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NITROGEN USE EFFICIENCY – STATE OF THE ART

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"Nitrogen Use Efficiency – State of the Art"

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Reactive nitrogen and the need to increase fertilizer nitrogen use efficiency

Nitrogenous fertilizers have contributed much to the remarkable increase in food production that has occurred during the past 50 years (Smil, 2001). Globally, however, N fertilizers also account for 33% of the total annual creation of Nr or 63% of all anthropogenic sources of reactive nitrogen (Nr) (Table 1). Reactive nitrogen is defined as all biologically, photochemically, and/or radiatively active forms of N -- a diverse pool of nitrogenous compounds that includes organic compounds (e.g. urea, amines, proteins, amides), mineral N forms, such as NO_3^- and NH_4^+ as well as gases that are chemically active in the troposphere (NOx, NH_3, N_2O) and contribute to air pollution and the greenhouse effect (Galloway et al., 1995). Asia alone accounts for more than 50% of the global N fertilizer consumption as well as 37% for the global Nr creation. Smil (1999) estimated that only about half of all anthropogenic N inputs to cropland are taken up by harvested crops and their residues, with the remainder contributing significantly to Nr enrichment of the atmosphere, ground and surface waters.

Table 1: Global creation of reactive N from anthropogenic and natural sources in the mid 1990s (Boyer et al., 2004).

	Anthropogenic (million t/yr)					**Natural (million t/yr)**			***Total***
Region	Fertilizer	BNF	Import	Depos.	Total	BNF	Lightng.	Total	
Africa	2.1	1.8	0.5	2.9	**7.3**	25.9	1.4	27.3	**34.6**
Asia	44.2	13.7	2.3	3.8	**64.0**	21.4	1.2	22.6	**86.6**
Europe + FSU	12.9	3.9	1.0	2.9	**20.7**	14.8	0.1	14.9	**35.6**
Latin America	5.1	5.0	-0.9	1.8	**11.0**	26.5	1.4	27.9	**38.9**
N. America	12.6	6.0	-2.9	2.7	**18.4**	11.9	0.2	12.1	**30.5**
Oceania	0.7	1.1	-0.3	0.3	**1.8**	6.5	0.2	6.7	**8.5**
Total	**77.6**	**31.5**	**-0.3**	**14.4**	**123.2**	**107.0**	**4.5**	**111.5**	**234.7**

It is widely believed that accumulation of excessive amounts of Nr in terrestrial and aquatic ecosystems as well as in the troposphere leads to significant costs to society that occur through direct and indirect negative effects on environmental quality, ecosystem services, biodiversity, and human health (Pretty et al., 2000; Schweigert and van der Ploeg, 2000; Townsend et al., 2003). Such estimates are not very precise, however, and it is not clear whether they place an appropriate value on the large *positive impact* of N fertilizer on ensuring food security and adequate human nutrition.

Environmental benefits also accrue from fertilizer use by avoiding expansion of agriculture into natural ecosystems and marginal areas that cannot sustain crop production and provide critical habitat for protecting biodiversity (Cassman et al., 2003). Regardless of what the true societal costs of accumulation of Nr in cultivated and natural ecosystems are, it is clear that Nr creation associated with human activities must slow down. Mitigation options include:

(i) Reduction of Nr emissions from fossil fuel combustion,
(ii) Transformation of Nr to non-reactive N forms (e.g., denitrification to N_2 or sequestration of N in soil organic matter),
(iii) Changes in human diet and associated changes in food, feed, and fertilizer demand, and
(iv) Improvements in fertilizer nitrogen use efficiency (NUE) in agricultural systems: less N fertilizer per unit food produced.

Many of these mitigation strategies are of long-term nature and they are closely linked to policy decisions that need to be made. However, improving NUE in agriculture has been a concern for decades and numerous new technologies have been developed in recent years to achieve this. Therefore, fertilizers and their management will be at forefront of measures to improve the global N balance over both the short- and long-term.

This paper addresses three issues: (i) definition and measurement of NUE, (ii) global status of NUE in agriculture, and (iii) a brief outline of major technology options for increasing NUE. I primarily focus on cereals because they account for nearly 60%% of global N fertilizer use (IFA, 2002) and represent 20% of the global annual creation of Nr.

Definition and measurement of nitrogen use efficiency

Nitrogen budgets

Nitrogen budgeting approaches are often used to evaluate system-level N use efficiency and to understand N cycling by estimates of input, storage and export processes by mass balance. A surplus or deficit is a measure of the net depletion (output > input) or enrichment (output < input) of the system, or simply of the 'unaccounted for' N. This approach is used in research studies that aim at the identification of the fate of N surpluses or in long-term assessment of N flows and their respective impact and soil and the environment in managed or natural ecosystems. Unlike many of the agronomic indices of NUE described below, N budgeting approaches are also suitable for systems that are not at a relative equilibrium in terms of N, i.e., systems in which either significant accumulation or losses of N from indigenous sources occur.

Nitrogen budgets can be constructed for a different time periods at any scale, ranging from an agricultural management unit to regional and continental scales. The degree of detail depends on the purpose of budgeting and on the resources available to collect the information. For example, partial budgets that do not include all inputs can be used to estimate the N balance, provided that the major fluxes in and out of the ecosystem are accounted for. Budgets constructed for the purpose of guiding agricultural management or government policy decisions often consist of simple mass balances.

A more complete budget analysis quantifying the relative role of various N inputs and outputs and the distribution and turnover of N among internal compartments is necessary in order to gain mechanistic understanding of the ecosystem. This limits the use of such approaches in evaluating fertilizer management strategies, new fertilizer products, or other technologies. Nitrogen budgets may also be difficult to compare because of different purposes and approaches used for making N budgets. Therefore, methodologies used must be clearly described and N budgets should include statements about scales and uncertainties associated with the estimates.

Agronomic indices of nitrogen use efficiency

Various indices are commonly used in agronomic research to assess the efficiency of applied N (Novoa and Loomis, 1981; Cassman et al., 2002), mainly for purposes that emphasize crop response to N (Table 2). In field studies, these indices are either calculated based on differences in crop yield and total N uptake with aboveground biomass between fertilized plots and an unfertilized control ('difference method'), or by using ^{15}N-labeled fertilizers to estimate crop and soil recovery of applied N. Time scale is usually one cropping season. Spatial scale for measurement is mostly a field or plot. Because each of the indices in Table 2 has a different interpretation value, research on fertilizer-N efficiency should include measurements of *several* indices in order to assess causes of variation in NUE.

The agronomic framework is most useful for understanding the factors governing N uptake and fertilizer efficiency, to compare short-term NUE in different environments, and to evaluate different N management strategies or technologies. The 'difference method' is simple and cost-efficient, which makes it particularly suitable for on-farm research. However, measurement of NUE requires careful experimentation and interpretation must consider potentially confounding factors. Agronomic efficiency (AE_N) and recovery efficiency (RE_N) are not appropriate indices of NUE when comparing cropping practices such as crop establishment methods or different water management regimes when the crop yield in control treatments (Y_0) differs significantly because of these management practices. In these instances, PFP_N is a more appropriate index for making comparisons. Comparisons of RE_N and physiological efficiency (PE_N) among genotypes should use agronomically fit varieties and avoid comparisons with 'inferior germplasm' not adapted to the particular growth conditions. Caution is required when using AE_N, RE_N or PE_N for assessing trends in NUE in long-term experiments because depletion of indigenous soil N in permanent 0-N plots will lead to overestimation of the true NUE in fertilized plots. Results obtained with the 'difference method' may also be confounded by added-N interactions, i.e., differences in N mineralization rates from soil organic matter and crop residues between +N and 0-N plots. Since many of the indices in Table 2 are ratios of several measurements, sampling and/or measurement errors can cause significant errors.

Agronomic NUE indices only provide accurate assessment of NUE for systems that are at a relatively steady-state with regard to soil organic N content and where differences in root systems between unfertilized and fertilized crops are relatively small. Nitrogen in roots as well as any net accumulation of N from fertilizer in soil organic matter and its effect on the indigenous soil N supply for subsequently grown crops cannot be easily accounted for. This may lead to an underestimation of the overall *system level efficiency* of applied N inputs. Therefore, N budgeting or ^{15}N methods should be used to assess the fate of N in the entire soil-crop systems over longer time periods and across different spatial scales. Compared to the difference method, no 0-N plot is required for estimating RE_N using ^{15}N, but costs tend to be higher and a generally higher level of sampling and measurement quality is required. This limits the use of this method in on-farm studies. In general, ^{15}N methods tend to produce results that are similar to those obtained with the difference method, but the relationships between RE_N values obtained with both methods is often quite scattered (Krupnik et al., 2004). Overall, RE_N values obtained with ^{15}N are often slightly lower than those estimated with the difference method because of confounding effects related to pool substitution, i.e., immobilization of ^{15}N fertilizer in microbial biomass and initial release of microbial-derived ^{14}N. Ladha et al. (2005) estimated an average worldwide RE_N for cereal research trials of 51% measured with the difference method as compared to 44% measured with the ^{15}N method. However, their estimates were not based on paired comparisons at the same sites.

Table 2: Agronomic indices of N use efficiency and their typical ranges in cereals.

NUE index	Calculation	Interpretation	Common values
PFP_N - Partial factor productivity of applied N (often simply called nitrogen use efficiency or NUE) (kg harvest product per kg N applied) see Fig. 1a insert	$PFP_N = Y_N/F_N$	• Most important for farmers because it integrates the use efficiency of both indigenous and applied N resources: $PFP_N = (Y_0/F_N) + AE_N$ • Increasing indigenous soil N (Y_0) and the efficiency of applied N (AE_N) are equally important for improving PFP_N • Limited potential for identifying specific constraints or promising management strategies .	40–70 kg grain kg^{-1} N >70 kg kg^{-1} at low rates of N or in very efficiently managed systems
AE_N = Agronomic efficiency of applied N (kg yield increase per kg N applied) see Fig. 1a	$AE_N = (Y_N - Y_0)/F_N$	• AE_N is the product of the efficiency of N recovery from applied N and the efficiency with which the plant uses each additional unit of N acquired: $AE_N = RE_N \times PE_N$ • AE_N can be increased by N, crop, and soil management practices that affect RE_N, PE_N, or both.	10–30 kg grain kg^{-1} N >30 kg kg^{-1} in well-managed systems or at low levels of N use or low soil N supply
RE_N = Crop recovery efficiency of applied N (kg increase in N uptake per kg N applied) see Fig. 1c	$RE_N = (U_N - U_0)/F_N$	• RE_N depends on the congruence between plant N demand and the quantity of N released from applied N. • RE_N is affected by the N application method (amount, timing, placement, N form) as well as by factors that determine the size of the crop N sink (genotype, climate, plant density, abiotic/biotic stresses).	0.30–0.50 kg kg^{-1} 0.50–0.80 kg kg^{-1} in well-managed systems or at low levels of N use or low soil N supply
PE_N = Physiological efficiency of applied N (kg yield increase per kg increase in N uptake from fertilizer) see Fig. 1d	$PE_N = (Y_N - Y_0)/(U_N - U_0)$	• PE_N represents the ability of a plant to transform N acquired from fertilizer into economic yield (grain). • PE_N depends on genotypic characteristics (e.g., harvest index), environmental and management factors, particularly during reproductive growth. • Low PE_N suggests sub-optimal growth (nutrient deficiencies, drought stress, heat stress, mineral toxicities, pests).	30–60 kg kg^{-1} >60 kg kg^{-1} in well-managed systems or at low levels of N use or low soil N supply

F_N – amount of (fertilizer) N applied (kg ha^{-1})
Y_N – crop yield with applied N (kg ha^{-1})
Y_0 – crop yield (kg ha^{-1}) in a control treatment with no N
U_N – total plant N uptake in aboveground biomass at maturity (kg ha^{-1}) in a plot that received N
U_0 – the total N uptake in aboveground biomass at maturity (kg ha^{-1}) in a plot that received no N

For the same soil and cropping conditions, NUE generally decreases with increasing N rate (Fig. 1). Crop yield (Y) and plant N accumulation (U) typically increase with increasing N rate (F) and gradually approach a ceiling (Figures 1a and 1c). The level of this ceiling is determined by the site yield potential. At low levels of N supply, rates of increase in yield and N uptake are large because N is the primary factor limiting crop growth and final yield. As the N supply increases, incremental yield gains become smaller because yield determinants other than N become more limiting as the maximum yield potential is approached.

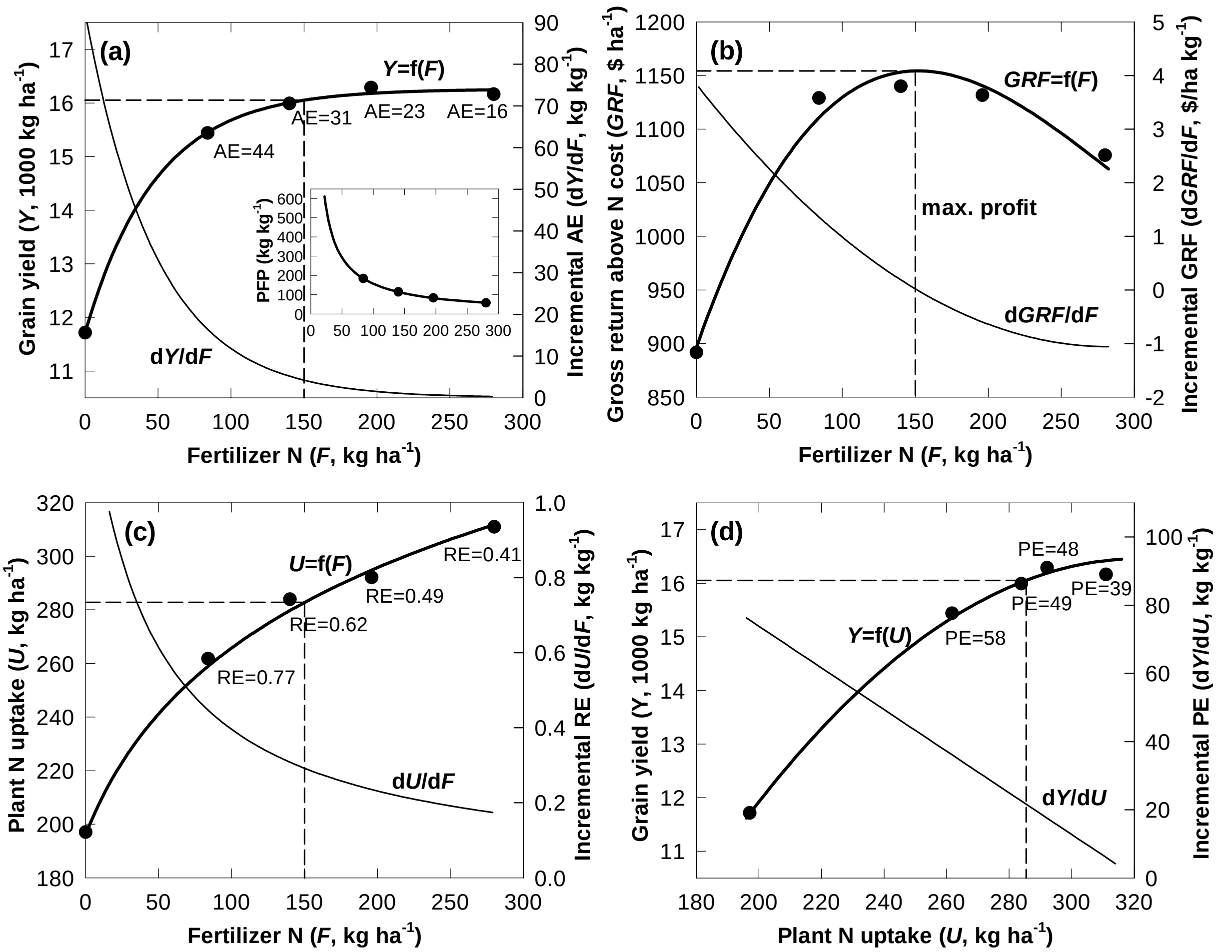


Figure 1: Response of irrigated maize to N application at Clay Center, Nebraska, 2002: (a) relationship between grain yield (*Y*) and N rate (*F*) and the incremental agronomic N efficiency (AE, kg grain yield increase per kg N applied); (b) relationship between gross return above fertilizer cost (*GRF*) and N rate and the incremental GRF (d*GRF*/d*F*); (c) relationship between plant N accumulation (*U*) and N rate and the incremental recovery efficiency of fertilizer N (RE, kg increase in N uptake per kg N applied), (d) relationship between grain yield and plant N accumulation (*U*) and the incremental physiological efficiency of fertilizer N (PE, kg increase in grain yield per kg N taken up). Dashed lines indicate where maximum profit occurred. Measured values of AE (a), RE (c) and PE (d) calculated by the difference method are shown for the four N rates used. The insert in graph (a) shows the decline in PFP_N (ratio *Y*/*F*) with increasing N rate (Dobermann and Cassman, 2004).

The broadest measure of NUE is the ratio of yield to the amount of applied N, also called the partial factor productivity [PFP_N] of applied N, which declines with increasing N application rates (Figure 1a insert). The PFP_N is an aggregate efficiency index that includes contributions to crop yield derived from uptake of indigenous soil N, N fertilizer uptake efficiency, and the efficiency with which N acquired by the plant is converted to grain yield. In addition to N uptake by the crop and N losses, a portion of the N applied is retained in soil as residual inorganic N (either ammonium or nitrate) or incorporated into various organic N pools—including microbial biomass and soil organic matter. Such retention should be considered a positive contribution to N input efficiency only when there is a net increase in total soil N content. Because more than 95% of total soil N is typically found in organic N pools, an increase in soil organic matter (i.e. carbon sequestration) is required to achieve increases in total soil N. Sustained increases in organic matter in cropping systems practiced on aerated soils (e.g. maize- and wheat-based systems without irrigated rice) result in greater indigenous N supply from decomposition of the organic N pools, which can reduce N fertilizer requirements to maintain yields and thereby increase PFP_N (Bell, 1993; Kolberg et al., 1999). In contrast, greater soil organic matter in continuous irrigated rice systems does not necessarily result in an increase in N mineralization because there is little relationship between soil organic matter content and indigenous soil N supply in anaerobic soils (Cassman et al., 1996a; Dobermann et al., 2003). For cropping systems in which soil organic matter is declining over time, there is an additional loss of N above that from applied N fertilizer and organic N sources. This additional loss of N reduces PFP_N and greater amounts of applied N are required to maintain yields.

Figure 1 also illustrates how, alternatively to calculating NUE indices for few fixed levels of N application only, continuous response functions between yield, plant N uptake, and fertilizer N input can be fitted to more accurately quantify the curvilinear nature of crop response to N application. The incremental yield increase that results from N application at any point along the N response curve is the first derivative of the fitted model describing the relationship between yield and N rate, which we may also call the *incremental agronomic efficiency* from applied N (AE_i = dY/dF in Fig. 1a). Likewise, the AE_i is the product of the efficiency of N recovery from applied N sources (*incremental recovery efficiency*, RE_i = dU/dF in Fig. 1c) and the efficiency with which the plant uses each unit of N acquired from applied N to produce grain (*incremental physiological efficiency*, PE_i = dY/dU in Fig. 1b). The RE_i largely depends on the degree of congruence between plant N demand and the available supply of N from applied fertilizer or organic N sources. Consequently, optimizing the timing, quantity, and availability of applied N is the key to achieving high RE_i.

Global status of N use efficiency

World consumption of N fertilizers has averaged 83 million metric tons (Mt) in recent years, of which about 47 Mt is applied to cereal crops (Table 3). The share of total N fertilizer consumption that is applied to cereals ranges from a low of 32% in Northeast Asia to more than 71% in SE Asia. At a global scale, cereal production (slope = 31 x 10^6 Mg yr^{-1}), cereal yields (slope = 45 kg yr^{-1}), and fertilizer N consumption (slope = 2 Mt yr^{-1}) have increased in a near-linear fashion during the past 40 years. However, significant differences exist among world regions, particularly with regard to N use efficiency. On a global or regional scale, PFP_N is the only index of NUE that can be estimated reasonably well, although not very precisely because of uncertainties about the actual N use by different crops. Because PFP_N is a ratio, it always declines from large values at small N application rates to smaller values at high N application rates. Thus, differences in the average cereal PFP_N among world regions depend on which cereal crops are grown, their attainable yield potential, soil quality, amount and form of N application, and the overall timeliness and quality of other crop management operations.

Table 3: Current levels of cereal production, nitrogen fertilizer use on cereals, and cereal nitrogen use efficiency by world regions. Values shown represent annual means for the 1999 to 2002/03 period.

	Developed					**Transitional/Developing**						**World**
	North America	NE Asia	W Europe	E Europe C Asia	Ocean.	Africa	W Asia NE Africa	South Asia	SE Asia	East Asia	Latin America	
Cereal prod. (Mt)	377	19	208	216	34	98	81	307	141	447	144	2072
Cereal yield (t ha^{-1})	5.1	6.1	5.5	2.1	1.9	1.1	2.3	2.4	3.2	4.8	2.9	3.1
Total N use (Mt)[1]	12.5	0.9	9.5	4.9	1.3	1.4	4.2	14.6	4.0	24.9	5.1	83.2
Cereal share N (%)[2]	66	32	45	51	67	56	56	50	71	58	53	57
N use cereals (Mt)	8.3	0.3	4.3	2.5	0.9	0.8	2.4	7.3	2.8	14.5	2.7	46.7
N rate (kg N ha^{-1})[3]	112	89	113	25	48	9	68	58	65	155	55	70
PFP_N (kg kg^{-1})[4]	45	71	59	90	46	123	34	44	53	32	55	44
Relative PFP[5]	1.0	1.6	1.4	2.1	1.1	2.8	0.8	1.0	1.2	0.7	1.3	1.0

[1] Total fertilizer N consumption by all crops (FAO, 2004).
[2] Estimated share of cereal N use of total N consumption, calculated as weighted average of country-specific estimates of fertilizer use by crops (IFA, 2002). Weights were proportional to N use by countries.
[3] Estimated average N application rate on all cereal crops.
[4] Average partial factor productivity of applied N = kg grain yield per kg N applied.
[5] PFP_N relative to world average (World = 1).

At global level, PFP_N in cereal production has decreased from of 245 kg grain kg^{-1} N in 1961/65, to 52 kg kg^{-1} in 1981/85, and is currently about 44 kg kg^{-1}. This decrease in PFP_N occurs as farmers move yields higher along a fixed response function unless offsetting factors, such as improved management that remove constraints on yield, shift the response function up. In other words, an initial decline in PFP_N is an expected consequence of the adoption of N fertilizers by farmers and not necessarily bad within a systems context.

In developing regions, N fertilizer use was small in the early 1960s and increased exponentially during the course of the Green Revolution. Although the growth rate in N consumption has slowed substantially in recent years, it still averaged 1.45 Mt N yr^{-1} (3.2% yr^{-1}) during the past 20 years. The large increase in N use since the 1960s resulted in a steep decrease in PFP_N in all developing regions (Fig. 2). However, average regional N rates on cereals range from less than 10 kg N ha^{-1} in Africa to more than 150 kg N ha^{-1} in East Asia (Table 3) and, with the exception of Africa, PFP_N continues to decline in all developing regions at rates of –1 to –2% yr^{-1} (Fig. 2). The low PFP_N in East Asia, which is dominated by China, is of particular concern for the global Nr budget because this region uses the greatest amount of N fertilizer (Table 1). Declines in PFP_N on cereal production in developing countries will likely continue without greater investment in research and extension to reverse this trend.

In developed regions, excluding Eastern Europe/Central Asia, cereal yields have continued to increase in the past 20 years without significant increases in N fertilizer use. As a consequence, average PFP_N has remained virtually unchanged at 49 kg kg^{-1} since the early 1980s. Trends of increasing PFP_N have occurred in some regions (Fig. 3), e.g., Western Europe (mostly rainfed wheat with high yields) and Northeast Asia (irrigated rice).

In North America, average cereal PFP_N has changed little because of low PFP_N in dryland wheat areas with low and variable yields, while PFP_N of maize has increased substantially (Dobermann and Cassman, 2002). At present, average cereal yields in North America, Western Europe, and East Asia are 60 to 100% above the world average, even though the N rates applied are only 30 to 60% above world average rates (Table 3). High yields and high PFP_N in these regions result from a combination of fertile soils, favorable climate, and improved crop and soil management practices, including N fertilizer management. Trends of increasing PFP_N are likely to continue in developed countries because they primarily result from investments in research and extension on crop improvement, new fertilizer products, and better management technologies by both public and private sectors, at levels that greatly exceed those currently available in the developing world.

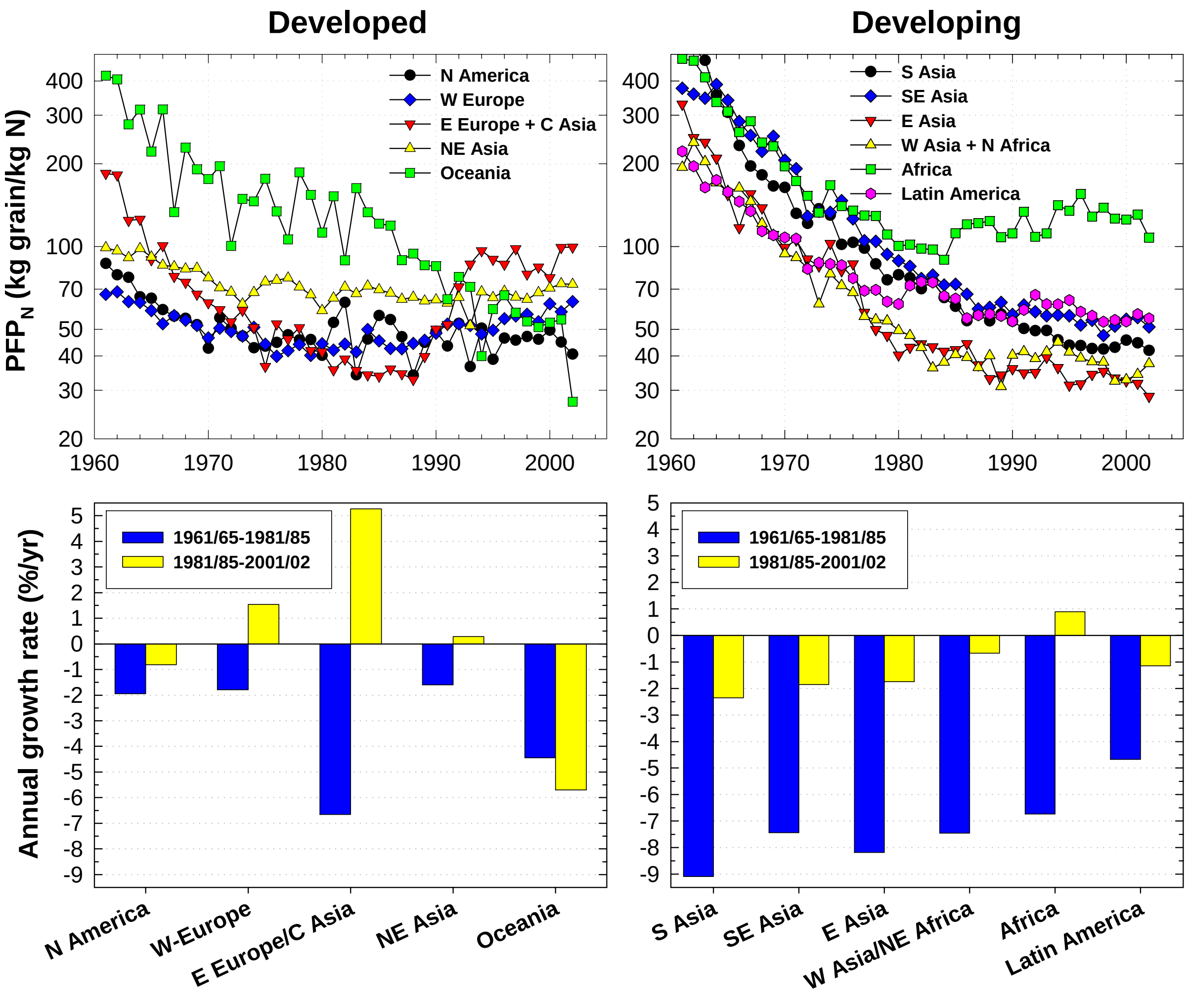


Figure 2: Regional trends in nitrogen use efficiency in cereals. Note: a logarithmic scale was used for the NUE axis.

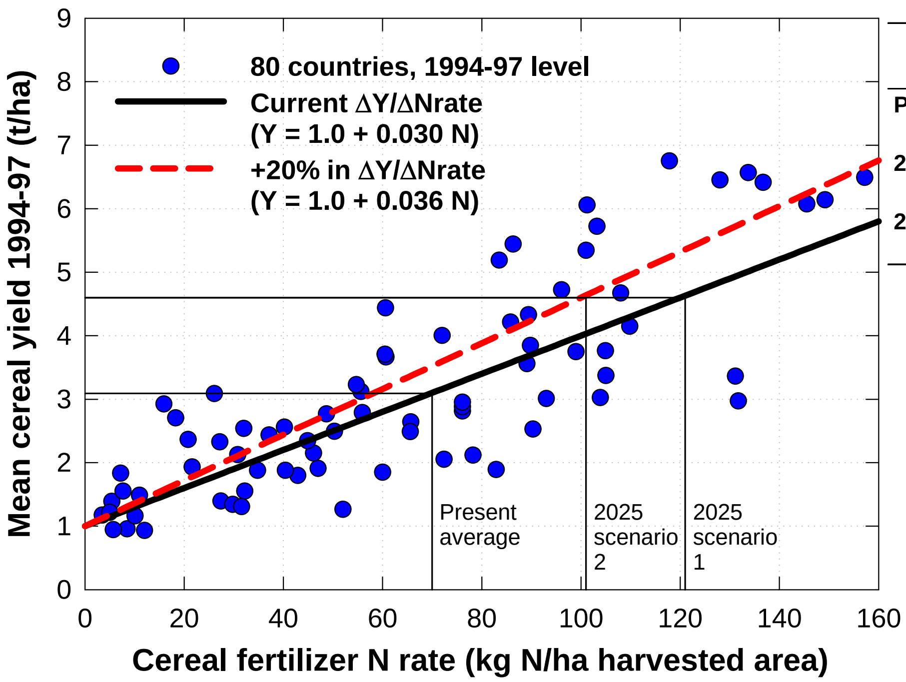
The very high PFP_N in Africa (123 kg kg^{-1}) and Eastern Europe/Central Asia (90 kg kg^{-1}) are indicative of soil N mining. Fertilizer use in Africa has lagged behind other world regions and is a major reason for the low cereal yields in this region (Table 3). In Eastern Europe and countries of the former Soviet Union (FSU), N fertilizer use on cereals dropped drastically in the late 1980s as a result of political and economic turmoil. Consequently, PFP_N doubled from 1988 to 2000 without improvements in yield potential or major changes in N management. Because these trends of increasing PFP_N in both Africa and Eastern-Central Europe are likely associated with a mining of soil N resources, they are not sustainable over the long-term and we would expect yields to stagnate or even decline unless greater amounts of N fertilizer are used in cereal production.

The trends shown in Figure 2 depend on the reliability of the aggregate data on crop yields and fertilizer use. Both are difficult to validate. Data on fertilizer use by individual crops within countries and regions are notoriously difficult to obtain and we do not have reliable series. For many countries, the values used were derived from estimated total N fertilizer use and expert estimates of the average N fertilizer use by crop (IFA, 2002). Very few countries collect more detailed information. Despite these caveats, there are several pieces of supporting evidence. One assumption we made in calculating trends in NUE (Fig. 2) is that the share of total N fertilizer consumption by cereals within a region has not changed substantially since the early 1960s. In the USA, for example, surveys of cropping practices are annually conducted with sample sizes of several thousand farmers (http://www.ers.usda.gov). Those data indicate that the cereal share of total N consumption has remained virtually unchanged since the mid 1960s. In our approach, average PFP_N for rice grown worldwide was estimated at 44 kg kg^{-1} (data not shown). This value is in reasonable agreement with an average PFP_N of 46 kg kg^{-1} as directly measured in on-farm studies conducted on 400 farmers' fields in South Asia, East Asia, Southeast Asia and West Africa (Adhikari et al., 1999; Wopereis et al., 1999; Haefele et al., 2001; Dobermann et al., 2002)

The relationship between the mean national cereal yield and the mean rate of N fertilizer applied to cereal crops on a country-by-country basis is linear and it provides an estimate of the 'global' average AE_N in cereals (Fig. 3). On a global basis, the slope of the regression suggests that global cereal production will increase by 30 kg ha^{-1} for each kg of additional N fertilizer. The slopes and intercepts (yield at zero N applied), however, differ significantly among crops (Cassman et al., 2003). Rice, for example, often yields more with no N fertilizer applied than wheat or maize because of greater N supply from indigenous soil resources. Thus the slope of the regression is lower for rice (26 kg kg^{-1}) than for wheat and maize (36-41 kg kg^{-1}, not shown). Actual N response within countries or at farm level varies widely due to differences in climate, soil fertility and the technological sophistication of crop management.

Figure 3 also illustrates the potential global impact of increasing NUE in agricultural systems. If losses of cereal cropping area continue at present rates and fertilizer-N efficiency cannot be increased substantially, a 60% increase in global N consumption by cereals or 74% increase in average N rates per ha would be required to meet the predicted 38% increase in cereal demand by 2025 (Scenario 1). Such a large increase in N consumption would have major environmental consequences at local, regional, and global scales through continued accumulation of different forms of Nr. On the other hand, the predicted cereal demand can be met by only a 30% increase in global N fertilizer use on cereals if the incremental cereal yield response to applied N can be increased by about 20% within a period of 20 years (Dobermann and Cassman, 2005). Such a level of increase in NUE is well within the scatter of the present 'global N response curve', i.e., there are many countries in which even higher NUE has already been achieved.

Ladha et al. (2005) provide a summary of published literature data on fertilizer-N efficiency in cereal crops. In their analysis, the average RE_N in aboveground biomass (grain+straw) in research plots was 44% in rice, 54% in wheat and 63% in maize (Table 4). Recovery in grain alone averaged 35 to 44% for the three major cereals, which is significantly higher than the crude global estimate (33%) suggested by Raun and Johnson (1999). Not included in this is fertilizer-N recovered in roots, N recovered in subsequently grown crops, and N that remains in the soil N.



Yield (t/ha)	N rate kg/ha	AE_N kg/kg	PFP_N kg/kg
Present average			
3.1	70	30	44
2025 scenario 1			
4.6	121	30	38
2025 scenario 2			
4.6	101	36	46

Figure 3: Global relationships between average cereal yields and average fertilizer-N use for 81 countries during the late 1990s. The solid line indicates the present average N response of all cereals to fertilizer N application. The dashed line indicates a possible increase in NUE due to a 20% increase in the slope of the average N response (Y/ Nrate), but no change in the intercept. Drop lines and values in the table show the effect of different N response on present and required N rates and NUE at global yield levels for two future scenarios in which cereal harvest area continues to decline slowly until 2025, but NUE either increases or decreases: [**1**]**:** No change in the global N response function. Yield increases are mainly associated with increasing N rates (move along the current N response function); [**2**]**:** A 20% increase in the slope of the global N response function. Yield increases are associated with increasing N rate and increasing NUE (Dobermann and Cassman, 2005).

In field studies with rice and dryland systems, average ^{15}N fertilizer recovery was 3.3% in the 1st subsequent crop, 1.3% in the 2nd subsequent crop, 1.0% in the 3rd subsequent crop, 0.4% in the 4th subsequent crop, and 0.5% in the 5th subsequent crop, or 6.5% in total (IAEA, 2003; Krupnik et al., 2004). Thus, together with an average first-crop RE_N of 51% (difference method) or 44% (^{15}N method), total crop N recovery from a one-time application of N averages about 50 to 57% in research trials with cereals. The remainder is either stored in soil organic matter pools or lost from the cropping system. In the IAEA trials, the average amount of ^{15}N fertilizer recovered in soil after five growing season was 15 %, suggesting that, under research conditions, about 30 to 35% of the fertilizer-N applied is typically lost from the system.

Detailed research studies provide valuable insides into N pathways and the processes that lead to N losses in agricultural systems. However, results from research plots cannot be extrapolated to obtain estimates of NUE at regional or global scales because N losses in farmers' fields are often much larger. Unfortunately, little is known about the current level of NUE in key cropping systems of the world at the scale of typical production fields. This shortage of information reflects the logistical difficulty and high cost of obtaining direct on-farm measurements and the lack of funding for what appear to be routine on-farm evaluations (Cassman et al., 2002).

Table 4. Average apparent first-crop recovery efficiency of applied fertilizer-N in cereals (RE_N = fertilizer-N recovery in above-ground biomass).

Crop	Region (no. of observations)	Average N rate (kg N ha^{-1})	RE_N (%)
Maize, research trials[1]	World (36)	102	63
Maize, on-farm[2]	USA (55)	103	37
Rice, research trials[1]	World (307)	113	44
Rice, on-farm[3]	Asia (179)	117	31
Wheat, research trials[1]	World (507)	117	54
Average research trials[1]	World (850)	-	51

1 Ladha et al. (2005)

2 Cassman et al. (2002)

3 Dobermann et al. (2002)

The few available on-farm studies generally suggest a greater disconnection between the amount of fertilizer N applied by farmers and the crop yield that is achieved, resulting in often low and highly variable NUE among and within farmers' fields. Irrigated rice is the only cropping system for which systematic on-farm measurements of NUE have been conducted for numerous regions in Asia and West Africa (Cassman et al., 1996b; Dobermann et al., 2002; Haefele et al., 2003). Average RE_N in irrigated rice fields in Asia was 31% as compared to 44% in research trials (Table 4). Similarly, whereas Ladha et al. (2005) cited an average AE_N in rice of 21.6 kg kg^{-1} and average PFP_N of 63.2 kg kg^{-1}, measured on-farm averages in south and southeast Asia were 11.5 kg kg^{-1} and 49.2 kg kg^{-1}, respectively (Dobermann et al., 2002). Major conclusions drawn from the on-farm studies with rice were (Olk et al., 1999; Dobermann et al., 2003; Dobermann et al., 2004):

(i) Large spatial and temporal variability exists among fields with regard to indigenous N supply, fertilizer use, crop yields, NUE, and marginal return from N fertilizer;
(ii) Grain yield obtained by farmers is closely correlated with plant N uptake, but not with fertilizer N use;
(iii) NUE varies widely and is often not related to N rates or the supply of N from soil;
(iv) Climate, the supply of other essential nutrients, disease, insect pest, and weed pressure, stand establishment, water management and N management technology (timing, forms, placement, etc.) have large effects on RE_N and PE_N and, therefore, the overall crop response to N fertilizer, and
(v) It is difficult to predict the dynamic N supply from indigenous sources using simple assessment methods such as soil tests.

Extensive on-farm studies of similar kind and nearly global scope have not been conducted in other environments or for other major cereal crops. This makes it difficult to judge whether the findings made for rice systems are applicable to other crops and cropping systems. However, there is some evidence that this may be the case for wheat grown in rice-wheat systems of south Asia and maize grown in rainfed and irrigated systems of the USA Corn Belt (Adhikari et al., 1999; Cassman et al., 2002). On-farm studies with maize in the U.S. Corn Belt also showed much lower average RE_N of 37% (Table 4) than the 'global' average of 63% cited for maize in Ladha et al. (2005). A similar discrepancy occurs for PFP_N in maize, with a computed research trial average of PFP_N of 69.9 kg kg^{-1} (Ladha et al., 2005) as opposed to an average value of 58 kg kg^{-1} estimated for maize in the USA (Dobermann and Cassman, 2002). The latter was estimated at national scale based on crop yield statistics and large annual surveys of farmers' fertilizer use.

Lower NUE in farmers' fields is usually explained by a lower level of management under practical farming conditions and greater spatial variability of factors controlling RE_N and other indices of NUE (Cassman et al., 2002). Considering this, NUE achieved in research trials is a good indicator of what can be targeted with good management, but farm-level NUE is always lower. It is reasonable to assume that, on a global scale, at least 50% of the fertilizer-N applied is lost from agricultural systems and most of these losses occur during the year of fertilizer application. It has also been demonstrated, however, how 30 to 50% increases in NUE in rice can be achieved through field-specific management approaches (Dobermann et al., 2002).

What can be done to increase nitrogen use efficiency?

Is a 20% increase in the incremental yield response to applied N (Fig. 3) achievable at the global scale over a time period of about 20 years? To answer this question it is important to re-iterate that a 20% increase in this incremental N efficiency, as estimated by the slope of the regression line in Figure 3, is not equivalent to a 20% increase in the overall NUE (or PFP_N). On a global scale, higher cereal yields are likely to be achieved through a combination of increased N applications in regions with low N fertilizer use, such as Africa and parts of Asia and Latin America, and improved N fertilizer efficiency in countries where current N fertilizer use is already high. For example, the global PFP_N in cereals only needs to increase at a rate of 0.1 to 0.4% yr^{-1} to meet cereal demand in 2025 (Dobermann and Cassman, 2005). Such rates have been achieved in some developed regions in the past 20 years (Fig. 2), and far greater rates of increase have been achieved in several countries.

In the UK, our estimates suggest an average cereal NUE of 36 kg kg^{-1} in 1981/85, which increased to 44 kg kg^{-1} by 2001/02 (+23%, 1.1% yr^{-1}). In the USA, annual surveys of cropping practices indicate that NUE in maize increased from 42 kg kg^{-1} in 1980 to 57 kg kg^{-1} in 2000 (+36%, 1.6% yr^{-1})(Dobermann and Cassman, 2002). In Japan, NUE of irrigated rice remained unchanged at about 57 kg kg^{-1} from 1961 to 1985, but it increased to more than 75 kg kg^{-1} (+32%, 1.8% yr^{-1}) in since 1985 (Suzuki, 1997; Mishima, 2001). In each of these countries, key factors that contributed to this improvement included: (i) increased yields and more vigorous crop growth associated with greater stress tolerance of modern cultivars, (ii) improved management of production factors other than N, and (iii) improved N fertilizer management. The latter may include use of better fertilizers and NUE-enhancing products as well as better application strategies and methods. The combination of these measures allowed achieving higher yields with either stagnating (USA) or declining N use (UK, Japan).

These improvements were achieved without general restrictions or regulations on N fertilizer use. They were driven by investments in public and private sector research and extension. Because of the large differences in NUE among countries, regions, farms, and fields within a farm, policies that focus only on increasing or decreasing N fertilizer use at a state or national level would have a widely varying impact on yields, farm profitability, and environmental quality. Instead, achieving greater NUE at state or national levels will require policies that favor increases in NUE at the field scale with emphasis on technologies that can achieve greater congruence between crop N demand and N supply from all sources—including fertilizer, organic inputs, and indigenous soil N (Cassman et al., 2002).

Most of the fertilizer-N is lost during the year of application. Consequently, N and crop management must be fine-tuned in the cropping season in which N is applied in order to maximize system-level NUE. Numerous concepts and tools needed to increase NUE have been developed. These technologies can be divided into (1) those that enhance crop N demand and uptake (genetic improvements, management factors that remove restrictions on crop growth and N demand) and (2) management options that influence the availability of soil and fertilizer-N for plant uptake. The latter primarily include more efficient fertilizers (new N forms, modified fertilizers & inhibitors that lead to slow/controlled release), more efficient N application methods, and various forms of site-specific N management. It is important to understand, however, that many of the technology options have different effects on crop yield response to N and that it is often the combination of measures that leads to the greatest benefit (Fig. 4).

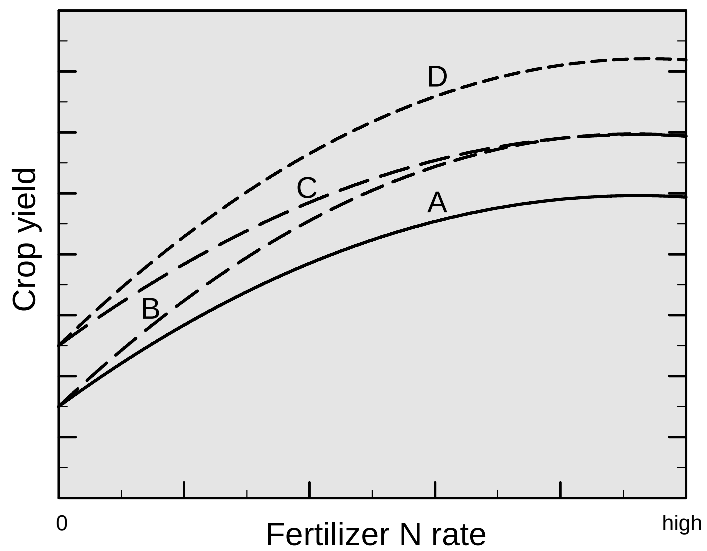


Figure 4: Generalized changes in crop yield response to fertilizer N application as affected by improvements in crops and/or crop and fertilizer management (Giller et al., 2004).
A: Average N response function with low to medium fertilizer N efficiency.
B: Shift in the curvature (slope) of the N response function due to increased fertilizer N efficiency. Measures to achieve this can include improved general crop management (plant density, irrigation, pest control, etc.) or improved N management technologies (placement, timing, modified fertilizers, inhibitors, etc.).
C: Upward-shifted N response function, i.e., increase in the intercept (yield at zero N rate) but no change in the curvature because there is no increase in fertilizer-N efficiency. An increase in the 0-N yield may be due to an improved variety with greater N acquisition or greater internal N utilization, amelioration of constraints that restricted uptake of indigenous N, or other measures that increase the indigenous N supply.
D: Shift in the intercept and curvature of the N response function, i.e., increase in both 0-N yield and slope through a combination of measures. Full exploitation of yield potential is achieved by implementation of a site-specific, integrated crop management approach, in which an advanced genotype is grown with near-perfect management, closely matching crop N demand and supply. As a result, both profit and fertilizer N use efficiency are highest.

It is beyond the scope of this paper to discuss specific technologies in more detail and the reader is referred to the recent literature on this (Schroeder et al., 2000; Cassman et al., 2002; Dobermann and Cassman, 2004; Giller et al., 2004; Ladha et al., 2005). Modern N management concepts usually involve a combination of anticipatory (before planting) and responsive (during the growing season) decisions. Improved synchrony, for example, can be achieved by more accurate N prescriptions based on the projected crop N demand and the levels of mineral and organic soil N, but also through improved rules for splitting of N applications according to phenological stages, by using decision aids to diagnose soil and plant N status during the growing season (models, sensors), or by using controlled-release fertilizers or inhibitors. The latter have a theoretical advantage over other, more knowledge-intensive forms of fined-tuned N management in a sense that the knowledge is ‘embedded’ in the product to be applied. As experience with seeds shows, embedded knowledge can lead to high adoption rates by farmers, provided that the benefit : cost ratio is high.

Important prerequisites for the adoption of advanced N management technologies are that they must be simple, provide consistent and large enough gains in NUE, involve little extra time and be cost-effective (Giller et al., 2004). If a new technology leads to at least a small and consistent increase in crop yield with the same amount or less N applied, the resulting increase in profit is usually attractive enough for a farmer. This is particularly relevant for developing countries or large-scale grain farms in North and South America or in Australia, where there is still potential and need to produce more food and feed. Where yield increases are more difficult to achieve, where increasing crop yield is of less priority, or where reducing the creation of Nr in agriculture is the top societal priority, adoption of new technologies that increase NUE but have little effect on farm profit may need to be supported by appropriate technology incentives.

Summary

Quantifying the status of NUE in agriculture is a difficult task because (i) definitions used in research papers and interpretation of different NUE indices vary and (ii) reliable data needed to compute NUE indices are often not available, particularly at national, regional and global scales. Worldwide, crops do not directly utilize about half of the applied N and the overall NUE has declined with increasing N fertilizer use. This trend seems to continue in many developing countries. In many industrialized countries NUE has been increased, even at high levels of cropping intensity and fertilizer use. Interventions to increase NUE and reduce N losses to the environment must be accomplished at the farm level through a combination of improved technologies and carefully crafted local policies that promote the adoption of improved N management practices while sustaining yield increases. Improved fertilizer products play an important role in the global quest for increasing NUE, but their relative importance varies by regions and cropping systems.

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