Chapter 1.

Nutrient/fertilizer use efficiency: measurement, current situation and trends

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Abstract

Nutrient use efficiency (NUE) is a critically important concept in the evaluation of crop production systems. It can be greatly impacted by fertilizer management as well as by soil- and plant-water management. The objective of nutrient use is to increase the overall performance of cropping systems by providing economically optimum nourishment to the crop while minimizing nutrient losses from the field. NUE addresses some but not all aspects of that performance. Therefore, system optimization goals necessarily include overall productivity as well as NUE. The most appropriate expression of NUE is determined by the question being asked and often by the spatial or temporal scale of interest for which reliable data are available. In this chapter we suggest typical NUE levels for cereal crops when recommended practices are employed; however, such benchmarks are best set locally within the appropriate cropping system, soil, climate and management context. Global temporal trends in NUE vary by region. For N, P and K, partial nutrient balance (ratio of nutrients removed by crop harvest to fertilizer nutrients applied) and partial factor productivity (crop production per unit of nutrient applied) for Africa, North America, Europe, and the EU-15 are trending upwards, while in Latin America, India, and China they are trending downwards. Though these global regions can be divided into two groups based on temporal trends, great variability exists in factors behind the trends within each group. Numerous management and environmental factors, including plant water status, interact to influence NUE. In similar fashion, plant nutrient status can markedly influence water use efficiency. These relationships are covered in detail in other chapters of this book.

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The Concept and Importance of NUE

Meeting societal demand for food is a global challenge as recent estimates indicate that global crop demand will increase by 100 to 110% from 2005 to 2050 (Tilman *et al.*, 2011). Others have estimated that the world will need 60% more cereal production between 2000 and 2050 (FAO, 2009), while others predict food demand will double within 30 years (Glenn *et al.,* 2008), equivalent to maintaining a proportional rate of increase of more than 2.4% per year. Sustainably meeting such demand is a huge challenge, especially when compared to historical cereal yield trends which have been linear for nearly half a century with slopes equal to only 1.2 to 1.3% of 2007 yields (FAO, 2009). Improving NUE and improving water use efficiency (WUE) have been listed among today's most critical and daunting research issues (Thompson, 2012).

NUE is a critically important concept for evaluating crop production systems and can be greatly impacted by fertilizer management as well as soil- and plant-water relationships. NUE indicates the potential for nutrient losses to the environment from cropping systems as managers strive to meet the increasing societal demand for food, fiber and fuel. NUE measures are not measures of nutrient loss since nutrients can be retained in soil, and systems with relatively low NUE may not necessarily be harmful to the environment, while those with high NUE may not be harmless. We will provide examples of these situations later in the chapter that illustrate why interpretation of NUE measurements must be done within a known context.

Sustainable nutrient management must be both efficient and effective to deliver anticipated economic, social, and environmental benefits. As the cost of nutrients climb, profitable use puts increased emphasis on high efficiency, and the greater nutrient amounts that higher yielding crops remove means that more nutrient inputs will likely be needed and at risk of loss from the system. Providing society with a sufficient quantity and quality of food at an affordable price requires that costs of production remain relatively low while productivity increases to meet projected demand. Therefore, both productivity and NUE must increase. These factors have spurred efforts by the fertilizer industry to promote approaches to fertilizer best management practices such as 4R Nutrient Stewardship, which is focused on application of the right nutrient source, at the right rate, in the right place and at the right time (IPNI, 2012b) or the Fertilizer Product Stewardship Program (Fertilizers Europe, 2011). These approaches consider economic, social, and environmental dimensions essential to sustainable agricultural systems and therefore provide an appropriate context for specific NUE indicators.

NUE appears on the surface to be a simple term. However, a meaningful and operational definition has considerable complexity due to the number of potential nutrient sources (soil, fertilizer, manure, atmosphere (aerial deposition), etc.), and the multitude of factors influencing crop nutrient demand (crop management, genetics, weather). The concept is further stressed by variation in intended use of NUE expressions and because those expressions are limited to data available rather than the data most appropriate to the interpretation.

The Objective of Nutrient Use and Nutrient Use Efficiency

The objective of nutrient use is to increase the overall performance of cropping systems by providing economically optimum nourishment to the crop while minimizing nutrient losses from the field and supporting agricultural system sustainability through contributions to soil fertility or other soil quality components. NUE addresses some but not all aspects of that performance (Mikkelsen *et al.*, 2012). The most valuable NUE improvements are those contributing most to overall cropping system performance.

Therefore, management practices that improve NUE without reducing productivity or the potential for future productivity increases are likely to be most valuable. If the pursuit of improved NUE impairs current or future productivity, the need for cropping fragile lands will likely increase. Fragile lands usually support systems with lower NUE that also use water less efficiently. At the same time, as nutrient rates increase towards an optimum, productivity continues to increase but at a decreasing rate, and NUE typically declines (Barbieri *et al.*, 2008). The extent of the decline will be determined by source, time, and place factors, other cultural practices, as well as soil and climatic conditions.

Intended Use and Available Data for NUE Expressions

The most appropriate NUE expression is determined by the question being asked and often by the spatial or temporal scale of primary interest for which reliable data are available. The scale of interest may be as small as an individual plant for a plant breeder or geneticist or as large as a country or set of countries for policy purposes, educators or marketers. Questions of interest may be focused on a singular practice or product during a single growing season or on a cropping system over a period of decades. Data available may be relatively complete, accounting for all major nutrient inputs and specific nutrient losses in an intensive research project, or limited to those generally available to nutrient managers.

A multitude of expressions and measurements have evolved to meet the needs of this diverse set of circumstances and all are commonly referred to as “NUE”. To be appropriately interpreted, the specific method used must be stated.

Common Measures of NUE and their Application

An excellent review of NUE measurements and calculations was written by Dobermann (2007). Table 1 is a summary of common NUE terms, as defined by Dobermann, along with their applications and limitations. The primary question addressed by each term and the most typical use of the term are also listed.

Partial factor productivity (PFP) is a simple production efficiency expression, calculated in units of crop yield per unit of nutrient applied. It is easily calculated for any farm that keeps records of inputs and yields. It can also be calculated at the regional and national level, provided reliable statistics on input use and crop yields are available. However, partial factor productivity values vary among crops in different cropping systems, because crops differ in their nutrient and water needs. A comparison between crops and rotations is particularly difficult if it is based on fresh matter yields, since these differ greatly depending on crop moisture contents (e.g. potato vs cereals). Therefore, geographic regions with different cropping systems are difficult to compare with this indicator.

Table 1. Common NUE terms and their application (after Dobermann, 2007).

Term	Calculation*	Question addressed	Typical use
Partial factor productivity	PFP = Y/F	How productive is this cropping system in comparison to its nutrient input?	As a long-term indicator of trends.
Agronomic efficiency**	AE = $(Y-Y_0)/F$	How much productivity improvement was gained by use of nutrient input?	As a short-term indicator of the impact of applied nutrients on productivity. Also used as input data for nutrient recommendations based on omission plot yields.
Partial nutrient balance	PNB = U_H/F	How much nutrient is being taken out of the system in relation to how much is applied?	As a long-term indicator of trends; most useful when combined with soil fertility information.
Apparent recovery efficiency by difference**	RE = $(U-U_0)/F$	How much of the nutrient applied did the plant take up?	As an indicator of the potential for nutrient loss from the cropping system and to access the efficiency of management practices.
Internal utilization efficiency	IE = Y/U	What is the ability of the plant to transform nutrients acquired from all sources into economic yield (grain, etc.)?	To evaluate genotypes in breeding programs; values of 30-90 are common for N in cereals and 55-65 considered optimal.
Physiological efficiency**	PE = $(Y-Y_0)/(U-U_0)$	What is the ability of the plant to transform nutrients acquired from the source applied into economic yield?	Research evaluating NUE among cultivars and other cultural practices; values of 40-60 are common.

* Y = yield of harvested portion of crop with nutrient applied; Y_0 = yield with not nutrient applied; F = amount of nutrient applied; U_H = nutrient content of harvested portion of the crop; U = total nutrient uptake in aboveground crop biomass with nutrient applied; U_0 = nutrient uptake in aboveground crop biomass with no nutrient applied; Units are not shown in the table since the expressions are ratios on a mass basis and are therefore unitless in their standard form. P and K can either be expressed on an elemental basis (most common in scientific literature) or on an oxide basis as P_2O_5 or K_2O (most common within industry).

** Short-term omission plots often lead to an underestimation of the long-term AE, RE, or PE due to residual effects of nutrient application.

Agronomic efficiency (AE) is calculated in units of yield increase per unit of nutrient applied. It more closely reflects the direct production impact of an applied fertilizer and relates directly to economic return. The calculation of AE requires knowledge of yield without nutrient input, so is only known when research plots with zero nutrient input have been implemented on the farm. If it is calculated using data from annual trials rather than long-term trials, NUE of the applied fertilizer is often underestimated because of residual effects of the application on future crops. Estimating long-term contribution of fertilizer to crop yield requires long-term trials.

Partial nutrient balance (PNB) is the simplest form of nutrient recovery efficiency, usually expressed as nutrient output per unit of nutrient input (a ratio of "removal to use"). Less frequently it is reported as "output minus input." PNB can be measured or estimated by crop producers as well as at the regional or national level. Often the assumption is made that a PNB close to 1 suggests that soil fertility will be sustained at a steady state. However, since the balance calculation is a partial balance and nutrient removal by processes, such as erosion and leaching are usually not included, using a PNB of 1 as an indicator of soil fertility sustainability can be misleading, particularly in regions with very low indigenous soil fertility and low inputs and production, such as Sub-Saharan Africa. Also, all nutrient inputs are rarely included in the balance calculations, thus the modifier, partial, in the term. Biological N fixation, recoverable manure nutrients, biosolids, irrigation water, and the atmosphere can all be nutrient sources in addition to fertilizer. Values well below 1, where nutrient inputs far exceed nutrient removal, might suggest avoidable nutrient losses and thus the need for improved NUE (Snyder and Bruulsema, 2007); attainable values, however, are cropping system and soil specific. A PNB greater than 1 means more nutrients are removed with the harvested crop than applied by fertilizer and/or manure, a situation equivalent to "soil mining" of nutrients. This situation may be desired if available nutrient contents in the soil are known to be higher than recommended. However, in cases where soil nutrient concentration is at or below recommended levels, a PNB >1 must be regarded as unsustainable (Brentrup and Palliere, 2010). Over the short term and on individual farms, PNB can show substantial fluctuations due to cash flow and market conditions, especially for P and K. Longer term assessment of PNB over several years is therefore more useful.

Apparent recovery efficiency (RE) is one of the more complex forms of NUE expressions and is most commonly defined as the difference in nutrient uptake in above-ground parts of the plant between the fertilized and unfertilized crop relative to the quantity of nutrient applied. It is often the preferred NUE expression by scientists studying the nutrient response of the crop. Like AE, it can only be measured when a plot without nutrient has been implemented on the site, but in addition requires measurement of nutrient concentrations in the crop. And, like AE, when calculated from annual response data, it will often underestimate long-term NUE.

Internal utilization efficiency (IE) is defined as the yield in relation to total nutrient uptake. It varies with genotype, environment and management. A very high IE suggests deficiency of that nutrient. Low IE suggests poor internal nutrient conversion due to other stresses (deficiencies of other nutrients, drought stress, heat stress, mineral toxicities, pests, etc.).

Physiological efficiency (PE) is defined as the yield increase in relation to the increase in crop uptake of the nutrient in above-ground parts of the plant. Like AE and RE, it needs a plot without application of the nutrient of interest to be implemented on the site. It also requires measurement of nutrient concentrations in the crop and is mainly measured and used in research.

NUE Application and Benchmarks

In most cases it is helpful to use more than one NUE term when evaluating any management practice, allowing for a better understanding and quantification of the crop response to the applied nutrient. The different indicators should be used simultaneously. Frequently, the highest AE is obtained at the lowest fertilizer rates being evaluated, rates associated with high PNB. Genetic modifications, such as the recent discovery of the Phosphorus Starvation Tolerance gene that helps rice access more soil P (IRRI, 2012), will increase PFP and P removal in crop harvest. Such a development has great short term value to farmers and may allow the system to operate at a lower level of soil P. However, if P use is less than the enhanced removal level, soil P depletion does occur (PNB is greater than 1). Therefore, even with such genetic changes, an appropriate PNB must be attained for system sustainability. Although individual NUE terms can each be used to describe the efficiency of fertilizer applications, a complete analysis of nutrient management should include other NUE terms, grain yield, fertilizer rates, and native soil fertility (Olk *et al.*, 1999). For example, under low soil P availability, AE for P could be very high with low P rates; however, PNB for P under this condition could be well above 1, depleting the already low soil P reserves as shown in Figure 8. In this case, a low P rate with high AE for P, though a better practice than no P application at all, would not be considered a best management practice (BMP).

This chapter will illustrate the great variability existing in the major NUE measures and trends and the primary factors affecting them. Improvement in nutrient stewardship can be facilitated by identifying relevant measures of NUE for the scale of interest, collecting data for those measures, then having benchmarks for evaluating the collected data. Benchmarks are best set locally within the appropriate cropping system, soil, climate and management context and with full knowledge of how NUE measures are being calculated. However, the focus of this chapter is to provide general guidelines for interpreting NUE measures. Table 2 provides such generalized guidelines for the most common NUE measures for N, P and K for cereal crops. These benchmarks should be replaced with levels based on local research and experience whenever possible.

Table 2. Typical NUE levels for cereal crops (primarily maize, rice, and wheat) when recommended management practices are employed and where soil available P and K levels are currently within a recommended range.

Measure	Typical level***			Interpretation
	N	P (P_2O_5)	K (K_2O)	
Partial factor productivity (kg grain/kg nutrient)	40-90	100-250 (45-110)	75-200 (60-165)	Lower levels suggest less responsive soils or over application of nutrients while higher levels suggest that nutrient supply is likely limiting productivity.
Agronomic efficiency* (kg grain/kg nutrient)	15-30	15-40 (7-15)	8-20 (7-15)	Lower levels suggest changes in management could increase crop response or reduce input costs.
Recovery efficiency* (%)	40-65	15-25	30-50	Lower levels suggest changes in management could improve efficiency or that nutrients are accumulating in the soil.
Partial nutrient balance** (kg nutrient/kg nutrient)	0.7-0.9	0.7-0.9	0.7-0.9	Lower levels suggest changes in management could improve efficiency or soil fertility could be increasing. Higher levels suggest soil fertility may be declining.

* Based on first year response.
** Inputs include fertilizer, applied manure nutrients, and nutrients in irrigation water.
*** Ranges were selected by the authors based on reported values in the published literature and best judgment on what typical levels are when practices recommended for the region are being followed. These values should be replaced with levels based on local research and experience whenever possible.

NUE AT DIFFERENT SCALES

The NUE terms in Table 1 could be estimated at scales ranging from global to small areas within individual fields. Scalability is a desired attribute for performance indicators, because it makes linkages more clear between local management practices and larger-scale impacts. However, the certainty and reliability of the estimation for specific sites decreases as the scale increases. In any case, these estimates depend on the quality of the data used in calculations. Simpler indicators such as PFP scale more easily than complex forms such as RE and PE. Several examples of NUE terms applied at different scales follow.

Regional-scale

Table 3 shows estimations of PFP and PNB for N for cereal crops of regions of the world sorted from lowest to highest average N rate. Regions differ considerably in these two measures of efficiency, with the two highest values occurring for the regions with the lowest N rates, Africa and Eastern Europe/Central Asia. These regions also have the lowest average yields and PNB values much greater than one, indicative of systems that are possibly mining N from soil organic matter and may not be sustainable (unless there are substantial contributions of N from rotational legumes, not taken into account in these PNB or PFP values).

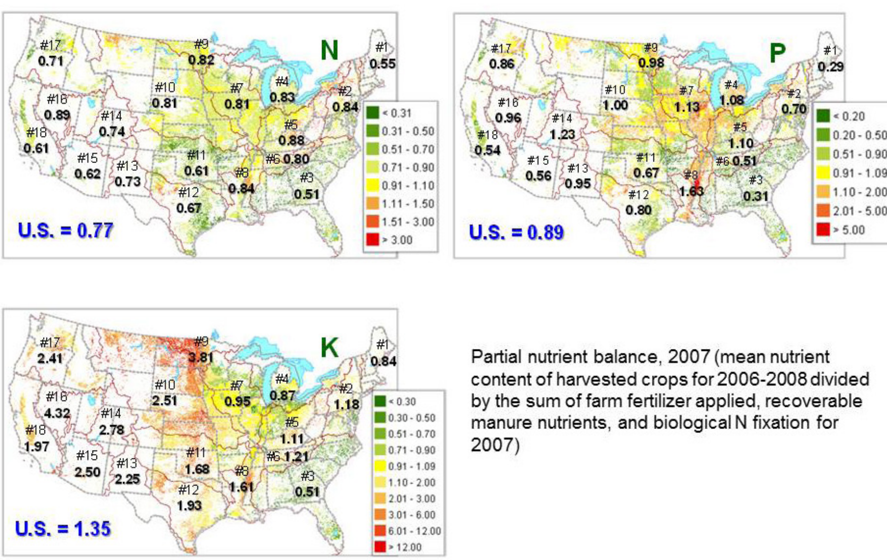
Table 3. Partial factor productivity and partial nutrient balance for N applied to cereals for world regions and associated average fertilizer N rates and crop yields.

Region	N rate kg/ha	Cereal yield t/ha	Grain N* kg/ha	PFP kg grain/kg N	PNB kg grain N/kg N
Sub-Saharan Africa	9	1.1	17	122	1.8
Eastern Europe, Central Asia	25	2.1	32	84	1.3
Oceania	48	1.9	29	40	0.59
Latin America	55	2.9	44	53	0.79
South Asia	58	2.4	36	41	0.62
Southeast Asia	65	3.2	48	49	0.74
West Asia, North Africa	68	2.3	35	34	0.51
Northeast Asia (Japan, S. Korea)	89	6.1	92	69	1.03
North America	112	5.1	77	46	0.68
Western Europe	113	5.5	83	49	0.73
East Asia (China, Viet-nam, Korea DPR)	155	4.8	72	31	0.46
World	70	3.1	47	44	0.66

*Assuming 15 kg N/t of cereal grain.
Fertilizer N rate and cereal yield for years 1999-2002/03 reported by Dobermann and Cassman, 2005.

The values in Table 3 represent very large regions and are averages across great variability. Sub-Saharan Africa (SSA), even with the extremely high average PNB, has great inter-country variability with generally higher values in the east and lower values in the central and western part of the continent (Smaling *et al.*, 1997). We also must recognize the high variability in PNB among farms within countries in SSA. Farms having good access to resources will have PNB values often less than 1 (nutrient input exceeds removal) while those with fewer resources will be greater than 1 as the aggregate data of Table 3 reflects (Zingore *et al.*, 2007). Farms with lower access to resources often rely more on N from legumes, an effect that is not captured in Table 3. East Asia shows the lowest PNB (0.46) at the highest average N input rate. This suggests the potential for improving NUE while maintaining productivity. At this very coarse scale, differences among other regions in Table 3 can be due to a complex set of factors including crop rotation, soil properties, climate, government policy, and management intensity.

The regional differences in PNB within a single country illustrate the impact of this complex set of factors on NUE. For example, PNB for watershed regions of the U.S. vary in a somewhat predictable fashion (Figure 1). The PNB values in Figure 1 are less "partial" than those in Table 3 since they include both N fixation and applied manure nutrients. PNB levels for N, P and K are generally low in the southeast US (Region 3), dominated by coarse-textured, low organic matter soils, which have very low water-holding and cation exchange capacities. Much of this region also produces high value crops, many of them inefficient nutrient users. At the other extreme is K in the western half of the country where PNB levels are extremely high due to generally high indigenous soil K levels resulting in infrequent response to K fertilization. Such factors need to be considered when interpreting NUE data at regional scales.



NuGIS, 1/12/2012

Figure 1. Partial nutrient balance for watershed regions of the U.S. (IPNI, 2012a).

Farm or field-scale

The PFP and PNB provide useful information for growers and can also be calculated for any farm that keeps records of inputs and outputs. Figure 2 shows trends in fertilizer use per ha and per ton of grain for a farm in Brazil and illustrates the kind of data often available at a farm scale. In this case, though fertilizer use per ha increased, PFP also increased (plotted as its inverse, kg of NPK per ton of crop yield) due to the accompanying increase in crop yields. Improvements in agronomic practices of a cropping system can markedly influence NUE and when implemented concurrently with increased nutrient rates can result in simultaneous increases in fertilizer rates, crop yields and NUE ("sustainable intensification").

Neither PFP nor PNB indicators consider inherent soil nutrient supplies; thus they do not fully reflect the true efficiency of fertilizer-derived nutrients. The short-term NUE of applied nutrients is better estimated using AE, RE and PE, but these indices require data that are not often available at a farm scale.

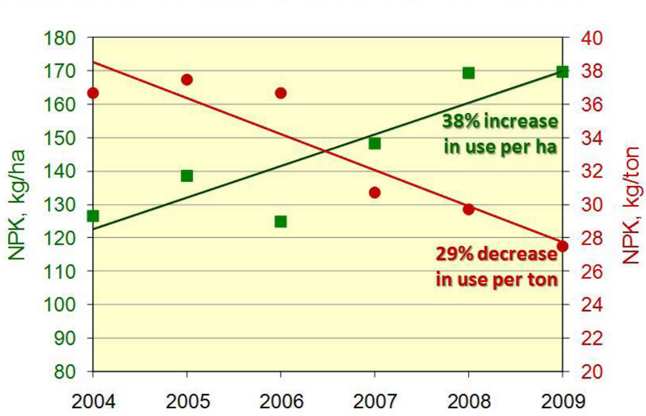


Figure 2. Evolution of fertilizer use per ha and per ton of crop yield in a farm near Itiquira, MT, Brazil (L. Prochnow, personal communication, 2012).

The use of a check plot or omission plot has traditionally been limited to research settings, but could be established on the farm if a grower has interest. There is merit to establishing both perennial check plots, where the same area remains unfertilized across years and that will reflect the long-term contribution of applied nutrients to productivity and soil quality, as well as annual check plots, where the response of a single crop to a nutrient application can be assessed. Such on-farm research is best done in cooperative groups, since inclusion of check plots can be costly to the grower in terms of lost yield and the loss of uniformity in quality of harvested product. This is an especially important limitation for check plot establishment where severe deficiencies exist such as in SSA. Also, shared results of on-farm research conducted across a production area are more meaningful than single observations.

Research plot-scale

Research plots typically offer a full complement of data on nutrient uptake and removal in crop harvest for fertilized and unfertilized plots, enabling calculation of all the common NUE forms (Table 1). Because each term addresses different questions and has different interpretation, research reports often include measurements of more than one NUE expression (Dobermann, 2007). A summary of NUE measurements from numerous field trials on rice, wheat, and maize in China is shown in Table 4 and from wheat field trials in three regions of China in Table 5. The regional wheat data illustrate the great differences that exist in NUE among regions within countries due to differences in climate, soil properties and cropping systems.

Estimates of NUE calculated from research plots on experiment stations are generally greater than those for the same practices applied by farmers in production fields (Cassman *et al.*, 2002; Dobermann, 2007). Differences in scale between research plots and whole fields for management of fertilizer practices, tillage, seeding, pest management, irrigation and harvest contribute to these differences.

Determination of RE in research plots is usually done by the difference calculations described in Table 1. An alternative method for N involves using the ^{15}N isotope as a tracer in the fertilizer to determine the proportion of fertilizer applied that was taken up by the crop. The two methods are usually related; however, RE determined by the ^{15}N method will usually be lower than the difference estimates due to cycling of the ^{15}N through microbially-mediated soil processes (Cassman *et al.*, 2002). Tracers are more useful when recovery is measured in the soil as well as in the plant, particularly in the longer term. Ladha *et al.* (2005) summarized results from several studies where ^{15}N was used to estimate N recovery by five subsequent crops, reporting a range of 5.7 to 7.1%, excluding the first growing season. With the first growing season, total RE ranged from 35 to 60%.

Table 4. Average yield response and NUE for field trials in China from 2002-2006 (Jin, 2012).

Crop	Nutrient	Number of trials	Avg fertilizer rate kg/ha	Yield increase %	AE kg/kg	RE %
Rice	N	51	187	40	12	25
Wheat	N	30	181	43	11	36
Maize	N	70	219	38	12	31
Rice	P	62	41	13	26	10
Wheat	P	39	52	24	21	16
Maize	P	71	49	15	26	15
Rice	K	67	122	21	11	25
Wheat	K	51	100	18	8	26
Maize	K	84	118	17	13	32

Table 5. A comparison of NUE expressions based on the optimal treatment from wheat field trials in three regions of China between 2000 and 2008 (Liu *et al.*, 2011).

Region*	Nutrient	Number of observa-tions**	Avg. fertilizer rate kg/ha	PFP*** kg/kg	AE kg/kg	RE %	PNB**** kg/kg
NC	N	122-210	199	38(518)	9.5	35.2	1.10
LY	N	60-155	220	34(234)	11.3	48.1	0.81
NW	N	13-34	169	37(108)	6.5	17.0	0.70
Avg.	**N**	**195-363**		**36(860)**	**9.8**	**37.9**	**0.95(0.73)**
NC	P	46-137	56	142(506)	23.0	17.8	1.07
LY	P	26-51	47	146(220)	18.4	25.9	0.91
NW	P	11-40	47	142(108)	7.0	7.4	0.43
Avg.	**P**	**83-223**		**143(834)**	**19.2**	**19.0**	**0.96(0.81)**
NC	K	70-374	111	71(481)	7.6	23.7	1.67
LY	K	26-69	96	76(234)	8.3	34.2	1.73
NW	K	14-77	70	66(102)	4.2	30.0	2.73
Avg.	**K**	**110-517**		**72(817)**	**7.2**	**27.0**	**1.82(0.60)**

*NC: North central with temperate climate and winter wheat-maize annual rotation; LY: Lower Yangtze River with temperate to subtropical humid climate and predominant rice-wheat rotation; NW: Northwest with continental climate and continuous spring wheat cropping system;
**range in obs for AE, RE and PNB;
***Number of observations for PFP in parentheses;
****Calculated as removal in grain and straw divided by applied fertilizer except values in parentheses where only grain removal is included. An average of 44% of wheat straw nutrient is returned to the field in China.

CURRENT STATUS AND TRENDS IN NUE FOR N

Current status of NUE for N

Ladha *et al.* (2005) conducted an extensive review of 93 published studies where NUE was measured in research plots (Table 6). This review provides estimates of the central tendency for NUE expressions for maize, wheat, and rice. Values for PFP and AE were generally higher for maize and rice than for wheat, at least in part due to the higher N content of wheat grain. Values for RE varied widely across regions and crops with a 10th percentile value of 0.2 and a 90th percentile value of 0.9 (grain plus straw). Much of the range in values was attributed to variations among studies in soil, climate, and management conditions. The overall average RE of 55% compares well to other published global estimates of 50% by Smil (1999) and 57% by Sheldrick *et al.* (2002) and to estimates for the US and Canada of 56% (Howarth *et al.*, 2002) and 52% (Janzen *et al.*, 2003) as summarized in Ladha *et al.* (2005).

As mentioned earlier, measured NUE in production fields is often less than from research plots such as those summarized in Table 6. An example offered by Cassman *et al.* (2002) was that average RE for N fertilizer applied by rice farmers in the major rice producing regions of four Asian countries was 0.31 (179 farms) compared to 0.40 for field-specific management (112 farms) and 0.50-0.80 in well-managed field experiments. Balasubramanian *et al.* (2004) reported RE for N in cereals of 0.17-0.33 under current farming practices, 0.25-0.49 in research plots, and 0.55-0.96 as a maximum of research plots. In India, RE averaged 0.18 across 23 farms for wheat grown under poor weather conditions, but 0.49 across 21 farms when grown under good weather conditions (Cassman *et al.*, 2002).

Whether trials are in farmer fields or on experiment stations, high yield cereal systems tend to have higher AE than systems at lower yield levels. This should not be surprising since the higher nutrient requirements of crops at high yield levels is likely to exceed the nutrient supplying ability of unfertilized soils to a greater extent than at lower yield levels. This increases the difference between the yield of the fertilized crop and the yield of the unfertilized crop. Additionally, a crop with a faster nutrient accumulation rate may reduce the potential for nutrient losses from the production field. In the dataset shown in Figure 3, which is composed of diverse summaries of cereal NUE from around the world, approximately one third of the variability in AE for N could be explained simply by average grain yield. Yield variation in the dataset was due to a multitude of factors including climate, cropping system, soil properties and system management.

Table 6. Common NUE values for N for maize, wheat, and rice and for various world regions in 93 published studies conducted in research plots compiled by Ladha *et al.* (2005).

Crop or region	Number of observa-tions*	Avg fertilizer rate kg/ha	PFP** kg/kg	AE** kg/kg	RE** %	PE** kg/kg
Maize	35-62	123	72(6)	24(7)	65(5)	37(5)
Wheat	145-444	112	45(3)	18(4)	57(4)	29(4)
Rice	117-187	115	62(3)	22(3)	46(2)	53(3)
Africa	2-24	139	39(11)	14(6)	63(5)	23(6)
Europe	12-69	100	50(6)	21(9)	68(6)	28(6)
America	119-231	111	50(5)	20(7)	52(6)	28(8)
Asia	161-283	115	54(3)	22(2)	50(2)	47(3)
Avg/totals	**411**		**52(2)**	**20(2)**	**55(2)**	**41(3)**

*Range in number of observations across NUE indices.
**See Table 1 for definitions of each term; Value in parentheses is relative standard error of the mean (SEM/mean*100).

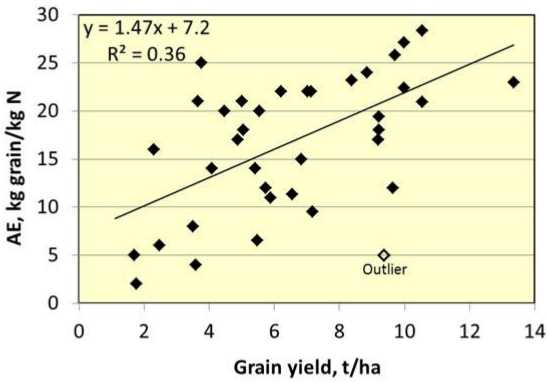


Figure 3. Influence of yield level of the fertilized treatment on typical AE for N reported in NUE summaries of farm and experiment station trials (n=37; data sources: Dobermann, 2007; Ladha *et al.*, 2005; Lester *et al.*, 2010; Liu *et al.*, 2011; Iowa State U. Agronomy Extension, 2011; Norton, R.M., Based on data from Long term NxP experiment in Australia – Dahlen, personal communication. 2011.; Singh *et al.*, 2007).

Trends in NUE for N

The considerable variability existing in NUE across regions and cropping systems manifests itself in temporal trends as well. Countries with intensive agriculture—such as US, Germany, UK, and Japan—generally show increasing NUE as a result of stagnant or even decreasing N use and increasing crop yields (Dobermann and Cassman, 2004). However, cropping systems within these countries can vary greatly in temporal trends. Understanding the whole-system context of NUE trends is critical to proper interpretation of those trends. Comparing PFP trends for N for maize and wheat in the US illustrates this point (Figure 4). Maize PFP increased approximately 50% from 1975 to 2005 while wheat PFP decreased 30% during this same time period, but then increased 30% from 2005 to 2010. The increase in maize PFP resulted mostly from improved genetics and crop, soil and nutrient management, which boosted yields by over 80% during this 30-year period. The net effect has been a linear increase in PFP for the last 25 years at a rate of 0.9 kg grain/kg N.

So, in the same country where growers had the same access to technology and innovation, why did wheat production not show a similar trend? The answer likely lies in differences between the dominant maize and wheat regions in cropping, tillage and fertilizing histories. The dominant wheat region has been undergoing a transition from management systems where the dominant N source was the tillage and fallow-induced mineralization of soil organic matter to a less tilled, more intensively cropped system that conserves or builds soil organic matter (Clay *et al.*, 2012). During this transition, wheat production became more dependent on fertilizer as an N source because of the reduction in mining of soil organic N, reducing apparent PFP and PNB (closer to 1). Comparison of PNB between Illinois (a maize-dominant state) and Montana (a wheat dominant state) shows unsustainably high N balances in the past for Montana which have been declining for the past 20 years, while Illinois had potential for closing the gap in the N balance (Table 7). More recently, the PFP trend for wheat has reversed due likely to the same factors that have been increasing PFP for maize systems (Figure 4).

Table 7. Partial nutrient balance for N in Illinois and Montana from 1987 to 2007 (IPNI, 2012a).

State	Dominant cropping system	Partial nutrient balance by year*				
		1987	1992	1997	2002	2007
Illinois	Maize-soybean	0.71	0.76	0.76	0.86	0.87
Montana	Wheat	1.35	1.33	1.00	1.04	1.01

*(Removal by harvest)/ (Fertilizer N + Recovered manure N + biological N fixation)

In countries where agriculture is in general undergoing intensification, PFP often shows decreasing trends because N fertilizer use increases at a faster rate than crop yields, though yields are also increasing (diminishing returns). Such is the case for wheat and maize in Argentina (Figure 5). As in the above case for wheat in the US, such declines in PFP are often accompanied with more sustainable PNB relationships where less mining of soil nutrients is occurring. If biological N fixation is not included in the N balances, such shifts can be misleading if the frequency of legumes in the rotation changes over time.

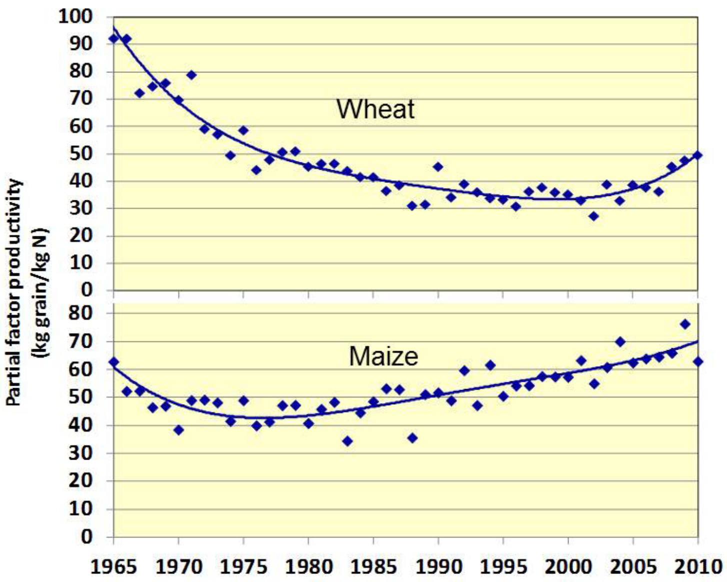


Figure 4. Partial factor productivity in the U.S. for fertilizer N used on maize and wheat from 1965 to 2010 (Adapted from USDA-ERS and USDA-NASS, 2011).

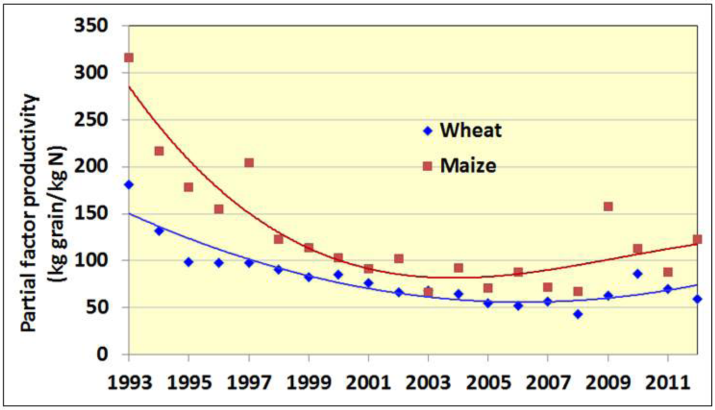


Figure 5. Partial factor productivity in Argentina for fertilizer N used on maize and wheat from 1993 to 2011 (Adapted from Garcia and Salvagiotti, 2009).

Developing a picture of regional trends in NUE around the world requires a systematic approach where all regions are estimated using a consistent protocol over time. We used that approach in developing Figures 6-7 for N and Figures 11-14 for P and K. The figures show NUE trends from 1983 to 2007 with each point representing the average of a 5-year period. Data availability (FAO, 2012; IFA, 2012) limited the indicators estimated to PFP and PNB. For nutrient inputs, only mineral fertilizer consumption was considered, excluding nutrients in livestock manure, atmospheric deposition, biological N fixation, and municipal wastes. The crops included from the FAO database were 38 fruits and vegetables, 9 cereals, 9 oil crops, 6 pulse crops, 5 root or tuber crops, and 5 other crops. The major category not included was forage crops that included crops such as silage maize, alfalfa and other hay. This category can be a large source of productivity and nutrient removal in regions where significant confinement livestock operations exist. For example, in the U.S. alfalfa and "other hay" account for over 15% of the total national P removal and over 40% of the K removal (PPI/PPIC/FAR, 2002). However, a proportion of the nutrients contained in forage crops will be returned to the fields as animal manure, but since both forage crops as output and manure as input are excluded from these NUE estimates, the error introduced should in most cases not be large at this broad regional scale. Since biological N fixation was not included for the input estimate, N removal by legumes was also not included for calculating PNB. This may skew regions with more legumes in the rotation towards higher PNB estimates. The nutrient concentration of harvested crops was based on literature values or research trial data (J. Kuesters (Yara), personal communication, 2012).

World PFP and PNB levels have shown a very slight increase over this 25-year period. Regional temporal trends in PFP for N are in most cases similar to PNB but trends among global regions clearly differ (Figures 6 and 7). Africa and Latin America in 1985 had by far the highest PFP and PNB values but with trends in opposite directions. The PFP data show that both these regions have extremely high productivity per unit of fertilizer N applied. However, the excessive PNB values for Africa show that it is becoming more dependent on non-fertilizer sources to balance crop removal of N, a precarious and unsustainable situation. In contrast, Latin America has maintained very high productivity per unit of N but has also moved towards a more sustainable nutrient balance.

In general, PNB and PFP for Africa, North America, Europe, and the EU-15 are trending upwards, while Latin America, India, and China are trending downwards. It is interesting to note that PNB for Europe during the last decade appears to have leveled off at around 70%, and that PNB for Latin America, India, and China has been declining at about the same rate for the 25-year period.

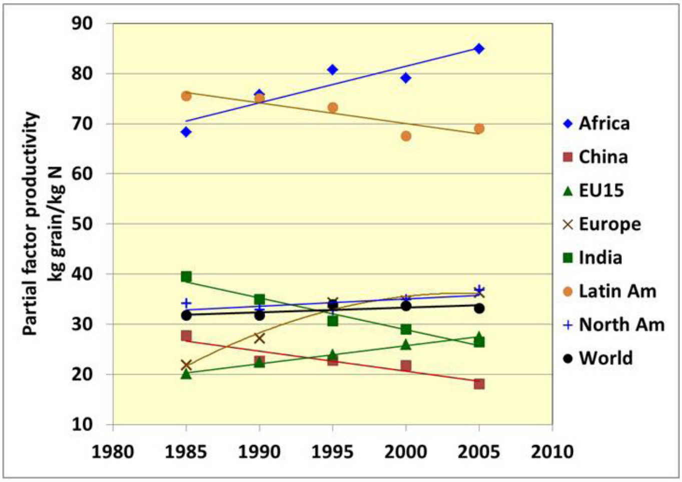


Figure 6. Partial factor productivity for N in global regions, 1983-2007.

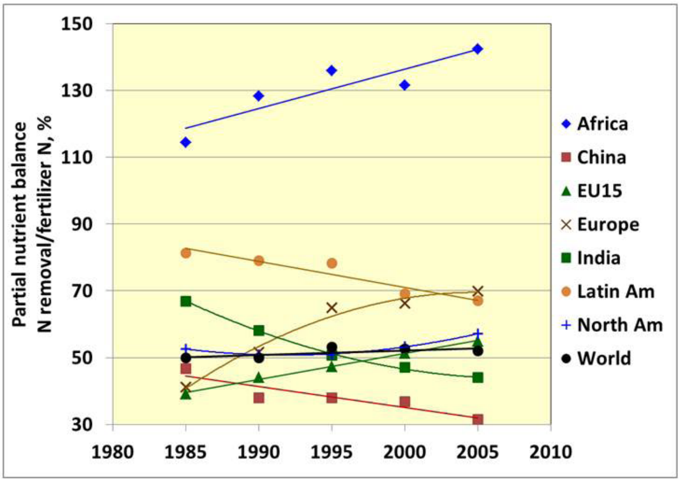


Figure 7. Partial nutrient balance for N in global regions, 1983-2007.

TRENDS IN NUE FOR P AND K

The major effects of soil properties and typically large legacy effects of previous management dominate NUE relationships for P and K. While most of the benefit and recovery of N addition occurs during the year of application, much of the benefit of P and K application on many soils occurs in subsequent years due to effects on soil fertility (Syers *et al.*, 2008). Appropriate evaluation of the current status and long-term trends of NUE for P and K needs to consider these residual effects. Short-term AE, RE and PFP for P and K are usually best interpreted within the context of current soil fertility status and associated PNB which indicates future soil fertility status if the current PNB remains unchanged.

Efficiency measures are greatly influenced by nutrient rate applied and by soil fertility. The P data summarized in Figure 8 are from research conducted in farmer fields in the Southern Cone of South America. Available P in all fields tested was lower than critical values, so a profitable response to P was expected. Agronomic efficiency was highest at low rates of P with the lowest rate (10 kg/ha) being common for soybean-based cropping systems of the region. This rate resulted in an average PNB of 1.85 where soil P levels would be depleted over time – a non-sustainable situation, but better than no fertilizer P at all. The higher rates generated somewhat lower AE values but had PNB values less than one where soil P would be maintained or increased with time. These data illustrate the value in considering multiple NUE indicators when assessing P management.

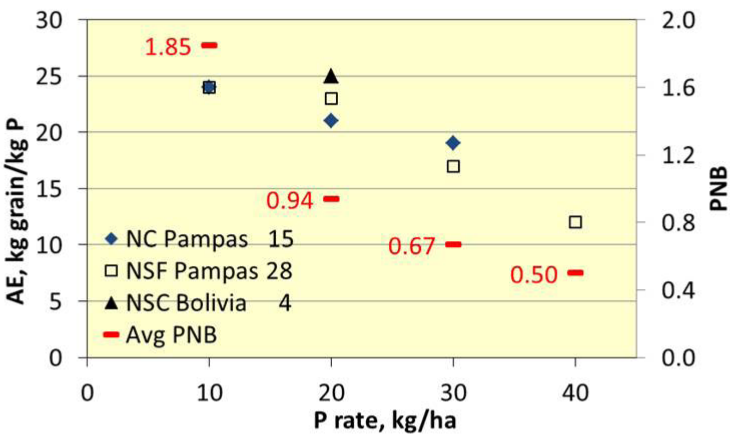


Figure 8. Influence of P rate on agronomic efficiency and partial nutrient balance of soybean in the Southern Cone of S. America (adapted from Ferrari *et al.*, 2005; H. Fontanetto, pers. comm.; and Terrazas *et al.*, 2011). Numbers for each group in the legend indicate the number of field trials (n).

The effect of soil P fertility on AE and RE is illustrated by wheat experiments from Argentina (Figure 9). Very high AE and RE are measured when soil fertility is well below critical levels and rapidly decline as soil fertility increases. Sustainability is associated with the intermediate AE and RE values observed when rates applied are close to removal, and soil fertility levels are maintained near the critical level.

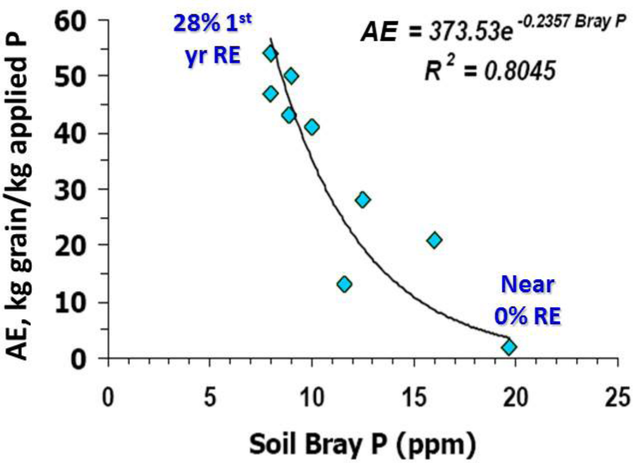


Figure 9. Influence of soil fertility on agronomic efficiency of P fertilizer in wheat experiments in Argentina (Garcia, 2004).

First year RE in field trials across Asia indicates P recoveries near 25% are typical in that region when fertilizer P is applied at recommended rates (Table 8). These studies were mostly on soils with low P fixation potential and were under favorable climate and management. Dobermann (2007) pointed out that though the average RE values were similar across studies, within-studies RE varied widely from zero to nearly 100%, but that 50% of all data fell in the 10 to 35% RE range. Such variability is to be expected due to the soil fertility and fertilizer rate effects discussed above.

Regional aggregate data can be used to evaluate the current status of P use and its impact on soil fertility temporal trends and to test the assumption that P balance impacts soil fertility. Soil tests conducted for the 2005 and 2010 crops in North America by private and public soil testing laboratories were summarized by IPNI. The change in median soil P levels for the 12 Corn Belt states over this 5-year period is plotted against the PNB for this same time period in Figure 10. Values of PNB above 0.94 resulted in declining soil P levels with substantial declines measured for the states with the most negative P balance. These data suggest that long-term PNB is a reasonably good indicator of the future direction of soil P fertility on non-P fixing soils. These relationships would likely differ for low P Oxisols and Andisols that typically have a high capacity to sorb or "fix" applied P; in these soils, a considerably lower PNB would be needed initially to build

Table 8. Average RE of P and K from mineral fertilizers in field trials with rice, wheat and maize in Asia. Values shown refer to recommended fertilizer rates or in the case of rice, those that were currently being applied by farmers (Dobermann, 2007; Liu *et al.*, 2006).

Crop, region or management	Number of field trials	Time period	P RE %	K RE %
*Rice in Asia; farmer's practice	179	1997-1998	24	38
*Rice in Asia; site-specific management	179	1997-1998	25	44
Wheat in India	22	1970-1998	27	51
Wheat in China	744	1985-1995	22	47
Maize in China	592	1985-1995	24	44

*China, India, Indonesia, Philippines, Thailand, and Vietnam.

soil P fertility until high affinity sorption sites are satisfied. Soils with large amounts of free calcium carbonate where precipitation reactions control P in solution, such as those in southern Australia, would also be exceptions where fertilizer P effectiveness in building soil fertility would remain low (McLaughlin, 2012).

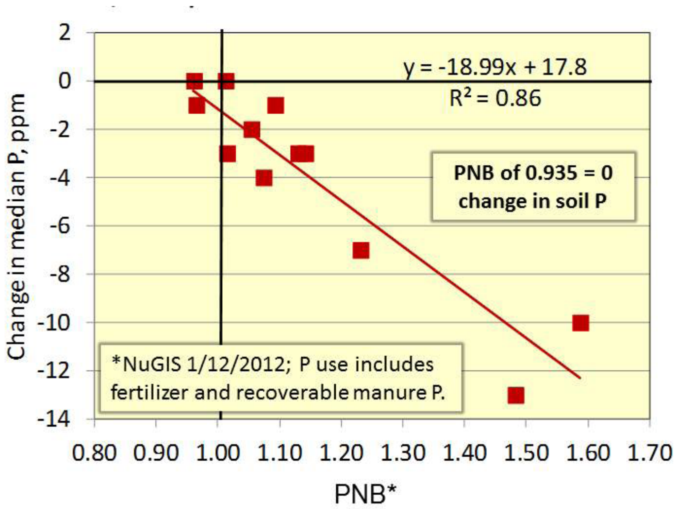


Figure 10. Change in median soil P level for 12 U.S. Corn Belt states as related to state PNB, 2005-2009 (updated from Fixen *et al.*, 2010).

The same approach used for N in developing a picture of regional trends in NUE around the world was used for P (Figures 11-12). As with N, world PFP and PNB for P have increased over this 25-year period with PFP in the last 5-year period (2003-2007) approaching 195 kg production per kg P and PNB approaching 70%. Regionally, Africa has markedly separated itself from all other regions in terms of both PFP and PNB. In the 1983-1987 period, Africa, India and China had nearly identical PNB levels for P of around 90%, but moved in opposite directions over the 25-year period with PNB in Africa doubling to over 180% while China and India dropped to approximately 50%. The PNB value for Africa indicates extreme mining of soil P while the values in China

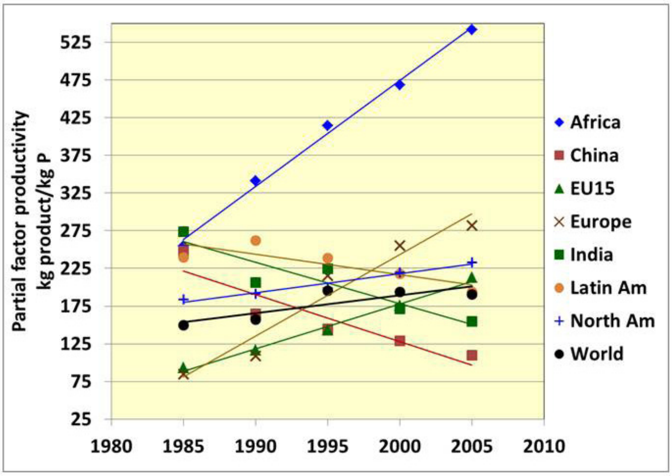


Figure 11. Partial factor productivity for P in global regions, 1983-2007.

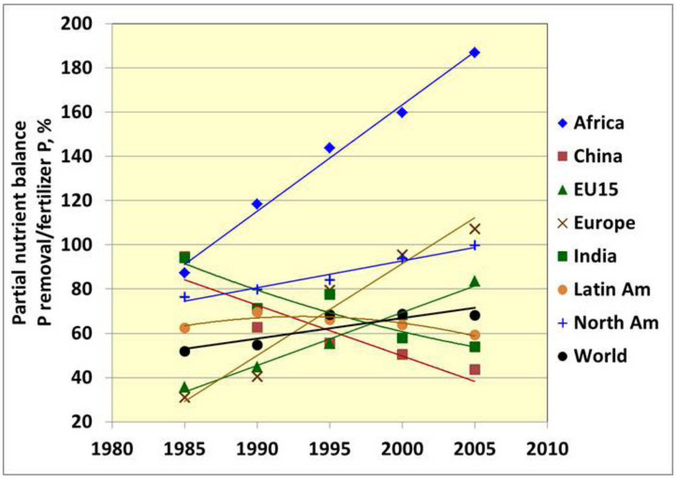


Figure 12. Partial nutrient balance for P in global regions, 1983-2007.

and India indicate that soil P levels should be increasing. These figures do not take into account changes in use of local rock phosphate but there is no evidence that this was significant. There is a paucity of reliable information on the use of rock phosphate as a direct application fertilizer in Africa, but various sources indicate that amounts used have remained very low. Average application rates at the country level are less than 0.5 kg/ha, even for countries with the highest application rates, indicating insignificant P contribution from rock phosphate sources.

In general, PNB and PFP for Africa, North America, Europe, and EU15 are trending upwards in P, while Latin America, India, and China are trending downwards, just as was the case for N. The absence of manure inputs in these NUE estimates impacts some regions much more than others and should be kept in mind in comparing the absolute values of the expressions. Differences in temporal trends (slopes of the lines) are likely to be more reliable.

Information on K use efficiency is more limited than either N or P. This is partly due to the environmentally benign nature of K where interest in efficiency is driven primarily by agronomic or economic factors. The result is less support for research and education on efficient use. First year recovery efficiency for K is generally believed to be higher than for P with the exception of some strongly-fixing clay soils. First year recovery of applied K has been reported in the range of 20% to 60% (Baligar and Bennet, 1986). Dobermann (2007) summarized average recovery efficiencies in field trials in Asia conducted prior to 1998 showing a range of 38 to 51% (Table 8). Jin (2012) summarized field trials on cereal crops in China, conducted from 2002 to 2006 using an omission plot design, and showed RE for K in the 25% to 32% range and average AE values of 8 to 12 (Table 4). In a more recent set of field trials on winter wheat in North-Central China, RE values for K were somewhat higher in the 34% to 44% range but AE values were again in the 8 to 10 range (Table 9; He *et al.*, 2012). The researchers indicated that the lower AE was likely due to K application rates exceeding the optimum for the soil K supply of individual site-years. Dobermann (2007) suggested that AE levels for K of 10-20 were realistic targets for cereals on soils that do not have high available K reserves.

The same approach used for N and P in developing a picture of regional trends in NUE around the world was used for K (Figures 13-14). As with N and P, world PFP and PNB for K have increased over this 25 year period, with PFP in the last 5-year period (2003-2007) approaching 145 kg of production per kg K and PNB approaching 140%. Globally, non-forage crops were removing 40% more K than was being applied as commercial fertilizer during this 5-year period. Regionally, across the 25-year period

Table 9. NUE of K from mineral fertilizers in three field trials with winter wheat in North-Central China. Average of 2007-2009 (He *et al.*, 2012).

Province	Average rate kg K/ha	RE %	AE kg/kg K
Hebei	81	43	10.2
Shandong	75	44	9.9
Shanxi	100	34	8.1

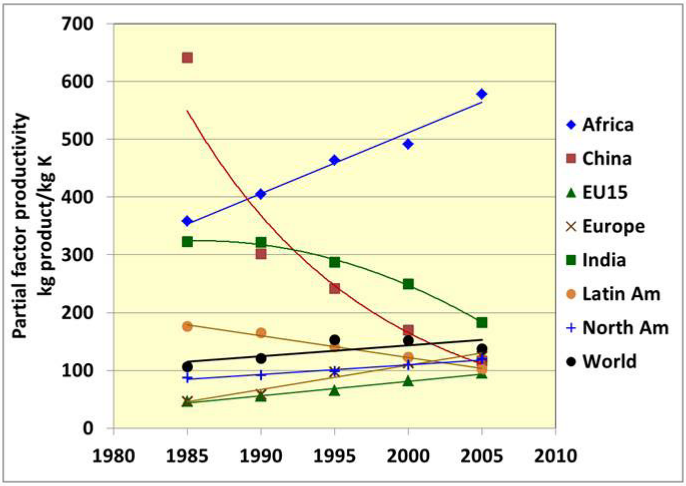


Figure 13. Partial factor productivity for K in global regions, 1983-2007.

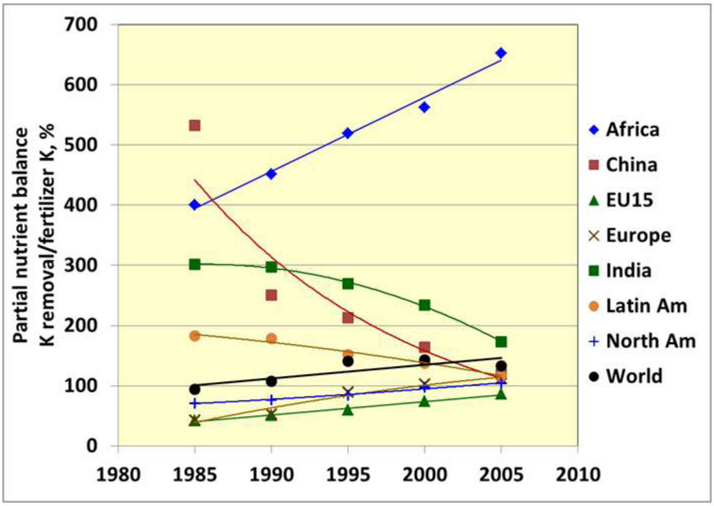


Figure 14. Partial nutrient balance for K in global regions, 1983-2007.

China underwent the greatest change in PNB, from removing more than 5 times as much K as was being applied to a PNB approaching 100% where K removal and fertilizer K application are equal. For Africa, both PFP and PNB increased markedly across the 25 years with a PNB in 2003-2007 indicating that crops removed more than 6 times the amount of K that was applied as fertilizer.

In general, PNB and PFP for Africa, North America, Europe, and EU15 are trending upwards in K, while Latin America, India, and China are trending downwards, just as was the case for N and P. The absence of forage crop production and K removal in these NUE estimates impacts some regions much more than others and should be kept in mind in comparing the absolute values of the expressions. Differences in temporal trends (slopes of the lines) are likely to be more reliable.

NUE, Water and a Look Forward

Numerous management and environmental factors interact to influence NUE including plant water status. In similar fashion, plant nutrient status can markedly influence water use efficiency (WUE). The rest of this book will explore the interaction between these two critical crop growth factors. Water use efficiency can be improved through nutrient management (Hatfield *et al.*, 2001) although in arid environments it can be important to balance pre- and post-anthesis growth to ensure adequate water remains to fill grain (van Herwaarden *et al.*, 1998). Nutrient availability affects aboveground biomass, canopy cover to reduce soil evaporation, plant residue production, nutrient dynamics in soil, and thereby improves crop growth and WUE (Maskina *et al.*, 1993; Halvorson *et al.*, 1999; Norton and Wachsmann, 2006). Adequate nutrient supply has shown to improve WUE in several crops (Smika *et al.*, 1965; Corak *et al.*, 1991; Campbell *et al.*, 1992; Varvel, 1994; Payne *et al.*, 1995; Davis and Quick, 1998; Correndo *et al.*, 2012).

Data from a lysimeter experiment conducted in Canada on spring wheat offers an excellent example of the relationship between NUE measures and WUE across a range of N levels (Figure 15). The study included both rainfed (dry) and irrigated (irr) treatments and shows the tremendous impact water status can have on yield response to N and the resulting AE and PNB. The lower graph in the figure shows that a water deficit markedly reduced both AE and PNB at all N levels, but that the efficiency reduction was considerably greater at the lower N levels. The upper graph in Figure 15 shows improvement in WUE as N levels increase for both the dryland and irrigated treatments. The lower apparent optimum N level for both yield and WUE for the irrigated treatment reflects higher NUE under irrigation shown in the bottom graph.

We draw this chapter to a close reinforcing a point made earlier – that the objective of nutrient use is to increase the overall performance of cropping systems. The data in Figure 15 illustrate that even though NUE generally decreased as N rates increased, the simultaneous increase in WUE and yield until an optimum N rate was attained improved over-all system performance. Efficient and effective use of either water or crop nutrients requires that both be managed at optimum levels for the specific system.

Continuous improvement in system performance is a fundamental objective in sustainable intensification. Such improvement is the product of management changes made by individual farmers for individual fields. Numerous efficiency and productivity enhancing nutrient management technologies and practices exist today and are described elsewhere in this book, but many are underutilized. Looking forward, locally defined guidelines for NUE indices that are specific for nutrients, soils, and cropping systems and that can be readily determined by farmers are needed. Such guidelines would help farmers identify what to measure and where improvement is most needed and may be easiest to advance. Guidelines would help define the need for and impact of changes in management on system performance.

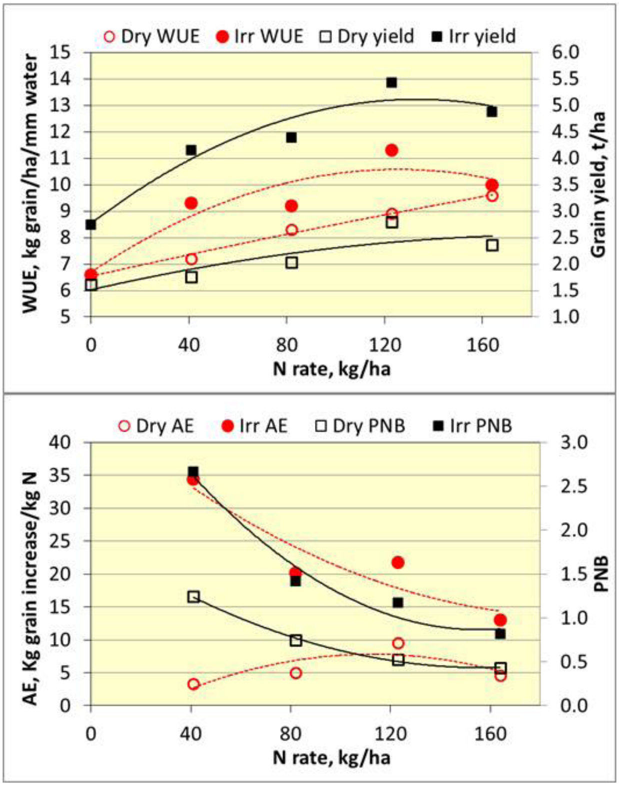


Figure 15. Influence of water status and N application on spring wheat yield and water and N use efficiency in a lysimeter experiment in Saskatchewan, Canada (Adapted from Krobel *et al.*, 2011 and Krobel *et al.*, 2012, based on original data from Campbell *et al.*, 1977a,b).

References

Balasubramanian, V., Alves, B., Aulakh, M. S., Bekunda, M., Cai, Z. C., Drinkwater, L., Mugendi, D., Van Kessel, C., and Oenema, O. 2004. Crop, environmental, and management factors affecting N use efficiency. In "Agriculture and the N Cycle: Assessing the Impacts of Fertilizer Use on Food Production and the Environment" (A. R. Mosier, J. K. Syers, and J. R. Freney, Eds.), pp. 19–33. SCOPE 65, Paris, France.

Baligar, V. and O. Bennet. 1986. Outlook on fertilizer use efficiency in the tropics. Fertilizer Research 10:83-96.

Barbieri, P., H. E. Echeverría, H. R. Saínz Rozas, and F. H. Andrade. 2008. Nitrogen Use Efficiency in Maize as Affected by Nitrogen Availability and Row Spacing. Agron. J. 100: 1094-1100.

Brentrap, Frank and Chritian Palliere. 2010. Nitrogen Use Efficiency as an Agro-Environmental Indicator. In Proceedings of the OECD Workshop on Agri-environmental Indicators, March 23-26. Leysin, Switzerland.

Campbell, C. A., Cameron, D. R., Nicholaichuk, W. and Davidson, H. R. 1977a. Effects of fertilizer N and soil moisture on growth, N content, and moisture use by spring wheat. Can. J. Soil Sci. 57: 289-310.

Campbell, C. A., Davidson, H. R. and Warder, F. G. 1977b. Effects of fertilizer N and soil moisture on yield, yield components, protein content and N accumulation in the aboveground parts of spring wheat. Can. J. Soil Sci. 57:311-327.

Campbell, C.A., R.P. Zentner, B.G. McConkey, and F. Selles. 1992. Effect of nitrogen and snow management on efficiency of water use by spring wheat grown annually on zero-tillage. Can. J. Soil Sci. 72:271-279.

Cassman, K. G., A Dobermann and D. T. Walters. 2002. Agroecosystems, nitrogen-use efficiency, and nitrogen management. Ambio 31(2):132-140.

Clay, David E., Jiyul Chang, Sharon A. Clay, James Stone, Ronald H. Gelderman, Gregg C. Carlson, Kurtis Reitsma, Marcus Jones, Larry Janssen, and Thomas Schumacher. 2012. Corn Yields and No-Tillage Affects Carbon Sequestration and Carbon Footprints. Agron. J. 104:763–770.

Corak, S.J., W.W. Frye, and M.S. Smith. 1991. Legume mulch and nitrogen fertilizer effects on soil water and corn production. Soil Sci. Soc. Am. J. 55:1395–1400.

Correndo A., M. Boxler, and F. Garcia. 2012. Oferta hídrica y respuesta a la fertilización en maíz, trigo y soja en el norte de la región pampeana argentina (Water availability and response to fertilization in maize, wheat, and soybean in the northern pampean region of Argentina). Proceedings XIX CLACS-XXII CACS. AACS. Mar del Plata, Buenos Aires.

Da Cunha, J. F., V. Casarin, and L.I. Prochnow. 2010. Nutrient balance in Brazilian Agriculture. In Boas Practicas Para Uso Eficiente de Fertilizantes. Vol. 2. IPNI, Piricicaba, Brasil.

Davis J. and J. Quick. 1998. Nutrient management, cultivar development and selection strategies to optimize watrer use efficiency. In Z. Rengel (ed.). Nutrient use in crop production. The Haworth Press, Inc. pp. 221-240.

Dobermann, A. 2007. Nutrient use efficiency – measurement and management. In "IFA International Workshop on Fertilizer Best Management Practices", Brussels, Belgium, p1-28.

Dobermann, A. and Cassman, K.G. 2005. Cereal area and nitrogen use efficiency are drivers of future nitrogen fertilizer consumption. Science in China 48:745-758.

Fageria, N.K., Balingar, V.C., and Li, Y.C. 2008. The role of nutrient efficient plants in improving crop yields in the twenty first century. Journal of Plant Nutrition 31:1121-1157.

FAO. 2009. FAOSTAT. FAO Statistics Division. On line at http://faostat.fao.org/

FAO. 2012. FAOSTAT. FAO Statistics Division. On line at http://faostat.fao.org/

Ferrari M., R. Melchiori and H. Fontanetto. 2005. Fósforo en soja: El aporte de la fracción orgánica lábil del suelo. Proceedings IV "Simposio de Nutrición Vegetal en SD", XIII Congreso de AAPRESID. Rosario, Argentina.

Fertilizers Europe. 2011. Product Stewardship Program. On line at http://www.productstewardship.eu.

Fixen, Paul E, Tom W. Bruulsema, Tom L. Jensen, Robert Mikkelsen, T. Scott Murrell,

Steve B. Phillips, Quentin Rund, and W. Mike Stewart. 2010. The fertility of North American soils, 2010. Better Crops 94(4): 6-8.

Garcia, F. 2004. Advances in nutrition management of wheat. Proceedings Wheat National Symposium. Mar del Plata, 13-14 May 2004. Federation of Grain Traders of Argentina.

Garcia, F. and Salvagiotti, F. 2009. Eficiencia de uso de nutrientes en sistemas agrícolas del Cono Sur de Latinoamerica. In J. Espinosa and F. Garcia (ed.). Proceedings of the Symposium on Nutrient Use Efficiency at the Latin American Congress of Soil Science, pp 35-46. San Jose, Costa Rica. IPNI.

Glenn J.C., Gordon TJ, Florescu E. 2008. The Millenium Project: State of the Future. World Federation of UN Associations, Washington, DC.

Halvorson, A.D., C.A. Reule, and R.F. Follett. 1999. Nitrogen fertilization effects on soil carbon and nitrogen in a dryland cropping system. Soil Sci. Soc. Am. J. 63:912–917.

Hatfield J., T. J. Sauer, and J. H. Prueger. 2001. Managing soils to achieve greater water use efficiency: A review. Agron. J. 93:271–280

He, Ping, Jiyun Jin, Hongting Wang, Rongzong Cui, and Chunjie Li. 2012. Yield responses and potassium use efficiency for winter wheat in North-Central China. Better Crops 96(3):28-30.

Howarth, R.W., Boyer, E.W., Pabich, W.J., and Galloway, J.N. 2002. Nitrogen use in the United States form 1961-2000 and potential future trends. Ambio 31: 88-96.

IFA (International Fertilizer Industry Association). 2012. IFA Statistics. http://www.fertilizer.org/ifa/HomePage/STATISTICS.

Iowa State Univ. Agronomy Extension. 2011. Corn nitrogen rate calculator. http://extension.agron.iastate.edu/soilfertility/nRate.aspx. Accessed Feb. 2011; USDA-NASS. 2003-2011.

IPNI. 2012a. A Nutrient Use Information System (NuGIS) for the U.S. Norcross, GA. On line at http://www.ipni.net/nugis.

IPNI. 2012b. 4R Plant Nutrition: A Manual for Improv¬ing the Management of Plant Nutrition (T.W. Bruulsema, P.E. Fixen, G.D. Sulewski, eds.), International Plant Nutrition Institute, Norcross, GA, USA.

IRRI (International Rice Research Institute). 2012. Underground solution to starving rice plants. On line at http://irri.org/index.php?option=com_k2&view=item&id=12275:underground-solution-to-starving-rice-plants&lang=en

Janzen, H.H., Beauchemin, K.A., Bruinsma, Y., Cambell, C.A., Desjardins, R.L. Ellert, B.H. and Smith, E.G. 2003. The fate of nitrogen in agroecosystems: An illustration using Canadian estimates. Nutr. Cycl. Agroecosyst. 67:85-102.

Jin, Jiyun. 2012. Changes in the efficiency of fertilizer use in China. J. Sci. Food Agric. 92:1006-1009.

Krobel1, R., C.A. Campbell, R. P. Zentner, R. Lemke, H. Steppuhn, R.L. Desjardins and R. De Jong. 2011. Nitrogen and phosphorus effects on water use efficiency of spring wheat grown in a semi-arid region of the Canadian prairies. Can. J. Soil Sci. 92: 573-587.

Krobel1, R., C.A. Campbell, R.P. Zentner, R. Lemke, R.L. Desjardins and Y. Karimi-Zindashty. 2012. Effect of N, P and cropping frequency on nitrogen use efficiencies of spring wheat in the Canadian semi-arid prairie. Can. J. Plant Sci. 92:141-154.

Ladha, J.K., Pathak, H., Krupnick, T.J., Six, J., and van Kessel, C. 2005. Efficiency of fertilizer nitrogen in cereal production: retrospects and prospects. Advances in Agronomy 87:85-156.

Lester, D.W., C.J. Birch and C.W. Dowling. 2010. Fertilizer N and P application on two Vertosols in northeastern Australia - Grain N uptake and yield by crop/fallow combination, and cumulative grain N removal and fertilizer N recovery in grain. Crop and Pasture Science 61: 24-31.

Liu, Mingqiang, Zhenrong Yu, Yunhui Liu, and N. T. Konijn. 2006. Fertilizer requirements for wheat and maize in China: the QUEFTS approach. Nutr Cycl Agroecosyst. 74:245-258.

Liu, Xiaoyan, Ping He, Jiyun Jin, Wei Zhou, Gavin Sulewski, and Steve Phillips. 2011. Yield gaps, indigenous nutrient supply, and nutrient use efficiency of wheat in China. Agron. J. 103:1452-1463.

Maskina, M.S., J.F. Power, J.W. Doran, and W.W. Wilhelm. 1993. Residual effects of no-till crop residues on corn yield and nitrogen uptake. Soil Sci. Soc. Am. J. 57:1555–1560.

McLaughlin, Mike J. 2012. Improving P fertilizer use efficiency – prospects and problems. Proceedings of the Latin America Congress of Soil Sci. April 16-20, 2012. Mar del Plata, Argentina.

Mikkelsen, Rob, Tom L. Jensen, Cliff Snyder, and Tom W. Bruulsema. 2012. Chapter 9. Nutrient Management Planning and Accountability. In 4R Plant Nutrition: A Manual for Improv¬ing the Management of Plant Nutrition (T.W. Bruulsema, P.E. Fixen, G.D. Sulewski, eds.), International Plant Nutrition Institute, Norcross, GA, USA.

Norton, R.M. and N.G. Wachsmann. 2006. Differences in crop water use in southeastern Australia. Aust. J. Agric. Res. 57:257-267.

Payne, W.A., L.R. Hossner, A.B. Onken, and C.W. Wendt. 1995. Nitrogen and phosphorus uptake in pearl millet and its relation to nutrient and transpiration efficiency. Agron. J. 87:425–431.

PPI/PPIC/FAR. 2002. Plant nutrient use in North Ameri¬can agriculture. PPI/PPIC/FAR Technical Bul. 2002-1. Norcross, GA.

Sheldrick, W.F., Syers, J.K., Lindgard, J. 2002. A conceptual model for conducting nutrient audits at the national, regional, and global scales. Nutr. Cycl. Agroecosyst. 62:61-72.

Singh, Y., Singh, B., Ladha, J. K., Bains, J. S., Gupta, R. K., Singh, J. and Balasubramanian, V. 2007. On-farm evaluation of leaf color chart for need-based nitrogen management in irrigated transplanted rice in northwestern India. Nutr Cycl Agroecosyst. 78:167-176.

Smaling, E.M., Nandwa, S.M., Janssen, B.H. "Soil Fertility in Africa is at Stake." In: Sanchez, P., and Buresh, R. (eds.), Replenishing Soil Fertility in Africa. Madison, WI: Soil Science Society of America Special Publication no. 51, pp. 47-62, 1997.

Smika, D.E., H.J. Haas, and J.F. Power. 1965. Effect of moisture and nitrogen fertilizer on growth and water use by native grass. Agron. J. 57:483–486.

Smil, V. 1999. Nitrogen in crop production: An account of global flows. Global Biogeochem. Cycl. 13: 647-662.

Snyder, C.S. and Bruulsema, T.W. 2007. Nutrient use efficiency and effectiveness in North America: indices of agronomic and environmental benefit. International Plant Nutrition Institute, Norcross, GA. Ref # 07076.

Syers, J.K., A.E. Johnson, and D. Curtin. 2008. Efficiency of soil and fertilizer phosphorus use: Reconciling changing concepts of soil phosphorus behaviour with agronomic information. FAO Fert. Plant Nutr. Bull. 18. Food and Agriculture Organization of the United Nations, Rome.

Terrazas J., G. Guaygua, E. Juárez, M. Crespo, and F. García. 2011. Crop Responses to Fertilization in the Eastern Plains of Bolivia. Better Crops 95(4): 19-21.

Thompson, Helen. 2012. Food science deserves a place at the table – US agricultural research chief aims to raise the profile of farming and nutrition science. Nature, July 12.

Tilman, David, Christian Balzer, Jason Hill, and Belinda L. Befort. 2011. Global food demand and the sustainable intensification of agriculture. Proc. Nat. Acad. Sci. 108(50):20260–20264.

USDA-ERS. 2011. Fertilizer Use and Price. On-line >http://www.ers.usda.gov/data-products/fertilizer-use-and-price.aspx< (validated 7/11/2012).

USDA-NASS. 2011. Quick stats. On-line >http://quickstats.nass.usda.gov/< (Validated 7/11/2012).

van Herwaarden, A.F., J.F. Angus, R.A. Richards and G.D. Farquhar. 1998. "Haying-off", the negative grain yield response of dryland wheat to nitrogen fertilizer. II. Carbohydrate and protein dynamics. Aust. J. Agric. Res. 49:1083-1093.

Varvel, G.E. 1994. Monoculture and rotation system effects on precipitation use efficiency of corn. Agron. J. 86:204–208.
Zingore, S., H.K. Murwira, R.J. Delve and K.E. Giller. 2007. Soil type, management history and current resource allocation: Three dimensions regulating variability in crop productivity on African smallholder farms. Field Crops Research 101: 296-305.

Chapter 1. Nutrient/Fertilizer Use Efficiency: Measurement, Current Situation and Trends.
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