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General Principles, Strategy for their Adoption and Voluntary Initiatives vs Regulations

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Nutrient use efficiency – measurement and management

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Nutrients in the global scheme

Mineral fertilizers have sustained world agriculture and thus global population and wealth growth for more than 100 years (Smil, 2001; Stewart *et al.*, 2005). Their contribution to increasing crop yields has spared millions of hectares of natural ecosystems that otherwise would have been converted to agriculture (Balmford *et al.*, 2005). However, lacking, imbalanced, inappropriate or excessive use of nutrients in agricultural systems remains a concern. Nutrient mining is a major cause for low crop yields in parts of the developing world, particularly Africa. In other situations, nutrients such as nitrogen (N) and phosphorus (P) often move beyond the bounds of the agricultural field because the management practices used fail to achieve good congruence between nutrient supply and crop nutrient demand (van Noordwijk and Cadisch, 2002). If left unchecked, such losses may bear significant costs to society (Mosier *et al.*, 2001). Hence, increasing nutrient use efficiency continues to be a major challenge for world agriculture.

This paper tries to summarize how the use efficiency of N, P and potassium (K) from mineral fertilizer is commonly defined and measured, what needs to be considered for interpreting such values, and how it can be improved through soil, crop and fertilizer management. It focuses on cereal systems because those consume the bulk of the world's fertilizer, but the principles discussed are similar in all agricultural crops. Where possible, attempts are made to discuss differences between developed and developing countries. Two key messages emerge: (i) Nutrient use efficiencies measured under practical farming conditions are mostly lower than those reported from research experiments, but information on current levels of fertilizer use and nutrient use efficiency by different crops, cropping systems and world regions remains insufficient; (ii) Numerous technologies for increasing nutrient use efficiency exist. They have been evaluated thoroughly, but adoption by farmers is lagging behind.

Measuring nutrient use efficiency

Agronomic indices for short-term assessment of nutrient use efficiency

Table 1 summarizes a set of simple indices that are frequently used in agronomic research to assess the efficiency of applied fertilizer (Novoa and Loomis, 1981; Cassman *et al.*, 2002), mainly for assessing the short-term crop response to a nutrient. A practical example is illustrated in Figure 1. Other indices are sometimes used (Gourley *et al.*, 1993; Huggins and Pan, 1993), but they have no additional advantages for understanding fertilizer best management practices (FBMPs). More detailed studies on the fate

Table 1. Indices of nutrient use efficiency, their calculation using the difference method, and their interpretation.

Index	Calculation	Interpretation	Nitrogen in cereals
RE = Apparent crop recovery efficiency of applied nutrient (kg increase in N uptake per kg N applied)	RE=$(U - U_0)/F$	• RE depends on the congruence between plant demand and nutrient release from fertilizer. • RE is affected by the application method (amount, timing, placement, N form) and factors that determine the size of the crop nutrient sink (genotype, climate, plant density, abiotic/biotic stresses).	0.30–0.50 kg/kg; 0.50–0.80 kg/kg in well-managed systems, at low levels of N use, or at low soil N supply
PE = Physiological efficiency of applied N (kg yield increase per kg increase in N uptake from fertilizer)	PE=$(Y- Y_0)/(U- U_0)$	• Ability of a plant to transform nutrients acquired from fertilizer into economic yield (grain). • Depends on genotype, environment and management. • Low PE suggests sub-optimal growth (nutrient deficiencies, drought stress, heat stress, mineral toxicities, pests).	40–60 kg/kg; >50 kg/kg in well-managed systems, at low levels of N use, or at low soil N supply
IE = Internal utilization efficiency of a nutrient (kg yield per kg nutrient uptake)	IE=Y/U	• Ability of a plant to transform nutrients acquired from all sources (soil, fertilizer) into economic yield (grain). • Depends on genotype, environment and management. • A very high IE suggests deficiency of that nutrient. • Low IE suggests poor internal nutrient conversion due to other stresses (nutrient deficiencies, drought stress, heat stress, mineral toxicities, pests).	30–90 kg/kg; 55-65 kg/kg is the optimal range for balanced nutrition at high yield levels

AE = Agronomic efficiency of applied nutrient (kg yield increase per kg nutrient applied)	AE=$(Y - Y_o)/F$ or AE=RE x PE	• Product of nutrient recovery from mineral or organic fertilizer (RE) and the efficiency with which the plant uses each additional unit of nutrient (PE). • AE depends on management practices that affect RE and PE.	10–30 kg/kg; >25 kg/kg in well-managed systems, at low levels of N use, or at low soil N supply
PFP = Partial factor productivity of applied nutrient (kg harvested product per kg nutrient applied)	PFP=Y/F or PFP=(Yo/F) + AE	• Most important for farmers because it integrates the use efficiency of both indigenous and applied nutrients. • High indigenous soil nutrient supply (Y_o) and high AE are equally important for PFP.	40–80 kg/kg; >60 kg/kg in well-managed systems, at low levels of N use, or at low soil N supply

F – amount of (fertilizer) nutrient applied (kg/ha)
Y – crop yield with applied nutrients (kg/ha)
Y_o – crop yield (kg/ha) in a control treatment with no N
U – total plant nutrient uptake in aboveground biomass at maturity (kg/ha) in a plot that received fertilizer
U – total nutrient uptake in aboveground biomass at maturity (kg/ha) in a plot that received no fertilizer

of nutrients in agro-ecosystems often involve isotopes, which are particularly useful for understanding loss, immobilization, fixation and release mechanisms.

In field studies, nutrient use efficiencies are either calculated based on differences in crop yield and/or nutrient uptake between fertilized plots and an unfertilized control ('difference method', Table 1), or by using isotope-labeled fertilizers to estimate crop and soil recovery of applied nutrients. Time scale is usually one cropping season. Spatial scale for measurement is mostly a field or plot. For the same soil and cropping conditions, nutrient use efficiency generally decreases with increasing nutrient amount added (Figure 1). Crop yield (Y) and plant nutrient accumulation/uptake (U) typically increase with increasing nutrient addition (F) and gradually approach a ceiling (Figures 1a and 1c). The level of this ceiling is determined by the climatic-genetic yield potential. At low levels of nutrient supply, rates of increase in yield and nutrient uptake are large because the nutrient of interest is the primary factor limiting growth (de Wit, 1992). As nutrient supply increases, incremental yield gains become smaller because yield determinants other than that nutrient become more limiting as the yield potential is approached.

Because each of the indices in Table 1 has a different interpretation value, fertilizer research should include measurements of *several* indices to understand the factors governing nutrient uptake and fertilizer efficiency, to compare short-term nutrient use efficiency in different environments, and to evaluate different management strategies. The

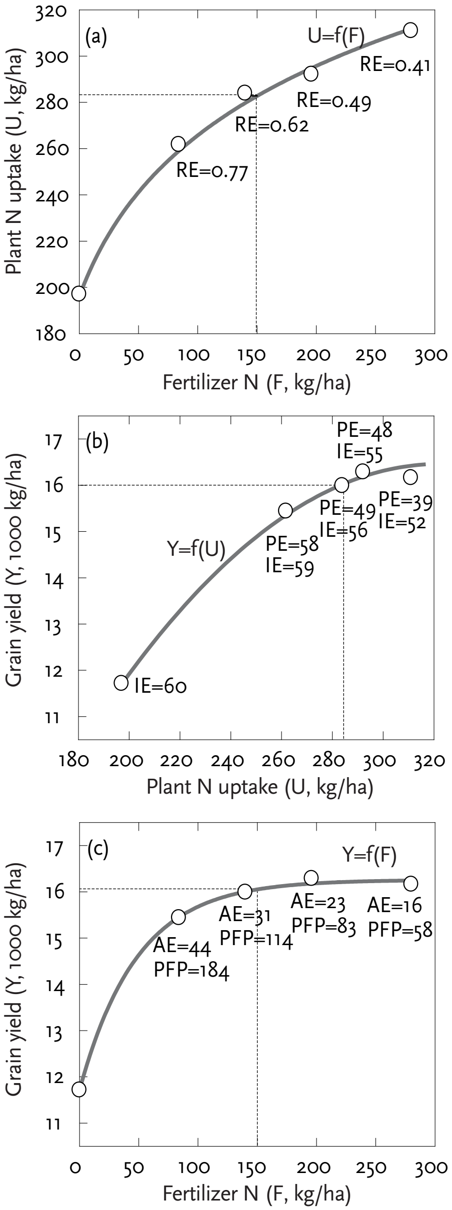

Figure 1. Response of irrigated maize to N application at Clay Center, Nebraska, USA: (a) relationship between plant N uptake (U) and N rate and the recovery efficiency of fertilizer N at four N rates; (b) relationship between grain yield (Y) and plant N uptake (U) and the physiological (PE) and internal efficiency (IE) of fertilizer N; (c) relationship between grain yield (Y) and N rate (F) and the agronomic efficiency (AE) and partial factor productivity (PFP) of applied N. Dashed lines indicate maximum profit (Dobermann and Cassman, 2004).

'difference method' is simple and cost-efficient, which makes it particularly suitable for on-farm research. However, sampling and measurement must be done with great care.

Interpretation must also consider potentially confounding factors. For example, agronomic efficiency (AE) and apparent recovery efficiency (RE) are not appropriate indices of nutrient use efficiency 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, partial factor productivity (the ratio of grain yield/nutrient amount applied, PFP) is a more appropriate index for making comparisons. Likewise, comparisons of RE and physiological efficiency (PE) among genotypes should use agronomically fit varieties and avoid comparison with 'inferior germplasm' not adapted to the particular growth conditions. Caution is required when using AE, RE or PE for assessing trends in nutrient use efficiency in long-term experiments because depletion of indigenous soil nutrient resources in permanent nutrient omission plots (0-N, 0-P or 0-K plots) will lead to overestimation of the true nutrient use efficiency in fertilized plots. For nitrogen, 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.

Agronomic indices only provide accurate assessment of nutrient use efficiency for systems that are at relatively steady-state with regard to soil nutrient content and where differences in root systems between unfertilized and fertilized crops are relatively small. For example, 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. In the example shown in Table 2, the average PFP of applied N suggested that the recommended management system was more N-efficient than the intensively managed system because it produced 70 kg grain/kg N applied (or 0.88 kg grain N/kg N applied) as opposed to 50 kg grain/kg N (or 0.65 kg grain N/kg N applied) in the intensive system. However, when the net change in soil N was included, both systems had nearly the same *system level* N use efficiency (0.92-1.01) because fertilizer-N contributed to build-up of soil organic matter in the intensive system. Over time, this will increase soil N supply, reduce the need for fertilizer, and increase PFP_N. Nutrient budgeting and isotope methods should be used to assess the fate of nutrients in the entire soil-crop-atmosphere system over different time periods and at different scales.

Nutrient budgets for medium- to long-term assessment

Nutrient budgeting approaches are used to evaluate system-level nutrient use efficiency and to understand nutrient cycling by estimating 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' nutrient. This approach is used in studies on the fate of nutrients, for medium- to long-term assessment of FBMPs, nutrient flows and their respective impact on soil and the environment in managed or natural ecosystems, and for regulatory purposes in industrialized countries.

Table 2. Nitrogen use efficiency in a long-term experiment with irrigated continuous maize systems (CC) managed at recommended (-rec) and intensive (-int) levels of plant density and fertilizer inputs. Total amounts for a five-year period (2000-2005) at Lincoln, Nebraska, USA.

2000-2005	CC-rec	CC-int
Average maize yield (t/ha/yr)	14.0	15.0
Fertilizer-N input (kg N/ha)	1005	1495
Nitrogen removal with grain (kg N/ha)	880	970
Measured change in total soil N (kg/ha)	139	404
N unaccounted for (kg/ha)	14	121
NUE 1: partial factor productivity (kg grain/kg N applied)	70	50
NUE 2: kg grain N/kg N applied	0.88	0.65
NUE 3: kg grain N + change in soil N/kg N applied	1.01	0.92

Nutrient budgets can be constructed for different time periods at any scale, ranging from small fields to whole countries or the globe. Budgets constructed for the purpose of guiding and regulating agricultural management or for policy decisions often consist of simple mass balances. For proper interpretation, methodologies must be clearly described and budgets should include statements about scales and uncertainties associated with the estimates (Oenema *et al.*, 2003). General methodologies for this have been proposed in recent years (Smaling and Fresco, 1993; Roy *et al.*, 2004), but the degree of detail depends on the purpose of budgeting and on the resources available to collect the information. Generally speaking, nutrient budgets for larger regions are often highly uncertain because of imprecise available information on key processes such as fertilizer input by different crops and cropping systems, N input from atmospheric deposition and biological N fixation, and gaseous, leaching and runoff losses.

Most common are partial budgets that do not include all inputs or outputs or make assumptions about those that are difficult to quantify at the scale of interest. For a correct interpretation, nutrient budgets must be compared with the nutrient stock in the soil and its availability. A negative nutrient balance on a soil that has excessive levels of that nutrient is not necessarily bad. Likewise, a neutral nutrient balance indicates that the total stock in the soil does not change, but the 'quality' of the stock, and hence soil fertility, may still alter. Hence, a differentiation between 'available' and 'not-immediately available' nutrients is useful in nutrient balance studies, but has only been attempted occasionally (Janssen, 1999; Hoa *et al.*, 2006). Table 3 shows different K balances for an irrigated rice system in South Vietnam. Partial K budgets resulted in K balance estimates that were too negative because of neglected K inputs via rain, irrigation water and sediments. Irrespective of fertilizer-K input, large annual K input from sediments resulted in a positive balance of total K, but most of this was not plant-available.

Table 3. Comparison of partial and complete K input-output budgets in two treatments of a long-term experiment with irrigated double-cropping of rice at Omon, Vietnam. NP: no K fertilizer; NPK: 150 kg K/ha/yr (Hoa *et al.*, 2006).

K budget (kg K/ha/yr)	NP	NPK
Balance of soluble K (partial budget)	-92	22
Balance of soluble K (complete budget)	-69	44
Balance of labile K (NH_4-acetate K, complete budget)	-66	47
Balance of non-labile K (NaTPB-K, complete budget)	-58	55
Balance of total K (complete budget)	251	364

Partial budget: Inputs: fertilizer; Outputs: crop K removal with grain and straw
Complete budget: Inputs: fertilizer, rain water, irrigation water, sediments from annual flood; Outputs: crop K removal with grain and straw, leaching, runoff, sediment removal

Current status of nutrient use efficiency

Nitrogen

World consumption of N fertilizers has averaged 83-85 million metric tonnes (Mt) in recent years, with nearly 60% of that amount applied to cereal crops (Table 4). At a global scale, cereal production (slope = 31 Mt/year), cereal yields (slope = 45 kg/year), and fertilizer N consumption (slope = 2 Mt/year) have all increased in a near-linear fashion during the past 40 years. However, significant differences exist among world regions with regard to N use efficiency (Table 4). At global or regional scales, PFP_N (Table 1) is the only index of N use efficiency that can be estimated more easily, although not very precisely because of uncertainties about the actual N use by different crops and about crop production statistics. Because PFP 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.

Globally, PFP_N in cereal production has decreased from 245 kg grain/kg N applied in 1961/65, to 52 kg/kg in 1981/85, and is currently about 44 kg/kg. 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 system context.

In many developed countries, cereal yields have continued to increase in the past 20 years without significant increases in N fertilizer use, or even with substantial declines in N use in some areas. This has resulted in steady increases of PFP_N in Western Europe (rainfed cereals systems), North America (rainfed and irrigated maize), Japan and South Korea (irrigated rice) since the mid 1980s (Dobermann and Cassman, 2005). At present, average cereal yields in these regions are 60 to 100% above the world average, even though the N rates applied are only 30 to 60% above world average rates (Table 4). High yields and high PFP_N in these regions result from a combination of fertile soils, favorable climate and excellent management practices. Investments in crop improvement (high yielding varieties with stress tolerance), new fertilizer products and application technologies, algorithms and support services for better fertilizer recommendations, better soil and crop management technologies, extension education, and local regulation of excessive N use by both the public and the private sector have contributed to the increase in N use efficiency (Cassman *et al.*, 2002; IFA, 2007). It is likely that this trend will continue.

In developing regions, N fertilizer use was small in the early 1960s and increased exponentially during the course of the Green Revolution. The large increase in N use since the 1960s resulted in a steep decrease in PFP_N in all developing regions. Regional N rates on cereals range from less than 10 kg N/ha in Africa to more than 150 kg N/ha in East Asia (Table 4) and, with the exception of Africa, PFP_N continues to decline in all developing regions at rates of –1 to –2%/year (Dobermann and Cassman, 2005). The very high PFP_N in Africa (122 kg/kg N applied) and Eastern Europe/Central Asia (84 kg/kg) are indicative of unsustainable soil N mining due to low N rates used at present. In some countries, e.g. India, PFP_N seems to have leveled off in recent years, but in many other developing countries it continues to decline because public and private sector investments in better technologies, services and extension education are far below those made in developed countries. Except for research and limited on-farm demonstrations, there are no documented cases for country-scale increase in N use efficiency in a developing country that could be ascribed to adoption of better N management technologies.

How does this compare with more detailed field-level measurements of N use efficiency? A clear distinction must be made between field experiments conducted under more controlled conditions in research stations and values measured on-farm, under practical farming conditions (Table 5). The latter are scarce in the literature, but from the few available studies it is clear that actual N use efficiency is substantially lower in most farms than what is achieved in research experiments. For example, in the worldwide research trials summarized by Ladha *et al.* (2005), the average RE_N in research plots was 46% in rice, 57% in wheat and 65% in maize, with a 'global' mean of 55% (Table 5). This is even higher than Smil's (1999) estimate, who suggested that, on a global scale, about half of all anthropogenic N inputs on croplands are taken up by harvested crops and their residues. In contrast, the few available on-farm studies suggest that average RE_N values are more commonly in the 30-40% range (Table 5). Similar differences between research trials and on-farm studies occur for other indices of N use efficiency (Table 5). Notably, average PFP_N in on-farm studies conducted in developing countries ranged from 44 to 49 kg/kg N, which is close to the estimated 'global' average of 44 kg/kg N (Table 4).

Lower N use efficiency in farmers' fields is usually explained by a lower level of management quality under practical farming conditions and greater spatial variability of factors controlling RE_N, PE_N and PFP_N (Cassman *et al.*, 2002). This is further supported

Table 4. Cereal production, N fertilizer use on cereals, and cereal N use efficiency by world regions. Annual means for 1999 to 2002/03 (Dobermann and Cassman, 2005).

	Developed					Transitional/Developing						World
	North America	NE Asia	West Europe	E Europe C Asia	Oceania	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)	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)[3]	112	89	113	25	48	9	68	58	65	155	55	70
PFP_N (kg/kg)[4]	45	68	49	84	40	122	34	41	49	31	53	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)

by the fact that in the on-farm studies cited (Table 5), N use efficiency varied widely among farmers in the domains sampled, with good farmers already achieving RE_N in the 50-80% range. For example, in widespread on-farm research on irrigated rice in Asia, average RE_N by farmers was only 31% (Table 5), but the top 25% of farmers exceeded RE_N levels of 42%. When a site-specific management was used in the same fields, average RE_N increased to 40% and the top quartile exceeded 53% (Dobermann *et al.*, 2002).

Considering this, N use efficiency achieved in research trials may serve as a reasonable indicator of what can be targeted with good management. It should be noted, however, that this holds only true for short-term field trials that represent N carry-over situations similar to those in farmers' fields, where fertilizer is commonly applied. In long-term experiments with stationary treatment plots, soil N depletion in control plots leads to bias in estimating N use efficiency by the difference method (Table 1), i.e. where soil N is gradually depleted the calculated N use efficiency will steadily rise over time. This methodological problem can only be overcome by using experimental designs with non-stationary treatment plots or by occasionally embedding 0-N microplots within N treatment plots and using those for estimating N use efficiency. This is not common yet. Hence, it is likely that the higher N use efficiencies reported in the literature for research station trials (Ladha *et al.*, 2005) have at least been partially inflated by such bias.

In general, for systems that are near steady-state, ^{15}N methods tend to produce results that are well correlated with those obtained with the difference method (Cassman *et al.*, 2002). Overall, RE_N values obtained with ^{15}N are often somewhat lower than those estimated with the difference method because of confounding effects caused by 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 'global' RE_N for cereal research trials of 55% measured with the difference method as compared to 44% measured with the ^{15}N method. However, their summary of literature data was not restricted to paired comparisons at the same sites. ^{15}N has the added advantage of allowing to also quantifying N recovery in subsequently grown crops. Typically, in addition to the first-crop RE_N, another 5-6% of the fertilizer-N applied is recovered over a period of five subsequent crops grown after harvesting the first crop (IAEA, 2003; Ladha *et al.*, 2005). Thus, total crop N recovery from a one-time application of N averages about 50 to 60% in research trials with cereals or 40-50% under most on-farm conditions. The remainder is mostly lost from the cropping system.

In summary, the shortage of information on farm-level N use efficiency in key cropping systems has hampered efforts on designing the right N management strategies for reducing reactive N loads and increasing farm-level profitability (Cassman *et al.*, 2002). 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. However, it has also been demonstrated through research, the best farmers and commercial implementation of new N management technologies that 30 to 50% increases in N use efficiency can be achieved in many crops (Dobermann and Cassman, 2004; Giller e*t al.*, 2004).

Table 5. Average N use efficiency terms for cereals in different world regions: literature summary of field trials conducted at research stations and averages of selected on-farm studies.

Region/crop	N rate	RE_{15N}	RE_N	PE_N	AE_N	PFP_N
	(kg/ha)			(kg/kg)		
Research station trials (stationary treatment plots)[1]						
Africa	139	0.37	0.63	23	14	39
Europe	100	0.61	0.68	28	21	50
America	111	0.36	0.52	28	20	50
Asia	115	0.44	0.50	47	22	54
Average		*0.44*	*0.55*	*41*	*21*	*52*
Maize (rainfed & irrigated)	123	0.40	0.65	37	24	72
Rice (irrigated)	115	0.44	0.46	53	22	62
Wheat (rainfed & irrigated)	112	0.45	0.57	29	18	45
On-farm studies (non-stationary treatment plots)						
Maize, USA (rainfed & irrigated)[2]	158	-	0.36	33	12	61
Maize, USA (irrigated)[3]	142	-	0.57	41	23	94
Maize, Indonesia (rainfed & irrigated)[4]	200	-	0.37	46	17	46
Rice in S, E and SE Asia (irrigated)[5]	117	-	0.31	39	12	49
Rice in West Africa (irrigated)[6]	106	-	0.36	47	17	46
Wheat in North India (irrigated)[7]	134	-	0.34	32	11	44

RE_{15N} – average N recovery efficiency measured with the ^{15}N isotope dilution method.
All other N use efficiency terms – difference method, as described in Table 1

[1] Research station trials summarized by Ladha *et al.*, 2005. Most of those are multi-year or long-term trials with stationary treatment plots

[2] 52 sites in IL, KS, MI, MN, MO, NE and WI, 1995-1998 (Cassman *et al.*, 2002)

[3] 32 site-years in Nebraska, 2001-2004 (Dobermann *et al.*, 2006)

[4] 25 farms in Indonesia, 2004-2005, at N rate of 200 kg N/ha (Witt *et al.*, 2006)

[5] Farmers' fertilizer practice, 179 farms in China, India, Vietnam, Indonesia and the Philippines, 1997-1999 (Dobermann *et al.*, 2002)

[6] Farmers' fertilizer practice, 151 farms in West Africa (Wopereis *et al.*, 1999; Haefele *et al.*, 2001)

[7] Farmers' fertilizer practice, 23 farms in Uttar Pradesh, 1998-1999

Phosphorus

The global patterns of P supply, consumption and waste production have become decoupled from natural P cycles (Tiessen, 1995). Global mobilization of P has roughly tripled compared to its natural flows, and global food production is now highly dependent on the continuing use of phosphates (Smil, 2000). Although most crops use P efficiently, lost P that reaches aquatic ecosystems downstream from agricultural areas is a main cause of eutrophication. Phosphorus surpluses due to fertilizer use, livestock industry and imports of feed and food have become widespread in industrialized countries. In contrast, both P surpluses and deficits are found in developing countries, including a large area of P deficient soils (largely in the tropics) for which additions of P are the only way to increase agricultural productivity and income.

Global agricultural P budgets (inputs are fertilizers and manures and outputs are agricultural products and runoff) indicate that average P accumulation in agricultural areas of the world is approximately 8-9 Mt P/year (Bennett *et al.*, 2001). Although this annual P accumulation has remained unchanged since the 1980s and appears to decline in recent years, cumulative P accumulation resulting from agriculture has reached more than 300 Mt P since 1960 (Bennett *et al.*, 2001). Rates of P accumulation on agricultural land have started to decline in many developed countries, but are still rising in many developing countries. Forty years ago, developing countries were net exporters of P from agricultural land, but they now accumulate more P per year than developed countries, accounting for 5 of the 8 Mt P/year total global P accumulation on agricultural lands (Bennett et *al.*, 2001).

Great diversity exists in P budgets among countries, within a country, or even between fields in the same farm. Nutrients audits for China suggest average annual P losses of 5 kg P/ha agricultural land (Sheldrick *et al.*, 2003). Similarly, an annual P loss of 3 kg P/ha was estimated for 38 countries of Sub-Saharan Africa (Stoorvogel *et al.*, 1993). In contrast, on-farm studies conducted in China, India, Indonesia, Thailand and the Philippines showed an average annual P surplus of 12 kg P/ha under double-cropping of irrigated rice (Dobermann and Cassman, 2002).

About two thirds of the world's P fertilizer is applied to cereals, mostly to wheat, rice and maize (FAO, 2002), but, because of lacking on-farm studies, it is difficult to judge the 'global' efficiency of fertilizer P. On responsive soils, P applications typically result in cereal yield increases (AE_P) of 20 to more than 50 kg grain/kg P applied. Under favorable growth conditions, most agricultural crops recover 20 to 30% of applied P during their growth. Much of the remainder accumulates in the soil and is eventually recovered by subsequent crops over time, but even small amounts of losses as runoff (particulate and dissolved P) or leaching can cause secondary off-site impacts. Table 6 summarizes RE_P values for a large number of field studies on rice, wheat and maize in Asia, mostly on soils with low P fixation and under favorable climate and management. For all three crops, average RE_P was similar (0.22 to 0.27 kg/kg P applied). However, in each of these studies RE_P varied widely, from 0 to nearly 100% recovery. Most common RE_P values (50% of all data) ranged from 0.10 to 0.35 kg/kg, which probably applies to the majority of agricultural land in the world.

Potassium

Global potassium flows are widely unbalanced because recoverable natural K resources are concentrated at few locations (Sheldrick, 1985) and potash use varies. Roughly 96% of all potash is produced in North America, Western and Eastern Europe and the Middle East. There is virtually no production in Africa and Oceania and only small amounts are produced in South America and Asia. As a result, large amounts of potash fertilizers are shipped around the globe to satisfy the needs of crop production for this important macronutrient. Fortunately, potassium is environmentally benign and its major role is that of increasing crop productivity.

In most developed countries, particularly in Europe, K use has been historically large and sufficient to sustain soil fertility and crop production at high levels. However, K use has declined in recent years. As a result, average crop K removal rates approach or exceed K inputs in these areas and many farmers appear to take advantage of mining soil K that had been accumulated over time. In many developing countries, K input-output budgets in agriculture are highly negative. Nutrient audits have been conducted for several developing countries (Sheldrick *et al.*, 2002) and they mostly show a negative K balance. Although K use has increased on agricultural land in China during the past 20 years, its overall annual K budget remains highly negative at about minus 60 kg K/ha. Similar estimates for India and Indonesia suggest annual K losses of about 20 to 40 kg K/ha and those have been increasing steadily during the past 40 years. An average annual K loss of nearly 20 kg K/ha was estimated for the whole of Sub-Saharan Africa (Stoorvogel *et al.*, 1993).

Table 6 summarizes RE_K values for a large number of field studies on rice, wheat and maize in Asia. Average RE_K ranged from about 0.4 to 0.5 kg/kg K. On soil with low K-fixation potential, with good management (high yield) and at relatively low K rates, RE_K is often in the 0.5 to 0.6 kg/kg range. In general, on-farm estimates of K use efficiency are scarce.

Table 6. Average recovery efficiencies (kg/kg) of N, P and K from mineral fertilizers in field trials with rice, wheat and maize in Asia. Values shown refer to recommended fertilizer rates (rice, wheat and maize) or those currently applied by farmers (rice).

Data set	RE_N	RE_P	RE_K
Rice in S, E and SE Asia, farmers' practice	0.33	0.24	0.38
Rice in S, E and SE Asia, site-specific management	0.43	0.25	0.44
Wheat in India	0.58	0.27	0.51
Wheat in China	0.45	0.22	0.47
Maize in China	0.50	0.24	0.44

Rice: 179 farmers' fields in five countries, 1997-1998, N=314, (Witt and Dobermann, 2004)
Wheat in India: field trials at 22 sites, 1970-1998. 120-26-50 kg/ha NPK (Pathak *et al.*, 2003)
Wheat and maize in China: field trials across China, 1985-1995 (Liu *et al.*, 2006)

Management strategies for increasing nutrient use efficiency

Nitrogen

On a global scale, higher crop 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. The global PFP_N in cereals needs to increase at a rate of 0.1 to 0.4%/year to meet cereal demand in 2025 at a modest pace of increased N consumption (Dobermann and Cassman, 2005). Such and far greater rates of increase have been achieved in several countries. In the UK, average cereal PFP_N rose from 36 kg/kg in 1981/85 to 44 kg/kg by 2001/02 (+23%, 1.1%/year). In the USA, annual surveys of cropping practices indicate that PFP_N in maize increased from 42 kg/kg in 1980 to 57 kg/kg in 2000 (+36%, 1.6%/year)(Dobermann and Cassman, 2002). In Japan, PFP_N of irrigated rice remained unchanged at about 57 kg/kg from 1961 to 1985, but it increased to more than 75 kg/kg (+32%, 1.8%/year) since then (Mishima, 2001).

Approaches for N management and increasing N use efficiency have been discussed in many recent publications (Schroeder *et al.*, 2000; Cassman *et al.*, 2002; Dobermann and Cassman, 2004; Giller *et al.*, 2004; Lemaire *et al.*, 2004; Ladha *et al.*, 2005; McNeill *et al.*, 2005; Lobell, 2007; IFA, 2007). The bullet points listed below re-iterate some of the major considerations.

- Knowing and managing the N supply from soil and other indigenous sources and maximizing the fertilizer efficiency ($AE_N = RE_N \times PE_N$) are equally important components for achieving high PFP_N. Because the relationship between yield and N uptake is tight and because losses of fertilizer-N are highest during the year of application, maximizing the first crop recovery of N from mineral fertilizer or organic amendments (RE_N) is of particular importance. In modern cereal production systems, management should aim to achieve AE_N of 20-35 kg grain/kg N applied. Typically, this requires an RE_N of 0.5-0.7 kg/kg.
- Achievable levels of RE_N depend on crop demand for N, supply of N from indigenous sources, fertilizer rate, timing, product and mode of application. Figure 2 illustrates these relationships by using a simple nutrient supply - demand index. With other factors held constant, RE_N declines with either increasing N rate, higher indigenous N supply or a smaller crop N sink. For any given level of the index, the range in RE_N between the minimum and maximum lines represents other factors, including those that can be controlled by better timing of N applications or other management factors. Changing only one component through a specific technology will not result in the maximum levels of RE_N and profit possible. Holistic management concepts are required that jointly optimize (1) the crop N sink for a specific environment and (2) the availability of soil and fertilizer-N for plant uptake at critical growth stages.
- Many technologies have synergistic effects on crop yield response to N. Hence, they must be applied in an integrated manner:
  1. **Optimize the crop N sink** and the internal plant N utilization: genetic improvements (yield potential and abiotic/biotic stress tolerance, N harvest index), understanding and exploiting the seasonal yield potential, removal of other constraints

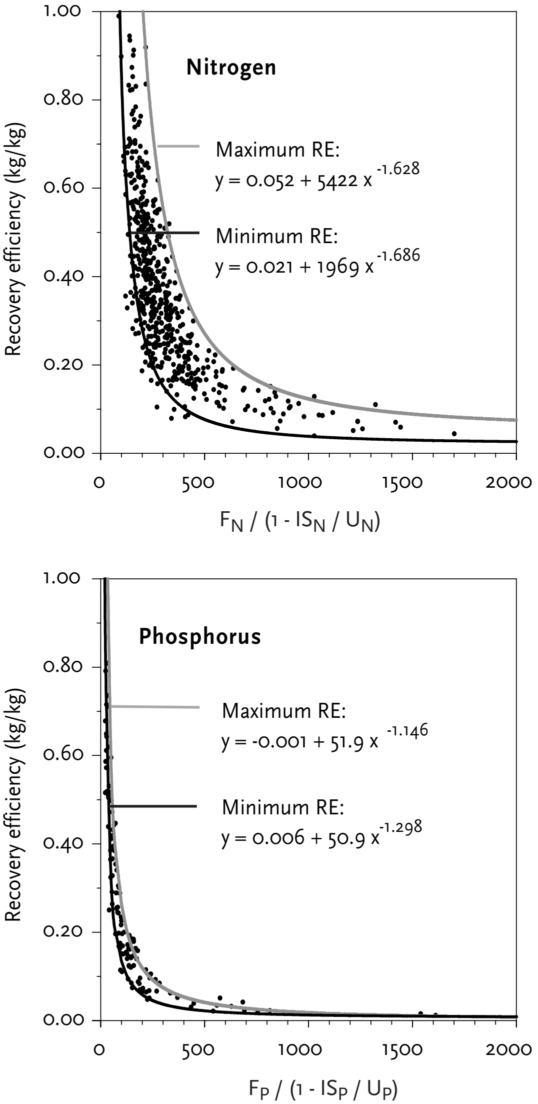

Figure 2. Influence of fertilizer rate (F, kg/ha), effective nutrient supply from indigenous sources such as soil, crop residues, manure or water (IS, kg/ha) and crop nutrient uptake (U, kg/ha) on the range of recovery efficiencies of N and P from applied fertilizer in irrigated rice. Values shown are based on on-farm studies conducted at 179 field sites in Asia during 1997-1998 (Witt and Dobermann, unpublished). F/(1-IS/U) represents a nutrient supply and demand index that determines how efficiently added nutrients are utilized.

for crop growth and internal N utilization (crop establishment, balanced nutrition, optimal water use, control weeds, insects and diseases).

2. **Manage soil and fertilizer-N** for better congruence with crop N uptake: better (site-specific) prescription algorithms, better timing of N applications according to phenological stages, more efficient N application methods, more efficient fertilizers (new N forms, modified fertilizers and inhibitors that lead to slow/controlled release), residue management for sustaining/increasing the indigenous soil N supply.

- Modern concepts for tactical N management should involve a combination of anticipatory (before planting) and responsive (during the growing season) decisions. Uncertainties in the prediction of the seasonal crop N demand require the use of N status indicators for fine-tuning of N rates and timing of N applications. This is of particular importance for high-yielding systems, but also for risk management in systems with relatively low N input. Crop-based approaches for in-season N management are now becoming widely available, ranging from simple tools such as a leaf color chart to crop simulation models or sophisticated on-the-go sensing and variable N rate application systems.
- Enhanced-efficiency N fertilizers have a theoretical advantage over other more knowledge-intensive forms of N management because 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. Improved fertilizer products can thus play an important role in the global quest for increasing N use efficiency, but their relative importance will vary by regions and cropping systems.
- Managing N in organic farming systems is as challenging as managing N from mineral fertilizer sources and must follow the same principles.
- Increasing N use efficiency must be accomplished at the farm level through a combination of improved technologies and local policies that support the adoption of such technologies. New technologies must be profitable and robust, provide consistent and large enough gains in N use efficiency, and involve little extra time. If a new technology leads to at least a small, 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. Where yield increases are more difficult to achieve, where increasing crop yield is of less priority, or where reducing reactive N is the top societal priority, adoption of new technologies that increase N use efficiency but have little effect on farm profit needs to be supported by appropriate incentives.

Phosphorus and potassium

Understanding and management of P and K in agriculture have advanced much. Much of the current knowledge has been captured in models and decision support systems for predicting soil and crop response to P and K (Wolf *et al.*, 1987; Janssen *et al.*, 1990; Greenwood and Karpinets, 1997; Chen *et al.*, 1997; Greenwood *et al.*, 2001; Karpinets *et al.*, 2004; Witt *et al.*, 2005; Smalberger *et al.*, 2006). Other models have been developed for simulating P and K in the rhizosphere of plants, predicting the fate of fertilizer in the soil, or predicting leaching and runoff losses. The main challenge for improving P and K use efficiency at the farm level is to apply the existing knowledge in a practical manner. Major considerations include:

- Cereals take up 2-3 kg P for each tonne of grain yield produced, 70-80% of which is removed from the field with the grain. In modern cereal production systems with no severe P fixation, management should aim to achieve AE_P of 30-50 kg grain/kg P applied. This requires an RE_P of 0.15-0.30 kg/kg. Because of its different physiological role, the relationship between crop yield and crop K uptake can vary widely, making it difficult to specify meaningful target values for K use efficiency. In cereals, AE_K of 10-20 kg grain/kg K applied and RE_K of 0.40-0.60 kg/kg are realistic targets on soils that do not have high available K reserves.
- On soils with low P or K status and/or high fixation capacity, capital investments are required to build-up soil nutrients to levels until the system becomes profitable and sustainable. This needs to be accompanied by other soil and crop improvement measures to ensure profitability. Adopted germplasm with improved P acquisition from more recalcitrant soil P pools and/or increased internal P utilization can be part of such an approach. Cumulative effects of repeated P additions on acid tropical soils are often more economical than single, large doses, primarily because of increasing RE_P and AE_P (Cassman *et al.*, 1993). Similar principles apply to the K management on K-fixing soils (Cassman *et al.*, 1989). The science for this is well understood, but, in the developing world, farmers require initial financial support for implementing such approaches.
- On soils with moderate P and K levels and little fixation, management must focus on balancing inputs and outputs at field and farm scales to maximize profit, avoid excessive accumulation, and minimize risk of P losses. This requires adequate prescription algorithms for calculating fertilizer requirements as a function of the effective soil supply, net crop removal, fertilizer recovery and the overall input-output balance. Replacement strategies are often most sustainable for such situations (Djodjic *et al.*, 2005), but they require accurate accounting of net P and K removal by crops and inputs of these nutrients from other sources, particularly manure (P) and water (K, Table 3). Soil testing is widely used in developed countries for guiding P and K management decisions by farmers. In the developing world, such services are rarely available, but alternative, crop-based approaches have been developed for site-specific P and K management under such conditions (Witt *et al.*, 2004a).
- Eliminate other factors that cause low P or K use efficiency – optimize crop management. Table 7 provides an example for this from a long-term experiment with rice in China. When no P was applied (NK treatment), rice had a high internal P efficiency (IE_P = 590 kg/kg), indicating P deficiency. Adding P but skipping K (NP treatment) alleviated the P deficiency (IE_P = 345 kg/kg), but, because the system was K-deficient, resulted in sub-optimal yield increase and an uneconomical soil P accumulation. With balanced fertilization (NPK), yield increased, primarily due to an increase in RE_P and hence AE_P and $PFP_{P.}$
- In developing countries, many P and K recommendations are based on field trials that emphasize short-term crop response to nutrient applications. Although the ini-

Table 7. Average rice yield (at 14% moisture), plant nutrient uptake, P use efficiencies and cumulative P mass balance of eight consecutive rice crops grown at Jinhua, China from 1997 to 2000 (Modified from Zhang *et al.*, 2006).

	Control	NK	NP	NPK
Grain yield (t/ha)	2.7d	4.2c	4.9b	5.7a
N uptake (kg/ha)	37d	75c	83b	89a
P uptake (kg/ha)	6d	8c	15b	17a
K uptake (kg/ha)	43d	78b	58c	93a
IE of P (kg grain/kg P)	497b	590a	345c	352c
RE of fertilizer-P (kg P/kg P applied)			0.28b	0.35a
PE of fertilizer-P (kg grain/kg P)			157a	171a
AE of fertilizer-P (kg grain/kg P)			44b	60a
PFP of fertilizer-P (kg grain/kg P)			196b	226a
P input-output budget (kg P/ha/year)	-12c	-16d	21a	17b

Within each row, means followed by the same letter are not significantly different at $P<0.05$ level.

tial yield response of cereals to P or K applications is often small, large cumulative yield increases can accrue over time. In the example shown in Figure 3, initial yield increases due to P or K application were not significant (<0.5 t/ha). However, yield increases were consistent and became larger over time as plant available soil P and K became exhausted. Neglecting P or K application caused a grain production loss of 16.5 or 11 t/ha, respectively.

- Most of the K taken up by plants is contained in vegetative plant parts. Improving the internal, on-farm and field recycling is the most important K management issue worldwide. Key components of this are better crop residue and organic waste management to avoid depletion of soils (developing countries) and a re-distribute nutrients from confined livestock operations back to agricultural land (Bijay-Singh *et al.*, 2004; Öborn *et al.*, 2005).
- As for N, the primary determinants for RE_P and RE_K are the size of the crop sink, soil supply and fertilizer rate (Figure 2). However, RE_P and RE_K also depend strongly on soil characteristics determining fixation of P or K in more recalcitrant soil fractions or losses by leaching or runoff. Hence, FBMPs for P and K must also consider the specific characteristics of crops, cropping systems, environments and soils. Examples include:
  - Site-specific measures for preventing runoff and erosion losses of P, e.g. no-till farming, terracing or buffer strips;
  - Band placement of P or K fertilizer in no-till systems to improve nutrient availability during early growth (Bordoli and Mallarino, 1998; Vyn and Janovicek, 2001);
  - Band placement of fluid P fertilizer on calcareous soils with high P fixation capacity;

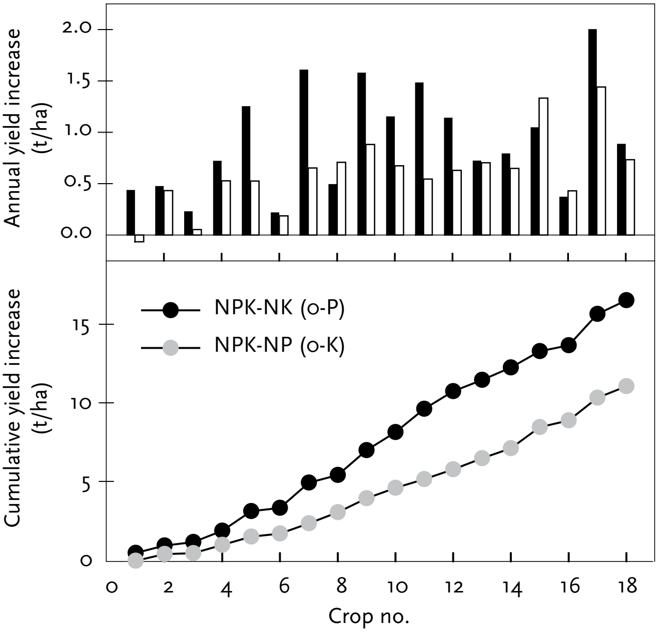

Figure 3. Annual and cumulative yield increases of irrigated rice due to P or K applied to each crop on a Vertisol at Maligaya, Philippines, 1968-76 (Witt *et al.*, 2004b).

- P management in rice-wheat: apply more P to wheat than rice to account for different P availability under aerobic and anaerobic conditions (Yadvinder-Singh *et al.*, 2000);
- Reduced K rates on soils with very high indigenous K supply from minerals or irrigation or for crops with high capability for mobilizing non-exchangeable K;
- Splitting of K applications to minimize leaching, increase stalk strength and resistance to diseases, and improve the quality of harvested products;
- Site-specific management of spatial variability in soil supply and/or crop removal (yield) through variable-rate application of P or K.

Summary and outlook

In North America and West Europe, future increases in fertilizer consumption will be slow or advanced technologies will even allow further reduction of N use without loss of crop production. Farm-level and regional nutrient budgeting are of particular importance in these regions. In many parts of Asia and South America, emphasis will be on improving N use efficiency and ensuring more balanced fertilization, particularly of K and micronutrients. In Sub-Saharan Africa, we hope to enter the beginning stages of a Green Revolution, including adoption of mineral fertilizers. This will require appropriate infrastructure and education.

Both agronomic indices (short-term) and nutrient budgets (medium- to long-term) are important tools for designing FBMPs that fulfill the needs of producers and those of the general public. Fertilizer management strategies should be balanced with regard to achieving high short-term efficiency as well as maximizing the cumulative crop yield response over time. Long-term benefits accruing from residual fertilizer availability (P, K) or increases in soil C and N storage should be included in assessing the *system level efficiency* of applied nutrients. Quantifying the true status of nutrient use efficiency in agriculture remains, however, difficult because reliable farm level data are not widely available. Data on fertilizer use by individual crops within countries and regions are notoriously difficult to obtain and we do not have reliable time series.

Experience from various developed countries has demonstrated that trends of declining N use efficiency can be reversed with the promotion of improved technologies. Research trials and the world's best farmers provide an indication of what levels of nutrient use efficiency can be achieved in both developed and developing countries. Particularly for nitrogen, the gap between achievable targets and current levels of fertilizer use efficiency is still large. Ample knowledge exists on what governs nutrient use efficiency. Public and private sector research and development have resulted in numerous technologies, tools and regulatory activities for increasing nutrient use efficiency under practical farming conditions, as illustrated by the examples shown in Table 8. Because the use efficiencies of all major nutrients are driven by a multitude of site-specific biophysical and socioeconomic factors, improvement is only possible by implementing FBMPs at the field and farm scales, through systematic, site-specific measures rather than promotion of general messages or 'blanket' solutions. The latter play an important role for raising awareness and providing basic education, but they need to be supported by suitable diagnostic tools and management approaches at the field level. Both public and private sector must jointly implement the broader adoption of FBMPs, including better support for 'greener fertilization technologies' that have recently become available.

Three new challenges are emerging for public and private sector research, the fertilizer industry and governments: climate change, bioenergy and micronutrient malnutrition. Global climate will have profound but still little understood influence on land use, crop yields, plant nutrition and a wide range of other abiotic and biotic factors affecting the response to fertilizers (Lynch and St.Clair, 2004; Pendall *et al.*, 2004; Garrett *et al.*, 2006; Long et al., 2006; Pielke *et al.*, 2007). It is largely unknown how it will affect soil nutrient supply and crop response to fertilizers and hence what impact this may have on regional as well as global fertilizer demand. One thing is clear: mitigation of greenhouse gas emission and global climate will be a slow process. In the near future, more emphasis will be placed on adaptation of crops, cropping systems and management practices to better cope with hotter, drier and generally more extreme climate. FBMPs will have to change along with this, but they are among the most cost-effective mechanisms for improving crop resilience to extreme weather and reducing greenhouse gas emissions (Stern, 2006).

Table 8. Recent public and private sector examples of new technologies, tools, support services or regulations for more balanced, efficient, and sustainable use of nutrients in agriculture.

Description	Web links
North America	
USA: Improved hybrids, better crop management practices and N technologies, detailed N algorithm, extension education and Nitrogen Management Zones in Nebraska. Steady increase in N use efficiency in maize since the mid 1980s.	http://soilfertility.unl.edu www.cpnrd.org
USA: InSite Information Management System® and InSite VRN® programs, Mosaic company. Precision agriculture solutions for fertilizer dealers and farmers, including variable rate nutrients.	www.mosaicco.com
USA & Canada: Commercialization of ESN Smart Nitrogen (controlled-release urea) for the commodity crop market, Agrium.	www.agrium.com/ESN/index.jsp
Mexico: Conservation agriculture and site-specific N management in the Yaqui Valley, Mexico, CIMMYT & Stanford University.	http://yaquivalley.stanford.edu
Europe	
Germany: Yara N-sensor® and N-sensor ALS® for site-specific N management and associated services for farmers; about 500 units in operation (half in Germany).	www.sensoroffice.com
Netherlands: Manure policy and MINAS farm accounting system for nitrogen and phosphorous, since 1998. Fees for surpluses.	
Denmark: Nitrogen quotas for farms – 10% below agronomic optimum.	
France: "Agriculture Raisonnée" scheme; whole farm auditing and certification program, including 18 obligations for soil and nutrient management, since 2004.	www.agriculture.gouv.fr
Africa	
Eastern and Central Africa Maize and Wheat (ECAMAW) Network, Quality Protein Maize Development (QPMD) project, IFDC and CIMMYT; crop improvement and nutrient management.	www.ifdc.org
Millenium Villages Project (MVP, The Earth Institute, Columbia University). Multi-sectoral approach with improving seed and fertilizer supply at villages scale as key entry point.	www.earthinstitute.columbia.edu/mvp

Fertilizer micro-packaging for smallholders in Sub-Saharan Africa, TSBF institute of CIAT in collaboration with private sector.	ww.ciat.cgiar.org/tsbf_institute
Asia	
Site-specific nutrient management for rice. 10 years of research and extension sponsored by public and private sector. Bangladesh, India, China, Myanmar, Vietnam, Philippines, Indonesia.	www.irri.org/irrc/ssnm
IPNI SE Asia program and partners: best management practices for oil palm management, including Oil palm Management Program (OMP) software for plantations.	www.eseap.org
IFDC program on Adapting Nutrient Management Technologies in south and southeast Asia: balanced fertilization and deep placement of urea briquettes in rice (Bangladesh, Cambodia, Vietnam).	www.ifdc.org
Oceania	
Australia: SoilMate, software & service for soil testing and fertilizer recommendations that integrates a large amount of public sector research and models, Nutrient Management Systems.	www2.nutrientms.com.au
Australia: Fertcare® program; national training and accreditation initiative for industry businesses and staff, Australian Fertiliser Services Association & Fertilizer Industry Federation of Australia.	www.fifa.asn.au
New Zealand: FBMPs for N and P and Code of Practice for Fertiliser Use, FertResearch, since 1998.	www.fertresearch.org.nz

Rapidly rising use of agricultural crops for biofuel production will have tremendous impact on land use at local to global scales (Cassman *et al.*, 2006; Hazell, 2006), but the consequences for nutrient management may vary widely. In general, demand for biofuels will provide incentives to (i) convert more land to agriculture and (ii) increase crop yields, both of which will lead to increased fertilizer consumption. In addition, a number of more regional or local developments will likely occur. Where land is converted from less fertilizer-intensive crops (e.g. soybean) to crops that require large amounts of nutrients (e.g. maize) N consumption will rise. Where competition for grain drives up grain prices, farmers will have more incentive for use high N rates to achieve high yields, which can lead to negative environmental impact. Where large amounts of crop biomass are removed from the field for ethanol production (sugarcane, sweet sorghum, C4 grasses or straw for cellulosic ethanol), soil organic matter levels may decline and nutrient balances will become negative, particularly for K. Where land is converted to oil palm plantations for biodiesel production, demand for nutrients such as K and Mg will rise rapidly. The fertilizer industry needs to address these issues now and support activities on FBMPs for integrated crop – livestock – biofuel systems in different parts of the world.

Malnutrition is one of the most pressing Millennium Development Goals, particularly in Sub-Saharan Africa and South Asia. The new framework (Graham *et al.*, 2007) calls for attention first to balancing crop nutrition to increase crop productivity, allowing sufficient staple to be produced on less land so that the remaining land can be devoted to more nutrient-dense and nutrient-balancing crops. Once this is achieved, the additional requirements of humans and animals for vitamins, selenium and iodine can be addressed. Hence, improving nutrition through a combination of diversified diets, enrichment of processed food and water supplies, and enrichment of crops with pro-vitamin A and micronutrients through biofortification (breeding) or better soil and fertilizer management is feasible. The fertilizer industry will have a significant future role in the quest for improving micronutrient nutrition in the developing world. Various options for micronutrient enrichment of fertilizers ('fertification') already exist (IFA, 2005), but more work is needed. Public policies must be established to favor the use of enriched fertilizers in specific target regions. Little is known about best management practices for growing biofortified crops. Many of those will only reach their full genetic enrichment potential with appropriate FBMPs, including a minimum level of micronutrient supply.

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