal consumption of N fertilizer is 56% of the total world N used in agricultural production (Heffer et al., 2017). However, for the individual country/region selected for this study, the proportion of N fertilizer used for cereal production was different; 48, 65, 62, and 60% for China, the United States, India, and LDC, respectively (Heffer et al., 2017). Second, N removal from cereals coming from soils is 50% of the total N used (Keeney, 1982). Lastly, N removed in cereals coming from the fertilizer is 50% of the total N used (Raun and Johnson, 1999). Aggregate cereal grain N removal was calculated by multiplying total grain produced by the percentage N of the respective cereal crops. The percentage N for wheat, maize, rice, barley, sorghum, millet, oat, and rye used in the calculation were 2.13, 1.26, 1.23, 2.02, 1.92, 2.01, 1.93, and 2.21, respectively (Raun and Johnson, 1999; Roberts, 2008). The use efficiency of the applied fertilizer N was then estimated by dividing N removed in cereals coming from the fertilizer (50% of total) by cereal N fertilizer consumption and expressed as a percentage. From Eq. [2], the procedure used to calculate NUE are summarized in steps below.

1. Consumption of N fertilizer for agricultural use (FAO, 2019) (A)
2. Total world cereal N fertilizer use; 56% × A (Heffer et al., 2017) (B)
3. Total cereal production; selected country/region (FAO, 2019) (C)
4. Aggregate cereal grain N removal; percent grain Nitrogen × C (D)
5. Aggregate cereal N removal from soil; 50% × D (Keeney, 1982) (E)
6. Estimated NUE = [(D – E)/B] × 100%

To help explain the NUE trends, N fertilizer consumption trends were also computed for the world and selected countries/region over 14 yr. Data analysis was conducted using the MS Excel (2016) statistical package. Simple linear regression was used to compare trends for cereal NUE and N consumption for the selected countries/region. The coefficient of determination (r^2 values) and slope significance (p values) were used to interpret the rate of increase

Table 1. Estimated world fertilizer nitrogen use efficiency (NUE) for cereal crops cultivated in large quantities, 2002–2015.

Year	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
N fertilizer consumption†	82.6	86.6	89.0	89.5	92.0	96.1	95.6	97.7	100.8	104.4	106.4	108.4	110.1	109.3
Cereal N consumption‡	46.3	48.5	49.9	50.1	51.5	53.8	53.5	54.7	56.4	58.4	59.6	60.7	61.6	61.2
cereal production, million Mg														
Wheat	592	550	635	627	615	607	681	684	640	698	673	711	734	737
Maize	604	645	730	714	708	793	829	820	851	886	874	1015	1038	1011
Rice	571	587	607	634	641	657	687	686	701	726	736	742	742	740
Barley	141	137	156	137	144	131	154	151	123	133	132	143	144	148
Sorghum	53	59	58	60	58	63	66	57	60	57	57	62	68	66
Millet	24	35	30	31	32	34	34	26	33	27	27	26	28	29
Oat	26	25	27	23	24	25	26	23	20	23	21	24	23	22
Rye	21	15	18	15	13	15	18	18	12	13	14	17	15	13
Total	2032	2052	2260	2241	2234	2324	2496	2465	2441	2562	2535	2740	2794	2766
cereal grain N removal (production × %N)§														
Wheat	12.6	11.7	13.5	13.4	13.1	12.9	14.5	14.6	13.6	14.9	14.3	15.1	15.6	15.7
Maize	7.6	8.1	9.2	9.0	8.9	10.0	10.4	10.3	10.7	11.2	11.0	12.8	13.1	12.7
Rice	7.0	7.2	7.5	7.8	7.9	8.1	8.5	8.4	8.6	8.9	9.1	9.1	9.1	9.1
Barley	2.8	2.8	3.2	2.8	2.9	2.6	3.1	3.0	2.5	2.7	2.7	2.9	2.9	3.0
Sorghum	1.0	1.1	1.1	1.1	1.1	1.2	1.3	1.1	1.2	1.1	1.1	1.2	1.3	1.3
Millet	0.5	0.7	0.6	0.6	0.6	0.7	0.7	0.5	0.7	0.5	0.5	0.5	0.6	0.6
Oat	0.5	0.5	0.5	0.4	0.5	0.5	0.5	0.4	0.4	0.4	0.4	0.5	0.4	0.4
Rye	0.5	0.3	0.4	0.3	0.3	0.3	0.4	0.4	0.3	0.3	0.3	0.4	0.3	0.3
Total N in cereals	32.6	32.5	36.0	35.5	35.3	36.3	39.4	38.8	37.9	40.0	39.4	42.5	43.4	43.1
N from soil	16.3	16.2	18.0	17.7	17.6	18.2	19.7	19.4	19.0	20.0	19.7	21.3	21.7	21.5
N from fertilizer	16.3	16.2	18.0	17.7	17.6	18.2	19.7	19.4	19.0	20.0	19.7	21.3	21.7	21.5
NUE, %	35.2	33.5	36.1	35.4	34.3	33.8	36.8	35.5	33.6	34.2	33.1	35.0	35.2	35.2

† Total world fertilizer N use (million Mg).

‡ Cereal world N use (million Mg).

§ Percentage N in cereals (wheat, maize, rice, barley, sorghum, millet, oat, and rye are 2.13, 1.26, 1.23, 2.02, 1.92, 2.01, 1.93, and 2.21%, respectively).

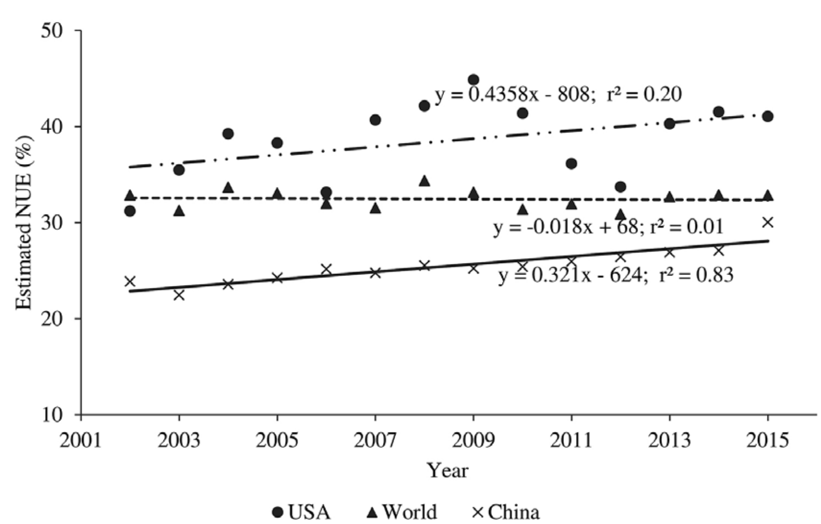

Fig. 1. Estimated trends in nitrogen use efficiency (NUE) for the world, the United States, and China, 2002–2015.

in NUE or growth in N consumption for the selected countries/region over the study period.

RESULTS AND DISCUSSION

The motivation for improving low NUE stems from the fact that it affects not only food production but also the environment. It is apparent from the world data that cereal crop producers still experience low NUE (Table 1). Despite recent gains from agronomic and genetic research, world NUE has barely increased. This is evidenced from the trend analysis indicating no significant increase ($p > 0.05$) from 2002 to 2015 in world NUE for cereal crops with $r^2 = 0.01$ (Fig. 1).

Indiscriminate use or high global N fertilizer consumption to maximize cereal crop yields largely account for the low NUE. Figure 2 indicates a significant ($p < 0.05$) increase in the consumption trend of world N with an r^2 of 0.98 from 2002 to 2015. The growth of N consumption would be expected, as the world population keeps rising against the more or less constant land resources. Erisman et al. (2008) indicated that external nutrient source, especially N fertilizer, accounts for nearly 50% of the increases in food production. This implies that chemical fertilizer use is always a factor in the food production equation. In the middle of the 19th century, the "Green Revolution" was adopted and implemented to increase food production, a product of heightened food demand and a growing human population. Much as this approach significantly increased global food production (Singh, 2000), whereas negative consequences included environmental degradation, it set a pace leading to the over use of N fertilizer, and low NUE (Raun and Johnson, 1999; Foley et al., 2005). Consequently, there is a need to analyze the capacity of the ecosystem to sustain food production for the rapidly growing global human population.

Apparently, it appears the Green Revolution approach is still being practiced, especially in some developed and developing agricultural systems that experience high productivity per unit area. For instance, results indicated relatively low NUE for China (Fig. 1) and India (Fig. 3) compared with that of the world. In China and India, intensive cereal crop production, which takes place on large land areas to meet food demand from the high human population, is sustained by high fertilizer N use. Although China showed a significant improvement ($p < 0.05$) in NUE ($r^2 = 0.83$) over the study period, the initial values were very low. Conversely, India showed a declining trend in NUE ($r^2 = 0.60$) over the study period, demonstrated by negative slope of the regression equation ($p < 0.05$). Figure 4 demonstrates that fertilizer N consumption for India is higher than that of LDC. However, both India ($r^2 = 0.92$) and LDC ($r^2 = 0.93$) showed an increasing trend in fertilizer N consumption over the study period ($p < 0.05$). On another perspective, the comparative marginal use of fertilizer N in LDC resulted in very high

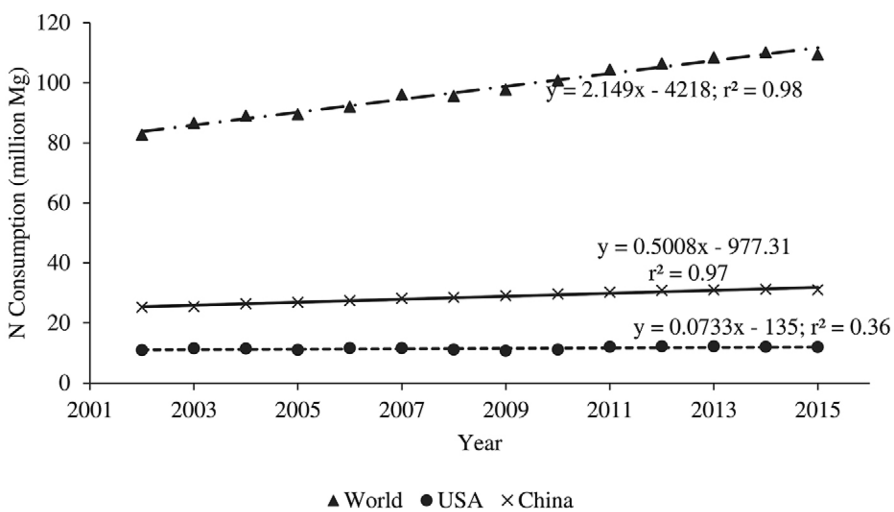

Fig. 2. Nitrogen fertilizer consumption (million Mg) for agricultural use in the world, the United States, and China, 2002–2015.

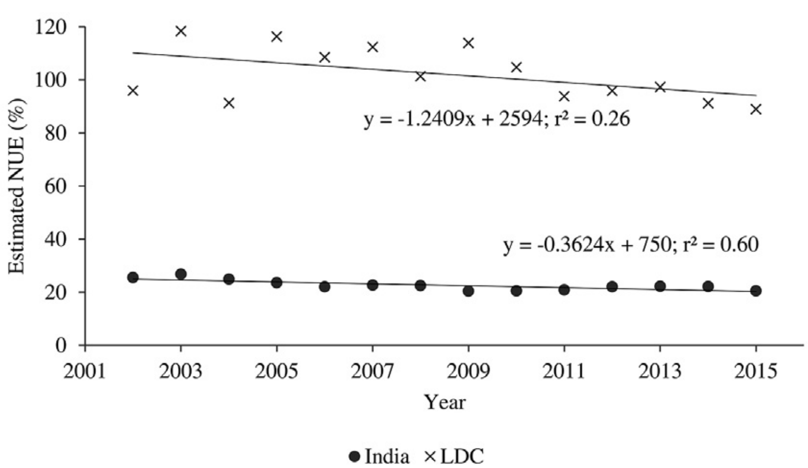

Fig. 3. Estimated trends in nitrogen use efficiency (NUE) for India and least developed countries (LDC), 2002–2015.

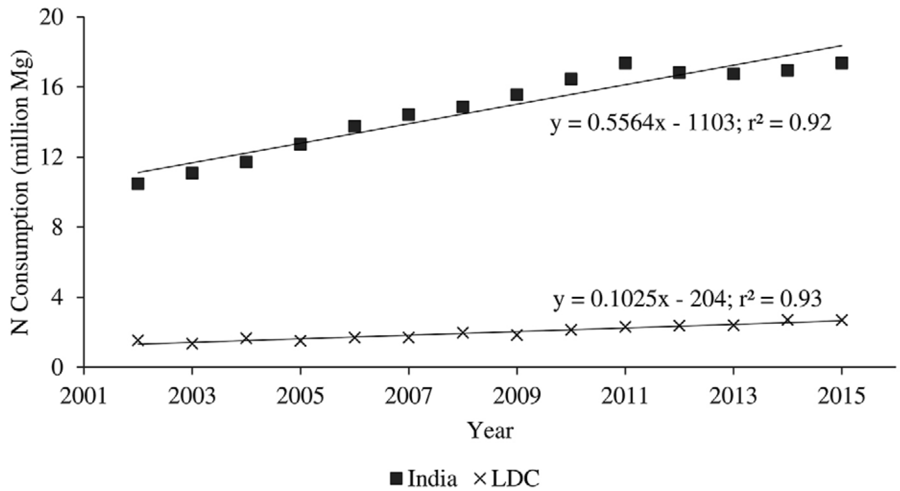

Fig. 4. Nitrogen fertilizer consumption (million Mg) for agricultural use in India and least developed countries (LDC), 2002–2015.

NUE values (Fig. 3). This confirms an earlier report by Edmonds et al. (2009), who estimated NUE for Sub-Saharan Africa at over 100%. They explained that continuous crop production with little or no fertilizer N use resulted in mining of the already depleted soils. On a similar account, Drechsel et al. (2015) reported mining of soil N for the past 30 yr in Sub-Saharan Africa at an annual rate of 22 kg N ha^{-1}. Crop production without replenishing soil nutrients would certainly deplete soil nutrient pools (Omara et al., 2017). Generally, high N fertilizer inputs result in low NUE, whereas low or no N input results in extremely high NUE. Clearly, there is a need to strike a balance while taking into consideration the food production needs and potential losses of N in to the environment.

Compared with the world, the United States has shown promise in improving cereal NUE with $r^2 = 0.20$ (Fig. 1). The use efficiency of the applied N increased from 31% in 2002 to 41% in 2015 (Table 2). This is probably because of planting cultivars that have been developed for improved nutrient use efficiency with high yield potentials. Advancement in crop genetic selection and

Table 2. Estimated fertilizer nitrogen use efficiency (NUE) in the United States for cereal crops cultivated in large quantities, 2002–2015.

Year	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Fertilizer N consumption†	10.9	11.5	11.4	11.0	11.6	11.6	11.1	10.6	11.1	12.0	12.2	12.2	12.0	11.9
Cereal N consumption‡	6.8	7.2	7.1	6.8	7.2	7.2	6.9	6.6	6.9	7.5	7.6	7.6	7.4	7.4
	cereal production, million Mg													
Wheat	43.7	63.8	58.7	57.2	49.2	55.8	68.0	60.4	60.1	54.4	61.7	58.1	55.1	55.8
Maize	227.8	256.2	299.9	282.3	267.5	331.2	305.9	331.9	315.6	312.8	273.2	351.3	361.1	345.5
Rice	9.6	9.1	10.5	10.1	8.8	9.0	9.2	10.0	11.0	8.4	9.1	8.6	10.1	8.7
Barley	4.9	6.1	6.1	4.6	3.9	4.6	5.2	4.9	3.9	3.4	4.8	4.7	4.0	4.7
Sorghum	9.2	10.4	11.5	10.0	7.0	12.6	12.1	9.7	8.8	5.4	6.3	10.0	11.0	15.2
Millet	0.1	0.3	0.3	0.3	0.2	0.4	0.3	0.2	0.3	0.2	0.1	0.4	0.3	0.3
Oat	1.7	2.1	1.7	1.7	1.4	1.3	1.3	1.3	1.2	0.7	0.9	0.9	1.0	1.3
Rye	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.3
Total	297.1	348.2	389.0	366.4	338.3	415.1	402.3	418.6	401.0	385.5	356.1	434.2	442.8	431.8
	cereal grain N removal (production × %N)§													
Wheat	0.931	1.359	1.250	1.219	1.048	1.189	1.449	1.286	1.279	1.159	1.314	1.238	1.175	1.189
Maize	2.870	3.228	3.778	3.557	3.371	4.173	3.854	4.182	3.977	3.941	3.442	4.426	4.550	4.353
Rice	0.118	0.112	0.130	0.124	0.109	0.111	0.114	0.123	0.136	0.103	0.112	0.106	0.124	0.107
Barley	0.100	0.122	0.123	0.093	0.079	0.092	0.105	0.100	0.079	0.068	0.096	0.095	0.080	0.094
Sorghum	0.176	0.201	0.221	0.192	0.135	0.243	0.232	0.186	0.168	0.104	0.121	0.191	0.211	0.291
Millet	0.002	0.005	0.007	0.006	0.005	0.008	0.007	0.004	0.005	0.004	0.001	0.008	0.006	0.006
Oat	0.032	0.040	0.032	0.032	0.026	0.025	0.025	0.026	0.023	0.014	0.017	0.018	0.020	0.025
Rye	0.004	0.005	0.005	0.004	0.004	0.004	0.005	0.004	0.004	0.003	0.004	0.004	0.004	0.006
Total N cereals	4.232	5.072	5.546	5.227	4.777	5.844	5.791	5.910	5.672	5.397	5.107	6.087	6.169	6.073
N from soil	2.116	2.536	2.773	2.614	2.388	2.922	2.895	2.955	2.836	2.699	2.553	3.044	3.085	3.037
N from fertilizer	2.116	2.536	2.773	2.614	2.388	2.922	2.895	2.955	2.836	2.699	2.553	3.044	3.085	3.037
NUE, %	31.2	35.5	39.2	38.3	33.1	40.7	42.1	44.9	41.4	36.1	33.7	40.3	41.5	41.0

† Total fertilizer N use in the United States (million Mg).

‡ United States cereal N use (million Mg).

§ Percentage N in cereals (wheat, maize, rice, barley, sorghum, millet, oat, and rye are 2.13, 1.26, 1.23, 2.02, 1.92, 2.01, 1.93, and 2.21%, respectively).

adoption of cultivars with efficient assimilation of N into plant tissue is one of the major gains for improving NUE. The contribution of crop improvement in increasing grain yield over time has been well documented by many authors (Cassman, 1999; Hoisington et al., 1999; Tester and Langridge, 2010). Although this appears to be a noble cause, it seems that high yielding cultivars bred with high nutrient use efficiency alone may not completely resolve the problem of low NUE. A combination of this and improved agronomic practices seems to have a profound impact on NUE.

In addition to planting crop cultivars that efficiently utilize nutrients, improved agronomic practices such as using sensor-based technology that allows for the right quantity of fertilizer to be applied mid-season has greatly contributed to improved NUE (Raun et al., 2002). Sensor-based N applications have allowed for site-specific placement of N fertilizer, thus reducing waste in N applied by accounting for within-field variability. Ultimately, this improves N management and use efficiency of the applied N to increase yields and reduce N loss to the environment. With advanced global positioning system (GPS) technologies, site-specific N management can be simple and cost-effective compared with grid-based systems (Khosla et al., 2002). A report by Drechsel et al. (2015) indicated that countries such as the United States, Germany, the UK, and Japan have increased NUE as a result of decreasing N use, with associated increases in crop yields. This is evident in Fig. 1, illustrating an increasing trend of NUE in the United States compared with the world average. To further support the point noted by Drechsel et al. (2015), there was a relatively slow growth in fertilizer N consumption for the United States ($r^2 = 0.36$) compared with China ($r^2 = 0.97$) and the world ($r^2 = 0.98$) from 2002 to 2015 (Fig. 2).

Generally, limiting biophysical or chemical processes like leaching and denitrification would be a focus for improving use efficiency of the applied N fertilizer. Unfortunately, some of these processes are random and are largely governed by changes in environment, in addition to management practices (Di and Cameron, 2002). As reported by Jabloun et al. (2015), nitrate concentration and the rate of leaching are site-specific and driven by climatic factors and crop management. For instance, heavy rainfall in early spring would encourage the leaching losses of applied N fertilizers in winter wheat fields. Donner et al. (2004) noted that the influence of late winter wheat snowmelt and early spring rainfall could increase leaching losses of nitrate. This was evidenced by a strong correlation between the nitrate leaching coefficient of variation (CV) and precipitation CV in the months of March, April, and May. Similarly, Jabloun et al. (2015) noted that the relative effects of temperature and precipitation varied differently according to seasons and cropping systems and that leaching increased with increases in temperature and precipitation. The rate at which nitrate is lost from the soil, therefore, strongly depends on the moderating environmental conditions. If plant N need could be supplied as ammonium as well as limiting its conversion to nitrate, which is susceptible to leaching and denitrification, NUE could be significantly improved (Subbarao et al., 2012). This approach has been proven beneficial and effective in reducing nitrate leaching, and hence improving NUE (Di and Cameron, 2016). Unfortunately, technologies such as use of nitrification inhibitors that reduce the rate of conversion of ammonium to nitrate is not widely practiced on a commercial scale. A more systemic approach of N management involving both agronomic and genetic approaches could help improve NUE for cereal crops.

CONCLUSION

It is apparent that world cereal NUE is low and has not significantly increased for the last decade. With increasing global N consumption trends, it is unlikely that world NUE can improve if the objective of increasing crop yield is at the center of a cereal production system. Much as high N input results in low NUE and/or low or no N input results in extremely high NUE, it is important to note that striking a balance between increased food production, and improving NUE, will be a key to sustainable food production. A range of research efforts are still needed to realize an appropriate level of NUE. A more systematic approach of N management involving both agronomic and genetic approaches are important for improving NUE in cereal crops. Since the biophysical loss pathways are inevitable and strongly influenced by the changes in the environment, incorporating seasonal changes and spatial variability into agronomic research could increase the efficiency of the apparent high global N consumption. Also, adoption of precision agriculture and in-season N management, in addition to planting improved cereal crop cultivars, could significantly contribute to increased NUE.

REFERENCES

Addiscott, T.M., and D.S. Powlson. 1992. Partitioning losses of nitrogen fertilizer between leaching and denitrification. J. Agric. Sci. 118:101–107. doi:10.1017/S0021859600068052

Blackmer, T.M., and J.S. Schepers. 1994. Techniques for monitoring crop nitrogen status in corn. Commun. Soil Sci. Plant Anal. 25:1791–1800. doi:10.1080/00103629409369153

Bongiovanni, R., and J. Lowenberg-DeBoer. 2004. Precision agriculture and sustainability. Precis. Agric. 5:359–387. doi:10.1023/B:PRAG.0000040806.39604.aa

Brentrup, F., J. Küsters, H. Kuhlmann, and J. Lammel. 2001. Application of the Life Cycle Assessment methodology to agricultural production: An example of sugar beet production with different forms of N fertilisers. Eur. J. Agron. 14:221–233. doi:10.1016/S1161-0301(00)00098-8

Cameron, K.C., H.J. Di, and J.L. Moir. 2013. Nitrogen losses from the soil/plant system: A review. Ann. Appl. Biol. 162:145–173. doi:10.1111/aab.12014

Cao, Y., H. Sun, J. Zhang, G. Chen, H. Zhu, S. Zhou, and H. Xiao. 2018. Effects of wheat straw addition on dynamics and fate of nitrogen applied to paddy soils. Soil Tillage Res. 178:92–98. doi:10.1016/j.still.2017.12.023

Cassman, K.G. 1999. Ecological intensification of cereal production systems: Yield potential, soil quality, and precision agriculture. Proc. Natl. Acad. Sci. USA 96:5952–5959. doi:10.1073/pnas.96.11.5952

Crews, T.E., and M.B. Peoples. 2004. Legume versus fertilizer sources of nitrogen: Ecological tradeoffs and human needs. Agric. Ecosyst. Environ. 102:279–297. doi:10.1016/j.agee.2003.09.018

Dalrymple, D.G. 1986. Development and spread of high-yielding rice varieties in developing countries. USAID, Washington, DC.

Desai, R.M., and C.R. Bhatia. 1978. N uptake and N harvest index in durum wheat cultivars varying in their grain protein concentration. Euphytica 27:561–566. doi:10.1007/BF00043182

Di, H.J., and K.C. Cameron. 2002. Nitrate leaching in temperate agroecosystems: Sources, factors and mitigating strategies. Nutr. Cycling Agroecosyst. 64:237–256. doi:10.1023/A:1021471531188

Di, H.J., and K.C. Cameron. 2016. Inhibition of nitrification to mitigate nitrate leaching and nitrous oxide emissions in grazed grassland: A review. J. Soils Sediments 16:1401–1420. doi:10.1007/s11368-016-1403-8

Dhillon, J., G. Torres, E. Driver, B.M. Figueiredo, and W.R. Raun. 2017. World phosphorus use efficiency in cereal crops. Agron. J. 109:1670–1677. doi:10.2134/agronj2016.08.0483

Dhital, S., and W.R. Raun. 2016. Variability in optimum nitrogen rates for maize. Agron. J. 108:2165–2173. doi:10.2134/agronj2016.03.0139

Donner, S.D., C.J. Kucharik, and J.A. Foley. 2004. Impact of changing land use practices on nitrate export by the Mississippi River. Global Biogeochem. Cycles 18:GB1028. doi:10.1029/2003GB002093

Drechsel, P., P. Heffer, H. Magen, R. Mikkelsen, and D. Wichelns, editors. 2015. Managing water and fertilizer for sustainable agricultural intensification. International Fertilizer Industry Assoc., Paris.

Edmonds, D.E., S.L. Abreu, A. West, D.R. Caasi, T.O. Conley, M.C. Daft, B. Desta, B.B. England, C.D. Farris, T.J. Nobles, and N.K. Patel. 2009. Cereal N use efficiency in sub Saharan Africa. J. Plant Nutr. 32:2107–2122. doi:10.1080/01904160903308184

Erisman, J.W., M.A. Sutton, J. Galloway, Z. Klimont, and W. Winiwarter. 2008. How a century of ammonia synthesis changed the world. Nat. Geosci. 1:636–639. doi:10.1038/ngeo325

Fageria, N.K., and V.C. Baligar. 2005. Enhancing N use efficiency in crop plants. Adv. Agron. 88:97–185. doi:10.1016/S0065-2113(05)88004-6

FAO. 2019. Food and Agriculture Organization of the United Nations. FAOSTAT statistics database. [Rome]. www.fao.org/faostat (accessed 1 May 2019).

Foley, J.A., R. DeFries, G.P. Asner, C. Barford, G. Bonan, S.R. Carpenter, F.S. Chapin, M.T. Coe, G.C. Daily, H.K. Gibbs, and J.H. Helkowski. 2005. Global consequences of land use. Science 309:570–574. doi:10.1126/science.1111772

Freney, J.R., A.C.F. Trevitt, S.K. De Datta, W.N. Obcemea, and J.G. Real. 1990. The interdependence of ammonia volatilization and denitrification as nitrogen loss processes in flooded rice fields in the Philippines. Biol. Fertil. Soils 9:31–36. doi:10.1007/BF00335858

Garnett, T., V. Conn, and B.N. Kaiser. 2009. Root based approaches to improving nitrogen use efficiency in plants. Plant Cell Environ. 32:1272–1283. doi:10.1111/j.1365-3040.2009.02011.x

Hansen, E.M., and J. Djurhuus. 1997. Nitrate leaching as influenced by soil tillage and catch crop. Soil Tillage Res. 41:203–219. doi:10.1016/S0167-1987(96)01097-5

Heffer, P., A. Gruère, and T. Roberts. 2017. Assessment of fertilizer use by crop at the global level. International Fertilizer Assoc. and International Plant Nutrition Institute, Paris.

Hirel, B., J. Le Gouis, B. Ney, and A. Gallais. 2007. The challenge of improving N use efficiency in crop plants: Towards a more central role for genetic variability and quantitative genetics within integrated approaches. J. Exp. Bot. 58:2369–2387. doi:10.1093/jxb/erm097

Hoisington, D., M. Khairallah, T. Reeves, J.M. Ribaut, B. Skovmand, S. Taba, and M. Warburton. 1999. Plant genetic resources: What can they contribute toward increased crop productivity? Proc. Natl. Acad. Sci. USA 96:5937–5943. doi:10.1073/pnas.96.11.5937

Houlton, B.Z., D.M. Sigman, and L.O. Hedin. 2006. Isotopic evidence for large gaseous nitrogen losses from tropical rainforests. Proc. Natl. Acad. Sci. USA 103:8745–8750. doi:10.1073/pnas.0510185103

Jabloun, M., K. Schelde, F. Tao, and J.E. Olsen. 2015. Effect of temperature and precipitation on nitrate leaching from organic cereal cropping systems in Denmark. Eur. J. Agron. 62:55–64. doi:10.1016/j.eja.2014.09.007

Kanampiu, F.K., W.R. Raun, and G.V. Johnson. 1997. Effect of N rate on plant N loss in winter wheat varieties. J. Plant Nutr. 20:389–404. doi:10.1080/01904169709365259

Keeney, D.R. 1982. Nitrogen management for maximum efficiency and minimum pollution. In: F.J. Stevenson, editor, Nitrogen in agricultural soils. Agron. Monogr. 22. ASA, CSSA and SSSA, Madison, WI. p. 605–649. doi:10.2134/agronmonogr22.c16

Khosla, R., K. Fleming, J.A. Delgado, T.M. Shaver, and D.G. Westfall. 2002. Use of site-specific management zones to improve nitrogen management for precision agriculture. J. Soil Water Conserv. 57:513–518.

Mandal, S., E. Donner, S. Vasileiadis, W. Skinner, E. Smith, and E. Lombi. 2018. The effect of biochar feedstock, pyrolysis temperature, and application rate on the reduction of ammonia volatilisation from biochar-amended soil. Sci. Total Environ. 627:942–950. doi:10.1016/j.scitotenv.2018.01.312

Martin, K.L., P.J. Hodgen, K.W. Freeman, R. Melchiori, D.B. Arnall, R.K. Teal, R.W. Mullen, K. Desta, S.B. Phillips, J.B. Solie, and M.L. Stone. 2005. Plant-to-plant variability in corn production. Agron. J. 97:1603–1611. doi:10.2134/agronj2005.0129

Omara, P., N. Macnack, L. Aula, and W.R. Raun. 2017. Effect of long-term beef manure application on soil test, organic carbon, and winter wheat yield. J. Plant Nutr. 40:1143–1151. doi:10.1080/01904167.2016.1264423

Peoples, M.B., D.F. Herridge, and J.K. Ladha. 1995. Biological nitrogen fixation: An efficient source of nitrogen for sustainable agricultural production. Plant Soil 174:3–28. doi:10.1007/BF00032239

Presterl, T., G. Seitz, M. Landbeck, E.M. Thiemt, W. Schmidt, and H.H. Geiger. 2003. Improving nitrogen-use efficiency in European maize. Crop Sci. 43:1259–1265. doi:10.2135/cropsci2003.1259

Raun, W., J. Solie, J. May, H. Zhang, J. Kelly, R. Taylor, B. Arnall, and I. Ortiz-Monasterio. 2010. Nitrogen rich strips for wheat, corn and other crops. Publ. E-1022. Oklahoma State Univ. Ext., Stillwater.

Raun, W.R., and G.V. Johnson. 1999. Improving nitrogen use efficiency for cereal production. Agron. J. 91:357–363. doi:10.2134/agronj1999.00021962009100030001x

Raun, W.R., J.B. Solie, G.V. Johnson, M.L. Stone, R.W. Mullen, K.W. Freeman, W.E. Thomason, and E.V. Lukina. 2002. Improving nitrogen use efficiency in cereal grain production with optical sensing and variable rate application. Agron. J. 94:815–820. doi:10.2134/agronj2002.8150

Roberts, T.L. 2008. Improving nutrient use efficiency. Turk. J. Agric. For. 32:177–182.

Ruttan, V.W. 2002. Productivity growth in world agriculture: Sources and constraints. J. Econ. Perspect. 16:161–184. doi:10.1257/089533002320951028

Sagoo, E., F.A. Nicholson, J.R. Williams, R.E. Thorman, A. Bhogal, T.H. Misselbrook, and D.R. Chadwick. 2018. MANNER-NPK nutrient management software. Nutrient Management and Decision-Support Systems, 20th Nitrogen Workshop, Rennes, France. 27 June. https://workshop.inra.fr/nitrogenworkshop2018/Media/Fichier/Posters-side-event/7-Poster-MANNER-Sagoo (accessed 28 May 2019).

Shanahan, J.F., N.R. Kitchen, W.R. Raun, and J.S. Schepers. 2008. Responsive in-season nitrogen management for cereals. Comput. Electron. Agric. 61:51–62. doi:10.1016/j.compag.2007.06.006

Singh, R.B. 2000. Environmental consequences of agricultural development: A case study from the Green Revolution state of Haryana, India. Agric. Ecosyst. Environ. 82:97–103. doi:10.1016/S0167-8809(00)00219-X

Sommer, S.G., J.K. Schjoerring, and O.T. Denmead. 2004. Ammonia emission from mineral fertilizers and fertilized crops. Adv. Agron. 82:557–622.

Stenberg, M., H. Aronsson, B. Lindén, T. Rydberg, and A. Gustafson. 1999. Soil mineral N and nitrate leaching losses in soil tillage systems combined with a catch crop. Soil Tillage Res. 50:115–125. doi:10.1016/S0167-1987(98)00197-4

Subbarao, G.V., K.L. Sahrawat, K. Nakahara, T. Ishikawa, M. Kishii, I.M. Rao, C.T. Hash, T.S. George, P.S. Rao, P. Nardi, and D. Bonnett. 2012. Biological nitrification inhibition—a novel strategy to regulate nitrification in agricultural systems. Adv. Agron. 114:249–302. doi:10.1016/B978-0-12-394275-3.00001-8

Sullivan, B.W., W.K. Smith, A.R. Townsend, M.K. Nasto, S.C. Reed, R.L. Chazdon, and C.C. Cleveland. 2014. Spatially robust estimates of biological N(N) fixation imply substantial human alteration of the tropical N cycle. Proc. Natl. Acad. Sci. USA 111:8101–8106. doi:10.1073/pnas.1320646111

Tester, M., and P. Langridge. 2010. Breeding technologies to increase crop production in a changing world. Science 327:818–822. doi:10.1126/science.1183700

Tilman, D., C. Balzer, J. Hill, and B.L. Befort. 2011. Global food demand and the sustainable intensification of agriculture. Proc. Natl. Acad. Sci. USA 108:20260–20264. doi:10.1073/pnas.1116437108

Torbett, J.C., R.K. Roberts, J.A. Larson, and B.C. English. 2007. Perceived importance of precision farming technologies in improving phosphorus and potassium efficiency in cotton production. Precis. Agric. 8:127–137. doi:10.1007/s11119-007-9033-1

Turner, F.T., and M.F. Jund. 1994. Assessing the nitrogen requirements of rice crops with a chlorophyll meter. Aust. J. Exp. Agric. 34:1001–1005. doi:10.1071/EA9941001

Wetselaar, R., and G.D. Farquhar. 1980. Nitrogen losses from tops of plants. Adv. Agron. 33:263–302. doi:10.1016/S0065-2113(08)60169-8

Woodley, A.L., C.F. Drury, W.D. Reynolds, W. Calder, X.M. Yang, and T.O. Oloya. 2018. Improved acid trap methodology for determining ammonia volatilization in wind tunnel experiments. Can. J. Soil Sci. 98:193–199. doi:10.1139/cjss-2017-0081

Xu, G., X. Fan, and A.J. Miller. 2012. Plant N assimilation and use efficiency. Annu. Rev. Plant Biol. 63:153–182. doi:10.1146/annurev-arplant-042811-105532

Zhu, J.H., X.L. Li, P. Christie, and J.L. Li. 2005. Environmental implications of low nitrogen use efficiency in excessively fertilized hot pepper (*Capsicum frutescens* L.) cropping systems. Agric. Ecosyst. Environ. 111:70–80. doi:10.1016/j.agee.2005.04.025

Zumft, W.G. 1997. Cell biology and molecular basis of denitrification. Microbiol. Mol. Biol. Rev. 61:533–616.