# Nutrient Use Efficiency


IPNI
International
Plant Nutrition
Institute

2009

# Proceedings of the Symposium **"Nutrient Use Efficiency"** presented by the International Plant Nutrition Institute (IPNI) at the XVIII Latin American Congress of Soil Science

**San José, Costa Rica**
**November 16-20, 2009**

**Editors**

**Dr. José Espinosa**
**Dr. Fernando García**

# FOREWORD

The International Plant Nutrition Institute (IPNI) considers benefits for the human family resulting from responsible management of plant nutrition as the general outcome of its programs. The anticipated economic, environmental, and social benefits from use of plant nutrients makes nutrient use efficiency a critical indicator of the success of nutrient management in agricultural systems. As the costs of nutrients climb, profitable use require high efficiency. As concerns about climate change, water quality, air quality, and biodiversity intensify, acceptable levels of nutrient loss from managed ecosystems require high efficiency from the lands we farm and high yields to reduce the need for farming fragile lands. And, 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, which some have estimated to be as much as a doubling of current production midway through this century.

These anticipated benefits from nutrient use clearly require efficiency to be a management objective, but they just as clearly require effectiveness in meeting production needs to be a critical objective. Indeed, increasing crop yields at a faster rate than has ever been accomplished in the past is a non-negotiable element of sustainable crop production. Future nutrient management must be both efficient and effective in delivering the anticipated benefits of nutrient use.

In this symposium, IPNI summarizes the state of the science of nutrient use efficiency for the Americas and the contemporary context within which nutrients must be managed. Since the principles of appropriate nutrient management are universal, the first part of the symposium focuses on general principles without geographic specificity. However, since best management practices which are the in-field manifestation of appropriate nutrient stewardship are site-specific, the second part of the symposium focuses on specific regions of Latin America.

Whether in the broad-acre regions of the Cerrado of Brazil or Pampas of Argentina or in the smallholder fields of Central American mountain villages, nutrient use efficiency will be of growing importance in the future. IPNI hopes that this symposium and the proceedings developed from it will be a useful tool in advancing efficient and effective nutrient management throughout Latin America.

Dr. Paul Fixen
Senior Vice President, Americas Group
and Director of Research, IPNI

## TABLE OF CONTENTS

# NUTRIENT USE EFFICIENCY IN THE CONTEXT OF SUSTAINABLE AGRICULTURE[1]

**Paul E. Fixen**

International Plant Nutrition Institute, pfixen@ipni.net

## Abstract

Considering the increasing societal demand for food, fiber and fuel, intense global financial stress, and growing concerns over impacts on water and air quality, simultaneous improvement of productivity and resource use efficiency, including nutrient use efficiency (NUE), is an essential goal for agriculture. Best management practices (BMPs) can be defined as actions applied to resources which have been demonstrated through research to provide the best known combination of economic, social, and environmental performance, the three pillars of sustainability. They are the basic tools for improving NUE while sustainably meeting the demands of society. For plant nutrients, BMPs are the in-field manifestation of the Four Rights (4Rs), application of the right nutrient source, at the right rate, in the right place, and at the right time. To truly be "right" they must be site-specific for the crop, field, and often for the zone within the field. Yet, the scientific foundation upon which 4R nutrient stewardship is built and that leads us to nutrient BMPs is universal. Therefore, though BMPs are site-specific, a global framework for developing, studying, and implementing them can facilitate nutrient management improvement within sustainable crop production systems.

## The Global Context of Contemporary Nutrient Management

Best management practices can be defined as actions applied to resources which have been demonstrated through research to provide the best known combination of economic, social, and environmental performance (IPNI, 2009). Other definitions have been offered with emphasis on certain aspects of BMPs including environmental protection (Sharpley et al., 2006; Tandon and Roy, 2004), saving money (Anonymous, 2006), optimizing growth and minimizing adverse environmental impacts (Lilly, 2009), or testing through farmer implementation (Griffith and Murphy, 1991). For plant nutrients, BMPs are the in-field manifestation of the Four Rights (4Rs), application of the right nutrient source, at the right rate, in the right place, and at the right time (Roberts, 2007; Bruulsema et al., 2009). To truly be "right" they must be site-specific for the crop, field, and often, for the zone within the field. Yet, the scientific foundation upon which 4R nutrient stewardship is built and that leads us to nutrient BMPs is universal. Therefore, though BMPs are site-specific, a global framework for developing, studying, and implementing them can facilitate nutrient management improvement (Fixen, 2007).

Because plant nutrients influence so many critical issues today within and beyond field boundaries, there is merit to reviewing the global context of contemporary nutrient management before delving into specifics. Three underlying factors that encompass many of the major issues humankind will be facing for the next several decades are human nutrition, carbon, and land (**Figure 1**). Two of these factors, carbon and land, were recently discussed in an inspiring paper presented by Dr. Henry Janzen at the International Symposium on Soil Organic Matter Dynamics (Janzen, 2009). Carbon issues include climate change, cheap energy, and bioenergy. Land issues include land use, soil quality, water use and quality, and waste disposal. Dr. Janzen astutely pointed out that soil organic matter is the common ground between these factors. The addition of human nutrition as a third factor brings into the picture the issues of food quantity, food quality, and food cost. Of critical importance in the discussion of nutrient management, is that a significant component of the common ground of all three of these huge factors is soil fertility and how the management of plant nutrients affects our food supply, our land, and the carbon cycle.

It has been estimated that the world will need twice as much food within 30 years (Glenn et al., 2008). That is equivalent to maintaining a proportional rate of increase of over 2.4% over that 30-year period. Sustainably meeting such demand is a huge challenge and will require close cooperation and understanding among disciplines, across geographies, and between public and private sectors. The magnitude of the challenge is appreciated when such a proportional rate of increase is 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 (**Figure 2**; FAO, 2009).

Sustainable nutrient management must support cropping systems that contribute to the economic, social, and environmental elements of sustainability. Considering the in-

[1]IPNI Symposium on Nutrient Use Efficiency at the Latin American Congress of Soil Science. San Jose, Costa Rica. November 16-20, 2009.

Figure 1. Underlying factors for the challenges of the coming decades.

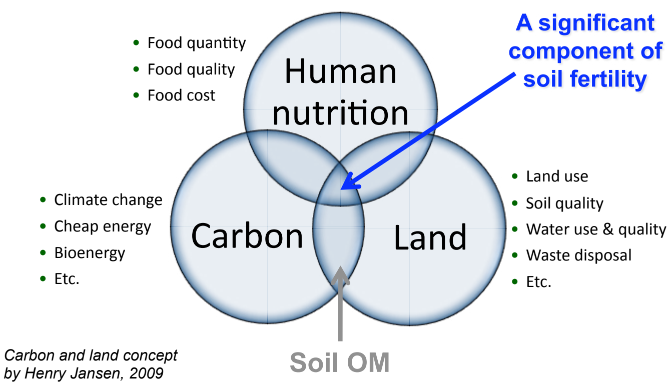
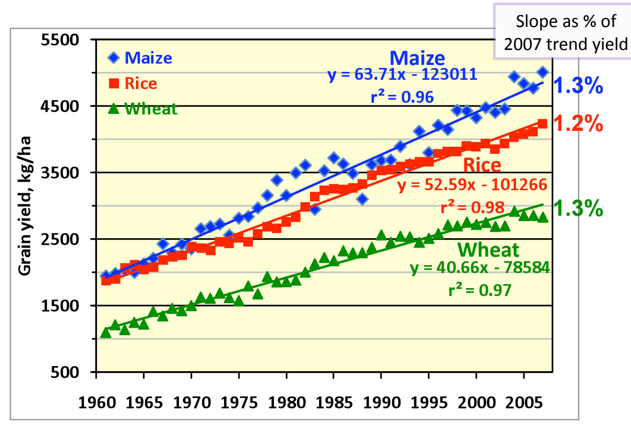



Figure 2. Global cereal yield trends, 1961-2007.




Data source: FAO, 2009.

creasing societal demand for food, fiber and fuel, intense global financial stress, and growing concerns over impacts on water and air quality, simultaneous improvement of productivity and resource use efficiency, including nutrient use efficiency (NUE), is an essential goal for agriculture (Fixen, 2009a). Globalization has linked the challenges of increasing productivity and improving efficiency. Striving to improve efficiency without also increasing productivity simply increases pressure to produce more on other lands and those lands may be less suited to efficient production. Likewise, the squandering of resources to maximize productivity resulting in increased environmental impact puts more pressure on other lands to reduce environmental impact while meeting productivity needs.

Dr. Norman Borlaug recently called for a second "Green Revolution" that would be a more extensive rebellion against world hunger. He has expressed hope that the U.S. Food Security Act of 2009 could help lead the way. Sen. Richard Lugar, cosponsor of the bill, described the bill as a "more focused effort on our part to join with other nations to increase yields, create economic opportunities for the rural poor and broaden agricultural knowledge ..."(TAMU, 2009).

Earlier this year the U.S. Secretary of Agriculture stated "So we have to figure out how to do more with what we have. And that means an investment by USDA in concert with the private sector and land grant universities in figuring out how we can be more productive; how we can use less natural resources to produce these crops (USDA, 2009)."

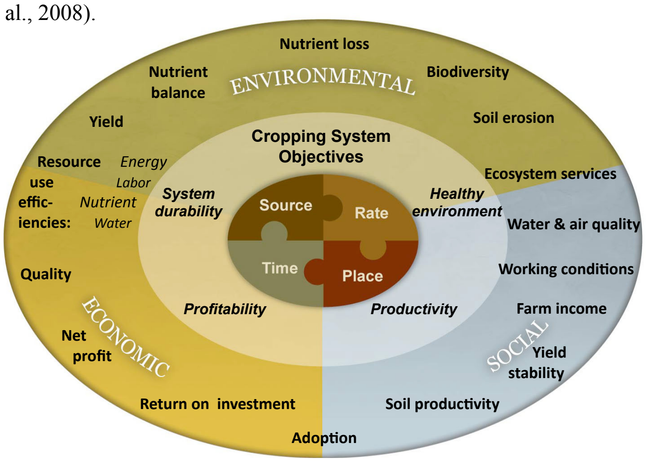
The need for simultaneous increase of productivity and efficiency has clearly caught the attention of private industry. Monsanto (2008) has announced its commitment to develop by 2030 seeds that can double crop yields and reduce by one-third the amount of key resources, e.g., nitrogen and water, required to grow crops. Dupont (2009) has stated that thanks to its global research efforts, Pioneer is on track to increase corn and soybean yields by 40% by 2018, more than doubling the current annual rate of gain.

As in the past, future yield increases will not likely be solely due to genetic improvement but due to changes in several interacting production factors. For example, evaluation of the grain yields of corn hybrids released in the U.S. Corn Belt by Pioneer Hi-Bred International from 1930 to 2007 by year of hybrid release shows an annual rate of yield increase of only 0.014 t/ha at 10,000 plants/ha, but 0.107 t/ha at 79,000 plants/ha (Hammer et al., 2009). Similarly, adjustments in nutrient management practices as changes in genetics, plant density, and other cultural practices occur must be considered, with or without genetic alterations specifically targeting NUE. With the greater nutrient levels contained in higher yielding crops, and potentially more nutrient inputs necessary to replace the increased harvest removal, more nutrients will be at risk of loss from the system. So, the challenge of increasing both productivity and NUE increases. These factors have spurred efforts by the fertilizer industry to develop a family of enhanced efficiency fertilizers designed to more effectively deliver nutrients to crop plants while minimizing loss to the environment (Motavalli et al., 2008).

## The 4R Nutrient Stewardship Framework

For plant nutrition science to work well across disciplines, between public and private sectors, and across geographies, a common framework for viewing goals, practices, and performance is likely helpful. The seeds for such a framework were planted more than 20 years ago by Thorup and Stewart (1988) when they wrote "This means using the right kind of fertilizer, in the right amount, in the right

Figure 3. The 4R nutrient stewardship framework (after Bruulsema et al., 2008).




place, at the right time." **Figure 3** is a schematic representation of the 4R nutrient stewardship framework based on the concepts described by Thorup and Stewart (Bruulsema et al., 2008). At its core are the 4Rs – application of the right nutrient source at the right rate, right time, and right place. Best management practices are the in-field manifestation of these 4Rs.

The 4Rs are shown within a cropping system circle because they integrate with agronomic BMPs selected to achieve crop management objectives. Those farm-level crop management objectives contribute toward the larger economic, social and environmental goals of sustainable development. Furthermore, the 4Rs cannot truly be realized if problems exist with other aspects of the cropping system. Darst and Murphy (1994) wrote about the lessons of the U.S. Dust Bowl coupled with a multitude of research studies showing the merits of proper fertilization and other new production technology, catalyzing the fusing of conservation and agronomic BMPs. Science and experience clearly show that the impact of a fertilizer BMP on crop yield, crop quality, profitability and nutrient loss to water or air is greatly influenced by other agronomic (plant population, cultivar, tillage, pest management, etc.) and conservation practices (terracing, strip cropping, residue management, riparian buffers, shelter belts, etc.). Practices defined with sufficient specificity to be useful in making on-farm fertilizer use decisions, often are "best" practices only when in the appropriate context of other agronomic and conservation BMPs. A fertilizer BMP can be totally ineffective if the cropping system in which it is employed has other serious inadequacies.

The focus of this paper is on fertilizer use efficiency and associated fertilizer BMPs in contrast to nutrient BMPs, which is a broader topic. Nutrient management BMPs include livestock manure management and practices designed to capture nutrients before they are lost from the agro-ecosystem, such as cover crops, crop residue management, contour planting, field buffer strips and controlled drainage. These practices, that extend beyond efficient fertilizer management, are often essential for farmers to accomplish many of the objectives of nutrient management, especially those related to the environment. Focus on fertilizer BMPs here should not be taken as diminishing the importance of these other nutrient management practices. As mentioned earlier, failure to follow BMPs in these other areas can cause failure of fertilizer BMPs as well.

Around the outer circle of the 4R framework are examples of performance indicators. A balanced complement of these indicators can reflect the influence of nutrient BMPs on accomplishment of the goals of sustainable development. The framework shows clearly that system sustainability involves more than yield and NUE, though these are critical indicators. Stakeholder input into performance indicators is an essential part of the process.

## Determining NUE as a Performance Indicator in a BMP Framework

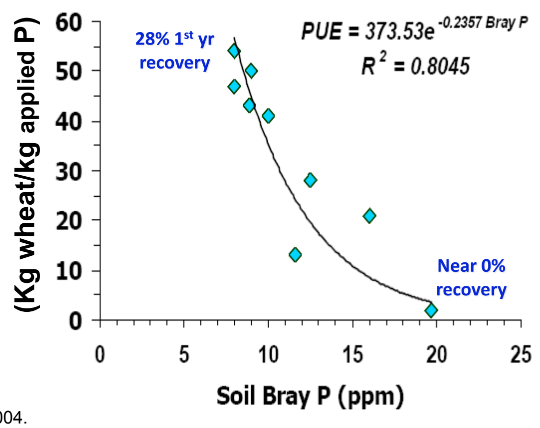
Seeing NUE as one of many system performance indicators, including system productivity, offers insights into NUE measurement. Methods of NUE determination and their interpretation were recently reviewed by Dobermann (2007) and an applied summary was developed by Snyder and Bruulsema (2007). Dobermann also summarized the current status of NUE for major crops around the world, pointing out that single year average recovery efficiency for N in farmer's fields is often less than 40% but that the best managers operated at much higher efficiencies. Dobermann used a six-year study in Nebraska on irrigated continuous maize managed at recommended and intensive levels of plant density and fertilization to illustrate how NUE expressions can be easily misinterpreted (**Table 1**). In this study comparing a higher yielding, intensively managed system to the recommended system for the region, partial factor productivity (PFP; grain produced per unit of N applied)

**Table 1. N use efficiency in a long-term experiment with irrigated continuous maize managed at recommended and intensive levels of plant density and fertilization.**

| 2000-2005, Lincoln, Nebraska | Recommended | Intensive |
|---|---|---|
| Average maize yield, t/ha/yr | 14.0 | 15.0 |
| Fertilizer N input, kg N/ha | 1005 | 1495 |
| N 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 prod.,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 |

Dobermann, 2007.

**Figure 4. Influence of soil fertility on agronomic efficiency of P fertilizer in wheat experiments in Argentina.**




Garcia, 2004.

indicated that the intensive system was considerably less N efficient than the recommended system. Because fertilizer N contributed to the buildup of soil organic matter in the intensive system, when the change in soil N was taken into account, the two systems had nearly the same system level N efficiency. Dobermann pointed out that over time, this increased soil N supply should eventually reduce the need for fertilizer N, resulting in an increase in PFP. Such effects are particularly noteworthy for researchers striving to increase productivity with more intensive methods where new practices are being implemented that differ from the history for the research plot area or farm field. If cultural practice changes are such that soil organic matter is no longer in steady state, temporary net nutrient immobilization or mineralization can impact apparent NUE.

Nutrients such as P and K that readily accumulate in plant available forms in most soils pose special challenges when evaluating systems based on both productivity and NUE. **Figure 4** which summarizes P studies on wheat in Argentina illustrates the challenge (Garcia, 2004). The lower the soil fertility level, the higher was agronomic efficiency ((treatment yield- control yield)/nutrient rate). At the lowest soil P levels, P recovery efficiency (by the difference method) was 28% and declined to near zero as soil P approached non-yield-limiting levels. So, neither agronomic efficiency nor recovery efficiency by the difference method alone offers direct indication of whether P efficiency is appropriate for the system. The same is true for K. Productivity must also be considered.

In a recent global review of the efficiency of soil and fertilizer P use, Syers et al. (2008) indicated preference for calculating recovery efficiency by the balance method where P removed by the crop is divided by P applied. This expression is also referred to as partial nutrient balance or the removal to use ratio (Snyder and Bruulsema, 2007). Syers et al. concluded that for many soils that are in the critical soil P range (where crop yields are maximized), application of P at rates similar to what is removed in the crop will maintain those soil levels, indicating very high P recovery efficiency, often approaching or exceeding 90%. Verification of this approach does require continual measurement of soil fertility status which may not be possible in developing countries.

The removal to use approach to NUE estimation suggested by Syers et al. for P can also be applied to a geographic region. The data required for such calculations were recently reported by Vitousek et al. (2009) for N and P in low-input corn-based systems of western Kenya, wheat/corn double crop systems of north China, and corn/soybean systems of the Midwest US. Removal to use ratios have been added to the nutrient balance data they reported in **Table 2**. These three regions have markedly different ratios. Some observations follow.

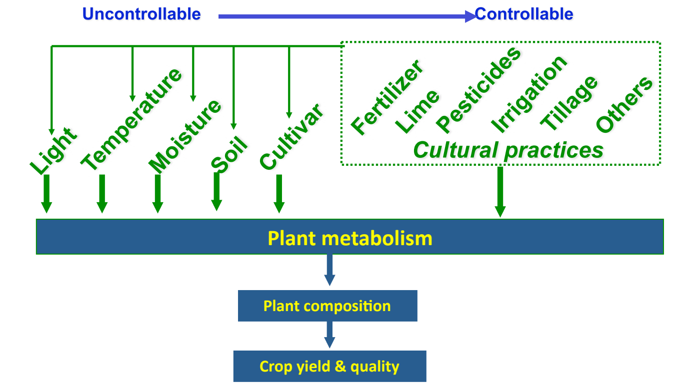
- Over 8 times as much N is being removed in the Kenya systems than is being applied indicating that substantial N is being mined from the soils of the region, reducing the nutrient capital for future crops. In this case, NUE for N could be said to be 800% but the system is clearly unsustainable because many other performance indicators are far from acceptable.
- Removal to use ratios for the north China systems are both rather low suggesting that NUE could probably be improved through management changes. However, soil P status and its direction would need to be known as well as other N-related performance indicators before a more definite interpretation could be made.
- The midwest U.S. ratio for N is close to one, but here again whether that is appropriate or not depends on other N performance indicators including change in soil organic matter and specific N losses from the cropping systems. The ratio for P seems too high to be sustainable,

**Table 2. Inputs and outputs of N and P by managed pathways.**

| | Nutrient balances by region (kg/ha/yr) | | | | | |
|---|---|---|---|---|---|---|
| | Western Kenya (low input corn-based) | | North China (wheat/corn double crop) | | Midwest U.S. (corn/soy-bean) | |
| **Inputs and outputs** | **N** | **P** | **N** | **P** | **N** | **P** |
| Fertilizer | 7 | 8 | 588 | 92 | 93 | 14 |
| Biological N fixation | | | | | 62 | |
| Total agronomic inputs | 7 | 8 | 588 | 92 | 155 | 14 |
| Removal in grain and/or beans | 23 | 4 | 361 | 39 | 145 | 23 |
| Removal in other harvested products | 36 | 3 | | | | |
| Total agronomic outputs | 59 | 7 | 361 | 39 | 145 | 23 |
| Agronomic inputs minus harvest removals | -52 | +1 | +227 | +53 | +10 | -9 |
| **Removal to use ratio** | **8.4** | **0.88** | **0.61** | **0.42** | **0.94** | **1.64** |

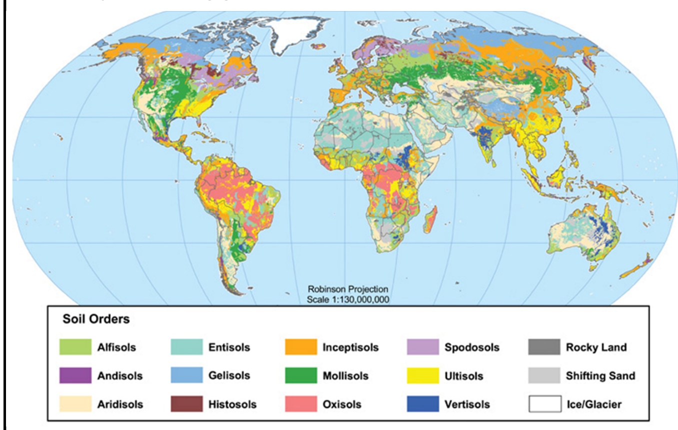
Vitousek et al., 2009.

Figure 5. A complex system involving uncertainty.




After Beaufils, 1973

Figure 6. Soil classification can help define global domains with relevancy for refining general principles.




USDA, 2005.

yet this is a region in Illinois with a history of rather high soil P levels so such ratios could possibly be maintained for a significant number of years before productivity would decline. These N and P ratios reported for Illinois are very similar to independent estimates for Illinois by IPNI in an on-going evaluation of nutrient budgets in the U.S.

In all three of the above cases, the BMP framework is a useful tool for interpreting a specific performance indicator and pointing out the need to consider a balanced set of performance indicators when evaluating any system.

## Universality of Science-based Framework Principles

The 4R Nutrient Stewardship Framework is based on universal scientific principles that lead to nutrient BMPs. The principles serve as a guide to practices with the highest probability of supporting the management objectives of the cropping system and more broadly, the economic, social, and environmental goals of sustainable development. Common cropping system management objectives usually involve the productivity, profitability, durability, and environmental impact of the system (IFA, 2009).

It is important that fertilizer BMPs be presented as offering the **highest probability** of accomplishing the objectives rather than **guaranteeing** that the objectives will be accomplished. **Figure 5** illustrates the complexity of the cropping systems in which fertilizers are managed. Many of the factors markedly influencing plant growth, metabolism and nutrient needs are uncontrollable, resulting in considerable uncertainty in what the right source, rate, place, or timing will be at a specific site in a specific growing season. The best the manager can do is employ those available practices that have the highest probability of meeting objectives. Science allows us to define those practices.

The science-based principles of nutrient cycles, soil fertility, and plant nutrition are indeed universal. How they manifest themselves in specific management practices varies with climate, soils, access to technology, local economic conditions, and culture. However, the global soil map (**Figure 6**; USDA, 2005) reminds us that there is predictable order in soils that can be invaluable in helping define the global inference space associated with specific research findings having the potential to reshape BMPs and their refinement to local conditions. In the "flat world" described by Thomas Friedman (2005), global plant nutrient users can be connected to the global plant nutrition science … in near real time.

Universal scientific principles relevant to each of the four rights and to all fertilizer nutrients follow (Bruulsema et al., 2008).

### Fertilizer management:

- Be consistent with understood process mechanisms.
- Recognize interactions with other cropping system factors.
- Recognize interactions among nutrient source, rate, time, and place.
- Avoid detrimental effects on plant roots, leaves and seedlings.
- Recognize effects on crop quality as well as yield.
- Consider economics.

### Source:

- Supply nutrients in plant-available forms.
- Suit soil physical and chemical properties.
- Recognize synergisms among nutrient elements and sources.

- Recognize blend compatibility.
- Recognize benefits and sensitivities to associated elements.
- Control effects of non-nutritive elements.

Rate:

- Use adequate methods to assess soil nutrient supply.
- Assess all indigenous nutrient sources available to the crop.
- Assess crop demand for nutrients.
- Predict fertilizer use efficiency.
- Consider soil resource impacts.
- Consider rate-specific economics.

Time:

- Assess timing of crop uptake.
- Assess dynamics of soil nutrient supply.
- Recognize timing of weather factors influencing nutrient loss.
- Evaluate logistics of field operations.

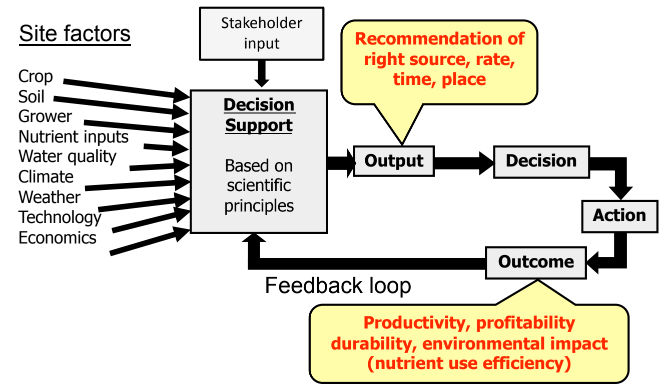
Place:

- Recognize root-soil dynamics.
- Manage spatial variability within fields and among farms.
- Fit needs of tillage system.
- Limit potential off-field transport of nutrients.

## Adaptive Nutrient Management for Improved NUE

Scientific truths are seldom permanent but change as scientific knowledge grows. Likewise, BMPs are dynamic and evolve as science and technology expands our understanding and opportunities, and practical experience teaches the astute observer what does or does not work under specific local conditions. Thorup and Stewart in the same paper quoted earlier wrote in 1988: "Research performed on university farms and by professional researchers on farmer's fields are extremely valuable. However, they do not necessarily relate directly to every farmer's fields. Soils have tremendous variability from one farm to another. Cultural practices vary markedly from one farmer to another. Even climatic factors can vary significantly over very short distances. All of these factors affect possible responses from fertilizer programs. All of this means that the farm operator who survives in the 1990s and beyond is going to have to experiment a little on his own, keep accurate records, be flexible to government programs, world market price fluctuations and soil and water conservation needs." Though the term did not yet exist, these agronomists were describing adaptive nutrient management.

**Figure 7. The site-specific nature of BMPS makes adaptive management important in their identification.**




After Fixen, 2005.

**Figure 7** (Fixen, 2005) illustrates schematically the process of adaptive nutrient management where science-based decision support facilitates the integration of multiple site-specific factors and input from stakeholders into a recommendation for right source, rate, time, and place. That recommendation leads to a management decision and associated action. With time the productivity, profitability and environmental impacts are known and resource use efficiency, including NUE, can be determined. With additional time the durability of the system utilizing the practices in place becomes evident and that collective experience is fed back into the decision making process, allowing for better future predictions of right source, rate, time, and place. In theory, every pass through the cycle has the potential to result in better decisions and more appropriate actions.

Consideration of the many possible site factors that can influence the exact nature of fertilizer BMPs reveals why local flexibility is critically important. For example (Fixen, 2007):

- Crop factors usually include yield potential and crop value and in some cases tissue nutrient concentrations or leaf color as several crop cultural practices can influence nutrient management;
- Soil factors often involve soil nutrient supplying indices or other physical, chemical or biological properties that influence nutrient cycling and crop growth;
- Grower factors might include land tenure, availability of

capital, opportunity costs, the experience/education of the farmer and local advisers, or philosophical nutrient management objectives;

- Nutrient input factors incorporate information on sources available such as commercial forms or nutrient-containing wastes, fertilizer costs and application costs;
- Water quality factors might include restrictions on nutrient application in riparian zones or near other water bodies or considerations due to ground water quality;
- Climate factors drive some types of model-based support systems while others respond to near real-time weather information for a specific growing season and short term weather forecasts;
- What relevant technologies are available at the site in question may certainly influence definition of best practices. For example, in-season refinement of N application rate and timing may be best accomplished with electronic sensor technology in some cases and leaf color charts in others.
- Economic factors beyond those tied directly to the grower can impact nutrient decisions.

The dynamic nature of site-specific fertilizer BMPs and importance of local flexibility present a significant challenge to mandated fertilizer BMP adoption. Mandates may speed adoption, but may also result in loss of beneficial fine-tuning based on local expertise and the adaptive management process.

## Stewardship of Nutrient Resources

The stewardship responsibilities of agriculture include the wise use of the raw materials from which commercial fertilizers are produced. Development and implementation of fertilizer BMPs focused on the 4Rs are called for not only for short-term economic and environmental reasons, but also for the wise stewardship of the non-renewable nutrient resources upon which food, feed, fiber, and fuel production depend.

Industry and USGS reports indicate that world reserves and resources for N, P, K and S appear adequate for the foreseeable future. The United States Geological Survey (USGS) estimates world reserves at nearly 100 years under current market conditions and nearly 300 years under improved conditions (Fixen, 2009b). Other studies have indicated that global P resources in terms of today's production could be as much as 700 years (Sheldon, 1987). Potash reserves have been estimated by USGS to be 235 years under current conditions and more than 500 years if they improve (Fixen, 2009b). However, some recent studies have suggested that phosphate rock production will peak around the year 2030 after which a rapid increase in cost will occur due to scarcity (Cordell et al., 2009). A recent commentary in Scientific American has referred to a phosphorus famine as "the threat to our food supply" (Vaccadi, 2009). Clearly great uncertainty exists in these estimates.

Regardless of the exact levels of nutrient reserves and resources, nutrient costs will rise over time as the most easily extracted materials are consumed. Therefore, an added incentive for continued refinement and implementation of fertilizer BMPs is that the resulting gain in NUE will slow the increase in fertilizer costs. Wise stewardship of nonrenewable nutrient resources is a critical responsibility for the agriculture industry.

## References

Anonymous. 2006. Take the BMP Challenge. On line at http://www.bmpchallenge.org/Nutrient_BMP_CHALLENGE.htm

Beaufils, E.R. 1973. Diagnosis and recommendation integrated system(DRIS). A general scheme for experimentation and an extension of the physiological diagnosis techniques. Soil Sci. Bull. No. 1, University of Natal, Pietermaritzburg.

Bruulsema, Tom, Jerry Lemunyon, and Bill Herz. 2009. Know your fertilizer rights. Crops and Soils 42(2):13-18.

Bruulsema, TW, Witt, C, García, Fernando, Li, Shutian, Rao, T Nagendra, Chen, Fang, and Ivanova, S. 2008. A global framework for fertilizer BMPs. Better Crops 92(2):13-15.

Cordell, Dana, Jan-Olof Drangert, and Stuart White. 2009. The story of phosphorus: Global food security and food for thought. Global Environmental Change 19: 292-305.

Darst, B.C. and L.S. Murphy. 1994. Keeping agriculture viable: Industry's viewpoint. J. Soil and Water Conservation 46(2):8-14.

Dobermann, A. 2007. Nutrient use efficiency – measurement and management. 2007. In Fertilizer Best Management Practices. International Fertilizer Industry Assoc., Paris, France.

Dupont. 2009. Agriculture is up to global productivity challenge (News release 4/16/2009). On line at http://www.pioneer.com/web/site/portal/menuitem.3dd40d3fde802efa4c844c84d10093a0/

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

Fixen, P.E. 2005. *Decision Support Systems in Integrated Crop Nutrient Management*. Proceedings No. 569. International Fertilizer Society, York, UK. 1-32.

Fixen, P.E. 2007. Can we define a global framework within which fertilizer best management practices can be adapted to local conditions. *In* Fertilizer Best Management Practices, First Edition. IFA, Paris.

Fixen, P.E. 2009a. Maximizing (productivity and efficiency) in contemporary agriculture. *In* Proceedings of the International Plant Nutrition Colloquium XVI. U. of California – Davis. On-line at http://repositories.cdlib.org/ipnc/xvi/1291

Fixen, P.E. 2009b. World fertilizer nutrient reserves. Proceedings of the Soil Fertility 2009 Symposium, Rosario, Argentina. May 12-13. International Plant Nutrition Institute, Buenos Aires (Spanish).

Friedman, Thomas L. 2005. *The World is Flat: a Brief History of the Twenty-first Century*. Farrar, Straus and Giroux, New York.

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.

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

Griffith, W.K. and L.S. Murphy. 1991. The development of crop production systems using best management practices. Potash & Phosphate Institute.

Hammer GL, Zhanshan D, McLean G, Doherty A, Messina C, Schussler J, Zinselmeier C, Paszkiewicz S, Cooper M. 2009. Can changes in canopy and/or root system architecture explain historical maize yield trends in the U.S. Corn Belt? Crop Sci. 49:299-312.

IFA. 2009. The Global "4R" Nutrient Stewardship Framework for Developing and Delivering Fertilizer Best management Practices. International Fertilizer Industry Association. Paris.

IPNI. 2009. 4R Nutrient Stewardship Style Guide. International Plant Nutrition Institute. Ref. # 09068. June, 2009. Norcross, GA.

Janzen, Henry, 2009. SOM research in 2030: what scientists then might ask of us now. In Program and Abstracts for the International Symposium on Soil Organic Matter Dynamics:Land Use, Management and Global Change. Colorado State University, Fort Collins. p. 114.

Lilly, J. Paul. 1991. Soil Facts: Best management practices for agricultural nutrients. North Carolina Cooperative Extension Service. AG-439-20.

Monsanto. 2008. New Initiative Focuses on Water Quality Improvement in the Mississippi River Basin and Gulf of Mexico (News release 12/8/2008). Company News On-Call: http://www.prnewswire.com/comp/114341.html/.

Motavalli, P. P., Goyne, K. W., and Udawatta, R. P. 2008. Use of enhanced-efficiency fertilizers for improved agricultural nutrient management: Introduction to the symposium. Online. Crop Management doi:10.1094/CM-2008-0730-01-PS.

North Carolina State University (NCSU). 2007. Best management Practices. On line at http://www.ces.ncsu.edu/gaston/Environment/bmps.htm#farm

Roberts, Terry L. 2007. Right product, right rate, right time, right place. The foundation of BMPs for fertilizer. IFA Workshop on Fertilizer Best Management Practices (FBMPs), 7-9 March 2007, Brussels, Belgium.

Sheldon, R.P. 1987. Industrial minerals – with emphasis on phosphate rock. P. 347-361. In D.J. McLaren and B.J. Skinner (ed.). Resources and World Development. John Wiley & Sons, New York.

Sharpley, A.N., T. Daniel, G. Gibson, L. Bundy, M Cabrera, T. Sims, R. Stevens, J. Lemunyon, P. Kleinman, and R. Parry. 2006. Best Management Practices to Minimize Agricultural Phosphorus Impacts and Water Quality. USDA-ARS 163, Washington, D.C.

Snyder, C.S. and T.W. Bruulsema. 2007. Nutrient Use Efficiency and Effectiveness in North America: Indices of Agronomic and Environmental Benefit. International Plant Nutrition Institute, Norcross, GA.

Syers, J.K., A.E. Johnston and D. Curtin. 2008. Efficiency of Soil and Fertilizer Phosphorus Use. Food and Agriculture Organization of the United Nations, Rome.

TAMU. 2009. Borlaug calls for second "Green Revolution". Texas A&M University Agricultural Communications. Mar. 16, 2009.

Tandon, H.L.S. and R.N. Roy. 2004. Integrated Nutrient Management – A Glossary of Terms. FAO-UN and the Fertilizer Development and Consultation Organization, Rome, Italy.

Thorup, J.T. and J.W.B. Stewart. 1988. Optimum fertilizer use with differing management practices and changing government policies. *In* Proceedings of the 25th Anniversary Symposium of Division S-8, Advances in Fertilizer

Technology and Use. Published for the Soil Sci. Soc. A. *by* the Potash & Phosphate Institute (now the International Plant Nutrition Institute, Norcross, GA).

USDA. 2005. Global Soil Regions Map. USDA-NRCS. On line at http://soils.usda.gov/use/worldsoils/mapindex/order.html

USDA. 2009. TRANSCRIPT: Keynote Address by Agriculture Secretary Tom Vilsack at the U.S. Department of Agriculture's Agricultural Outlook Forum, Feb. 26, 2009. Release No. 0048.09. U.S. Department of Agriculture, Washington, DC.

Vaccari, D.A. 2009. Phosphorus: A looming crisis. Scientific American, June 3.

Vitousek, P.M., R. Naylor, T. Crews, M. B. David, L. E. Drinkwater, E. Holland, P. J. Johnes, J. Katzenberger, L. A. Martinelli, P. A. Matson, G. Nziguheba, D. Ojima, C. A. Palm, G. P. Robertson, P. A. Sanchez, A. R. Townsend, and F. S. Zhang. 2009. Nutrient imbalances in agricultural development. Science 324:1519-1520.

# NITROGEN USE EFFICIENCY: GLOBAL CHALLENGES, TRENDS AND THE FUTURE[1]

**C.S. Snyder**

Nitrogen Program Director, International Plant Nutrition Institute

## Abstract

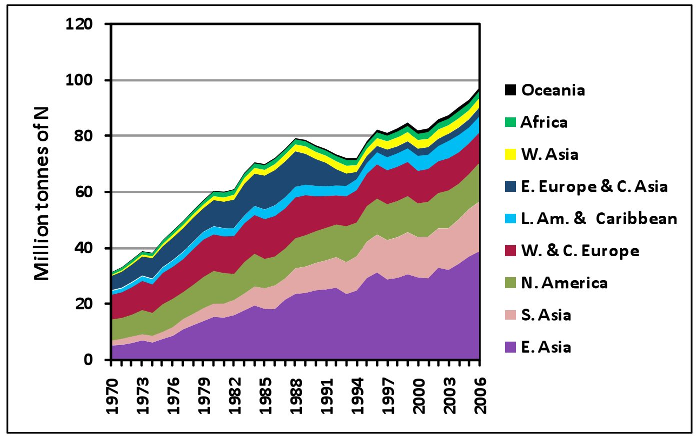
Human demands for food, fiber, and biofuel production are rising with the world's population. Nitrogen (N) fertilization is expected to increase to satisfy these growing human needs. Risks of increased environmental N losses via leaching, runoff, volatilization and denitrification, which may be associated with increased global N use, are a concern to agricultural stakeholders, environmentalists, and public policymakers. Future fertilizer N management decisions must be increasingly based on economic, social, and environmental goals which are identified by diverse stakeholders. On-farm N use efficiency and effectiveness can be improved, through better management of N sources, rates, timing, and placement. A goal of improving N use efficiency by 25% from current levels is considered achievable in the United States and may also be within the reach of many developing countries. Progress is being made to optimize crop production per unit input of fertilizer N with some cereal crops in many regions, and some environmental indicators reflect these improvements. By raising N use efficiency and effectiveness through better cropping system and fertilizer N management, societal food fiber and biofuel demands may be met while also protecting air, water, and soil resources for current and future generations. Sustainable success will depend on commitments to the basic science of N management and the outreach and education of fertilizer N consumers.

## Introduction

World food, fiber, and biofuel demands associated with population growth require an emphasis on increased global crop production. As fertilizer nitrogen (N) consumption increases, global concerns about environmental consequences are increasing (Beman et al. 2005; Galloway and Cowling 2002; Galloway et al. 2002, 2003, 2004, 2008; Schlesinger 2009).

Because much of the growth in fertilizer N use is expected to occur in the tropical and sub-tropical regions of the world (**Figure 1**), and because future N deposition is expected to increase in tropical regions (Galloway and Cowling 2002), there is a heightened need to ensure that fertilizer N use efficiency and effectiveness by cropping systems are managed optimally, especially in these regions.

**Figure 1** - Global fertilizer N consumption (IFA Statistics 2009)

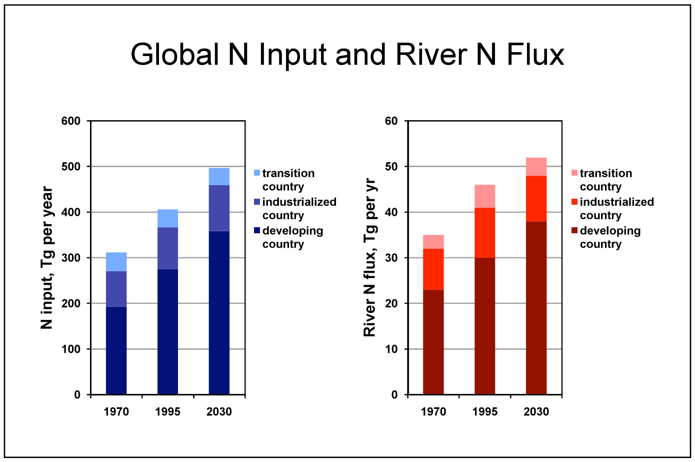



Gruber and Galloway (2008) noted the importance of "nitrogen-carbon-climate" interactions and raised questions about the availability of N and its effect on C sequestration in the Earth's biosphere and the implications for climate change mitigation. Considering the linkage between N and carbon (C) in soil organic matter, and the linkage of the N cycle to the C cycle, it is clear that agronomists and soil scientists have important roles and significant challenges in addressing both agronomic and environmental pressures associated with a growing world population: from both short term economic and long-term sustainability perspectives. More agricultural research is needed to better quantify cropping system and N management effects on the magnitude of losses from the soil-crop system via the principal N loss pathways (volatilization, leaching, denitrification, runoff).

## N Losses via River N Flux

Since pre-industrial times, the flux or discharge of N to coastal waters by rivers around the world has doubled; rising from roughly 21 Tg/yr to over 40 Tg/yr, based on simulation modeling by Green et al. (2004). River export of N ranges from 7 to 13% of total N inputs in developing, industrialized, and transition countries, according to Bouwman et al. (2005), but total N inputs and total river N export have increased since 1970 and are projected to continue to increase through 2030 (**Figure 2**); especially in developing countries. Total N inputs to the landscape by natural sources, which was suggested as mostly from biological N fixation, dominates the N budgets in Latin America (72%), Africa (79%), and Oceania (79%); while anthropogenic N sources were cited as greater than natural sources in Europe/FSU (59%), North America (61%), and Asia (74%) (Boyer et al. 2006).

**Figure 2** – Estimated global total N input and river N flux in developing, industrial, and transition countries (adapted from Bouwman et al. 2005).




Using an empirical model, Boyer et al. (2006) estimated that global riverine N transport may exceed 80% of the river load, but they also reported that N delivery to coastal waters varies greatly among countries. Subramanian (2008) stated that there is a great deal of uncertainty in the river N flux because "according to the river database(GEM/UNESCO), only about 40% of rivers have reliable dissolved N values, whereas for organic nitrogen it is even lower, at about 33%". Studies of watershed loading and river system N export in South Asia were urgently called for by Subramanian (2008) because rivers in South Asia export at least six percent of the global water runoff, 10% of the global sediment flux, and fertilizer N use is increasing. Channelization of many river systems for transportation and for reduced risks of local flooding has altered the streamflow and processing of N in many streams and river systems (Goolsby et al. 1999). Increased annual and seasonal water flow and N flux, associated with climate change-induced increases in rainfall amounts and intensity, may present elevated threats to the health and function of coastal waters, beyond current eutrophication and hypoxia risks (Rabalais 2009).

## N Losses via Nitrous Oxide Flux

Among the three prominent greenhouse gases (GHGs) - carbon dioxide ($CO_2$), methane ($CH_4$), and nitrous oxide ($N_2O$), $CO_2$ is the dominant $CO_2$-equivalent GHG emitted from all economic sectors at 77%. Methane emissions represent 15% and nitrous oxide emissions represent 8% of global $CO_2$-equivalent GHG emissions (EPA 2006). These three GHGs also differ in their effectiveness in trapping heat and in their turnover rates in the atmosphere. Unit masses of $CH_4$ and $N_2O$ are considered to have 23 and 296 times the global warming potential (GWP), respectively, as a unit of $CO_2$ for a 100-year timeframe (IPCC 2001).

The U.S. EPA (2006) estimated the emissions of non-$CO_2$ (i.e. $N_2O$ and $CH_4$) GHGs on an individual country basis. China, Brazil, India, and the U.S. showed the largest absolute increases in projected non-$CO_2$ GHG emissions between 1990 and 2020 (**Figure 3**).

**Figure 3** – Regional contributions to total global non-$CO_2$ GHG emissions (EPA 2006)

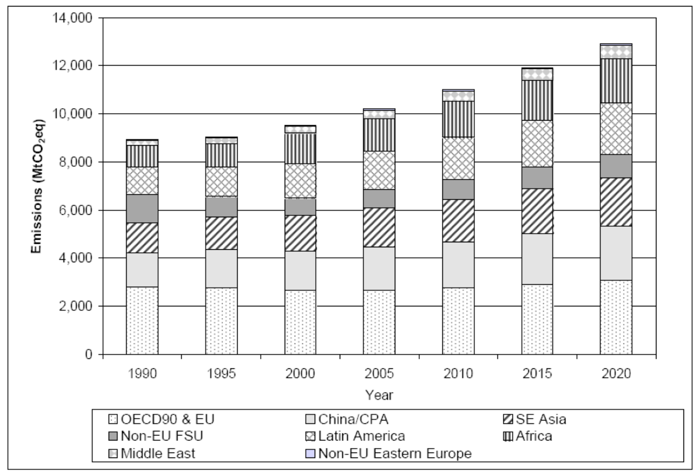



*Figure note*: OECD is the Organization for Economic Cooperation and Development (which includes the U.S. and Canada), EU is the European Union, and FSU is the Former Soviet Union.

Agriculture contributed 32% (13,360 Tg or million tonnes) of the world's 41,382 Tg of $CO_2$-equivalent GHG emissions in 2000. Sixty-three percent of agriculture's GHGs were considered non-$CO_2$ GHGs (EPA, 2006). Baumert et al. (2005) reported that about 15% of the world's GHGs were associated with agricultural activities in 2004. Countries having the largest portion of the global agricultural sector GHG emissions in 2000 were: China-18%, India-11%, EU-25-9%, U.S. -9%, and Brazil-8% (Baumert et al. 2005). Countries which each contributed approximately two percent of the world's portion of agricultural GHG emissions included: Pakistan, Indonesia, Argentina, Russia, France, Australia, and Germany. All other countries had one percent or less of the global agricultural GHG emissions (Baumert et al. 2005). Soil management activities were thought to contribute 40% of the global agricultural sector GHGs, with an even division (45-46% each) between $N_2O$ and $CH_4$ emissions, on a CO2 -equivalent basis (Baumert et al.

2005). Emissions of GHGs are known to vary, depending on the land use and its management (Bellarby et al. 2008; Snyder et al 2009).

In developed countries, agriculture is generally a relatively small contributor to total GHG emissions among all economic sectors, but it may account for a larger percentage of the total GHG emissions in developing countries. For example, the agricultural sector accounted for 24% (~ 412 Tg $CO_2$ - equivalent) of India's GHG emissions in 2005 (Garg et al., 2006), but less than 7% (~413 Tg $CO_2$ - equivalent) of national GHG emissions in the United States (U.S.) in 2007 (EPA, 2009). Nitrous oxide emissions from agricultural soils were projected to increase through 2020 (**Figure 4**), with China, Latin America, Africa, and Southeast Asia accounting for the largest portion of the increases (EPA 2006). The factors expected to cause the increased emissions of $N_2O$ were: crop and livestock production and increased fertilizer N use, necessary to meet the growing requirements of the human population.

**Figure 4** – Nitrous oxide ($N_2O$) emissions from agricultural soils, 1990-2020 (EPA 2006)

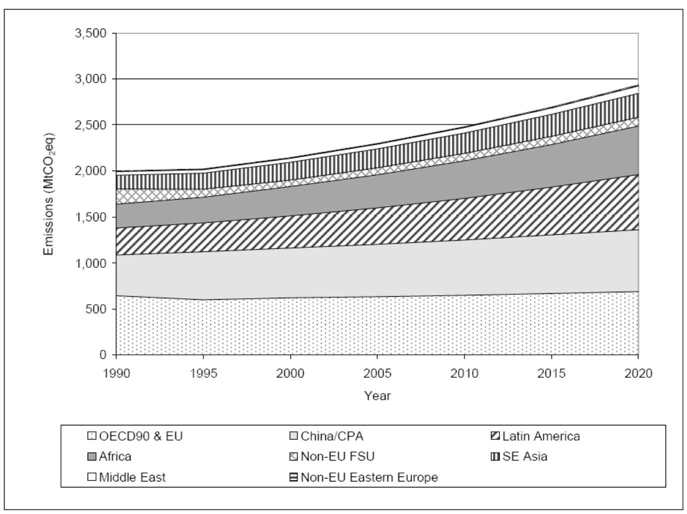



*Figure note*: OECD is the Organization for Economic Cooperation and Development (which includes the U.S. and Canada), EU is the European Union, and FSU is the Former Soviet Union

## N Losses via Ammonia Volatilization

Urea is the dominant fertilizer N source used in the world, and volatilization loss of $NH_3$ from urea can exceed 45% of the urea-N applied under surface-applied, warm, moist field conditions (Watson, 2005). Volatilization of ammonia from N fertilizers has been estimated at 18% in developing countries, based on N sources used and environmental conditions, while volatilization losses in industrialized countries was estimated at 7% (Bouwman et al. 2002). The global median $NH_3$ loss was 14% for fertilizer N and estimated to be 23% for manure N.

When urea-containing fertilizer sources or manure are applied on the soil surface and not incorporated, especially in humid environments, a large portion of the N can be lost to the air as $NH_3$ (Follett 2001; Kissel 1988). Ammonia volatilization losses have exceeded 50% of the applied urea N in transplanted rice paddy systems in Asia. Peak losses occurred in rice less than 3 weeks old after transplanting, within 7-10 days after N application, but losses were much lower during panicle initiation and ranged from 10-15% of the applied urea N (Buresh and Witt 2008). In drill-seeded flood-irrigated rice systems in the southern U.S., $NH_3$ volatilization can exceed 30% of the applied N if flooding is delayed for up to 14 days after urea is surface broadcast. Most of this $NH_3$ loss occurs within 7-10 days after N fertilization if flooding is delayed, but immediate flooding after fertilization to incorporate the urea in dry-seeded flood-irrigated rice systems minimizes loss and optimizes crop recovery of applied N (Griggs et al. 2007).

Although subsurface banding of urea is a relatively common practice in drier environments for small grain production (e.g. northern Great Plains in the U.S. and Canada), Rochette et al. (2009) found that increased hydrolysis of urea can occur in dry acidic soils, raise soil pH (up to 8.7) around the banded urea, and increase the $NH_3$ loss. Losses of $NH_3$ were 16% of the applied N with broadcast soil-incorporated urea and 27% with subsurface banded urea on a plowed and harrowed silty clay loam soil near Quebec City, Canada. Losses of $NH_3$ were 5% or less when polymer coated urea or urea with a urease inhibitor were surface broadcast, but not incorporated (Rochette et al. 2009).

The results of these $NH_3$ volatilization studies from contrasting environments emphasize the importance of the principal factors governing potential $NH_3$ volatilization, and the need for locally-developed, site-specific management recommendations for urea-containing fertilizers.

## Reducing reactive N losses to the environment

Galloway et al. (2004) estimated that of the ~268 Tg N/yr of new reactive N (Nr; essentially all N that is not $N_2$) that entered continents, ~81 Tg N/yr was transferred to the marine environment via atmospheric deposition and river N flux, while ~12 Tg N/yr was emitted as $N_2O$ to the atmosphere. They also estimated that of the remaining 175 Tg Nr/yr that remained, ~115 Tg N/yr is converted to $N_2$ and about 60 Tg N/yr may be accumulating in terrestrial systems.

Galloway et al. (2008b) have suggested four principal ways

**Table 1** –Selected terms for nitrogen use efficiency (NUE) (after Snyder and Bruulsema 2007)

| NUE term | Calculation | Reported Examples |
|---|---|---|
| **$PFP_N$**<br>Partial factor productivity | Y/F | 40 to 80 units of cereal grain per unit of N |
| **$AE_N$**<br>Agronomic efficiency of applied N | $(Y-Y_0)/F$ | 10 to 30 units of cereal grain per unit of N |
| **$PFP_N$**<br>Partial N balance (removal to use ratio) | $U_H/F$ | 0 to greater than 1.0- depends on native soil fertility and fertility maintenance objectives<br><1 in nutrient deficient systems (fertility improvement)<br>>1 in nutrient surplus systems (under-replacement)<br>Slightly less than 1 to 1 (system sustainability) |
| **$RE_N$**<br>Apparent crop N recovery efficiency | $(U-U_0)/F$ | 0.3 to 0.5 – N recovery in cereals – typical<br>0.5 to 0.8 – N recovery in cereals – best management |

F - amount of N applied (as fertilizer, manure, etc.)
Y - yield of harvested portion of crop with applied N
$Y_0$ - yield of control with no applied N
$U_H$ - N content of harvested portion of crop
U - total N uptake in aboveground crop biomass with applied N
$U_0$ - total N uptake in aboveground crop biomass with no N applied

to reduce the amount of reactive N in the environment: 1) control NOx emissions from fossil-fuel combustion using maximum feasible reductions (provides 18 Tg N/yr decrease), 2) increase nitrogen-uptake efficiency of crops (decreases Nr creation by about 15 Tg N/yr), 3) improve animal management strategies (decreases Nr creation by about ~15 Tg N/yr, and 4) provide half the 3.2 billion people living in cities with access to sewage treatment (converts 5 Tg N/yr to $N_2$ ). When combined these four approaches were reported to have the potential to reduce reactive N in the environment by 53 Tg N/yr, or about 28% of the reactive N created since 2005.

Schlesinger (2009) estimated that river N flux was 27 Tg/yr in pre-industrial times and is now near 61.5 Tg/yr, and suggested that "policy makers should focus on increasing nitrogen-use efficiency in fertilization, reducing transport of reactive N to rivers and groundwater, and maximizing denitrification to its $N_2$ endproduct".

## Reducing environmental N losses by improving nutrient use efficiency and effectiveness

There are many different nutrient use efficiency terms reported in the literature (Dobermann 2007; Ladha et al. 2005). Fertilizer nitrogen use efficiency (NUE) is generally influenced by three major factors: 1) N supply from the soil, fertilizer, and other inputs, 2) crop N uptake, and 3) N losses from the soil–plant system (Ladha et al. 2005); each of which is affected by cropping system management and environmental conditions. Because of the risk of confusion among efficiency terms, the International Plant Nutrition Institute (Snyder and Bruulsema 2007) has advocated the use of four simple terms which may be used by extension workers, crop advisers, and farmers to evaluate and track nutrient (i.e. N) use efficiency on farms and in fields (**Table 1**).

The $PFP_N$ for maize in the U.S. has steadily improved since the mid-1970s (**Figure 5**), which reflects better fertilizer management, improved cropping system practices, and enhanced crop genetics.

**Figure 5** – Partial factor productivity ($PFP_N$) for maize in the U.S., based on fertilizer N applied for maize in the U.S.

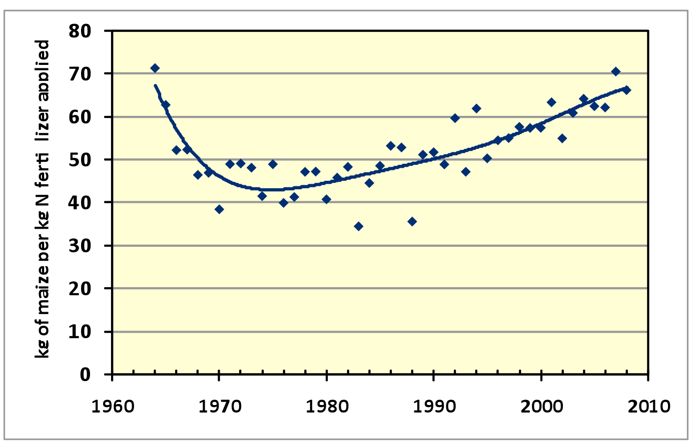



*Figure note*: Data sources include the United States Department (USDA) of Agriculture National Agricultural

Statistics Service and the Economic Research Service. Survey data were not collected by the USDA for fertilizer applied to corn in 2003 or 2006-2008. The value shown for 2003 is the average of 2002 and 2004, and values for 2006-2008 were extrapolated based on prior relationships between total fertilizer N sales and fertilizer N applied to corn in 15 selected maize-producing states (personal communication with T.W. Bruulsema, International Plant Nutrition Institute).

Although $PFP_N$ for maize has improved in the U.S. over the last three decades (**Figure 4**), there have been concerns that increased fertilizer N consumption in the Mississippi River Basin - where more than 80% of the maize is produced and more than 80% of the fertilizer N is consumed - has led to increased flux of N via the Mississippi River to the Gulf of Mexico. This increased N flux has been partially blamed for coastal eutrophication and seasonal hypoxia development in the northern Gulf of Mexico (EPA 2008). However, largely because of increased maize yields and crop harvest removal of N within the upper Mississippi River Sub-Basin and the Ohio-Tennessee River Sub-Basin, the flux of N reaching the Gulf of Mexico has declined by 21% from 2001 to 2005 compared to 1980 to 1996 (EPA 2008). These two Sub-Basins account for more than 70% of the total N loading to the Mississippi River. (EPA 2008; Snyder 2008b).

If N use efficiency and effectiveness were improved, concomitant reductions in many environmental N losses may be expected; especially N losses per unit of crop product produced. For example, the U.S. EPA has stated that 25% improvement in crop N uptake efficiency is one of the principal means to help reduce reactive N in the environment by 25% (*unpublished June 22, 2009 draft report by the Science Advisory Board Integrated Nitrogen Committee: Reactive Nitrogen in the United States; An Analysis of Inputs, Flows, Consequences, and Management Options.* http://yosemite.epa.gov/sab/SABPRODUCT.NSF/81e39f4c09954fcb85256ead006be86e/c83c30afa4656bea85256ea10047e1e1!OpenDocument&TableRow=2.2#2 ).

A comparison of the $PFP_N$ for maize in the entire U.S. with the flux of total N from the Mississippi River Basin to the Gulf of Mexico shows that there is a negative correlation between total N flux and maize $PFP_N$ (**Figure 6**). As $PFP_N$ increased, the delivery of total N to the Gulf of Mexico decreased. It is important to note that this correlation does not necessarily imply cause and effect, since there are numerous factors that influence $PFP_N$ for maize. For example, it is possible for $PFP_N$ and flux of N in river systems draining agricultural areas to actually move in the same direction. If N were applied to a soil which also received high rates of carbonaceous residues (i.e high C/N ratio), much of the applied N may be immobilized, which could reduce maize yields and lower $PFP_N$ values; simultaneously, leaching, runoff, and field drainage losses of N from the soil may also be reduced. There are many other complicating factors which influence crop N response and $RE_N$ including: crop rotation, changes in crop genetics, irrigation, rainfall intensity and seasonality, pest incidence and management, prices and use of the various crop inputs, harvest efficiency and weather affecting the harvest, etc. Nevertheless, this large-scale example (**Figure 6**) illustrates that it may be possible to relate reductions in some environmental N losses (e.g. N flux to coastal areas) to improved N use efficiency and effectiveness associated with increased crop production and harvest removal of N (EPA 2008).

**Figure 6** – Relationship between flux of total N from the Mississippi River Basin to the Gulf of Mexico and partial factor productivity ($PFP_N$) for maize in the entire U.S., 1984-2007

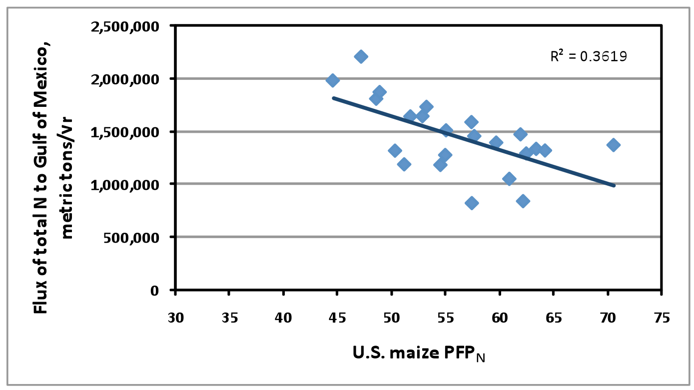



*Figure note*: Drought year 1988 excluded.

Good fertilizer stewardship (Roberts 2007) - applying the right fertilizer source, at the right rate, right time, and right place (i.e. 4R Nutrient Stewardship) - leads to improved economic crop production and helps minimize environmental impacts. Adoption of 4R Nutrient Stewardship (Bruulsema et al., 2009), implementation of fertilizer best management practices (BMPs) (Bruulsema et al. 2008; IFA 2007), and Site-Specific Nutrient Management (SSNM) are being advanced to help achieve improved economic results and environmental objectives (Adviento-Borbe et al. 2007; Dobermann and Fairhurst 2000; Dobermann and Cassman 2002; Fixen et al. 2005; Snyder 2008a; Snyder et al. 2007, 2009).

Although N from soil, fertilizer and manure sources may be used relatively inefficiently by most crops, with 50% or less N use efficiency globally (Balasubramanian et al. 2004; Ladha et al. 2005), N use efficiency can be increased to 60 to 70% or more with improved management in many cropping systems (Cassman et al. 2002; Kitchen and Goulding 2001; Ladha et al. 2005; Raun and Johnson 1999). Dobermann and Cassman (2002) reported that typical on-farm apparent crop recovery of applied N ($RE_N$) was only 30% in rice and 37% in maize, but with good management $RE_N$ could be 50 to 80%. Increasing the crop $RE_N$ is expected to reduce the potential for N losses that risk impacts to water and air resources, and which lower economic returns to farmers.

Based on many literature reports involving the use of $^{15}N$ labeled fertilizer, the maximum recovery of N in irrigated wheat (*Triticum aestivum* L.) research plots was 96% (Balasubramanian et al. 2004), 87% for irrigated maize, and 83% for rice research plots in the year of application (Krupnik et al. 2004). Plant recovery of the residual applied N by subsequent crops was reported to be 5% or lower, which indicated that much of the environmental loss occurs during or shortly after the year of N application (Krupnik et al., 2004). Dobermann (2007) observed that in cereal crop research, total $RE_N$ from a one-time application of N averages 50 to 60%, and 40 to 50% under most on-farm conditions. Although many factors besides N management affect crop growth and response to fertilizer inputs, these review articles illustrate the sizeable gap between $RE_N$ in many farm fields and the $RE_N$ that can be achieved in research plots.

Any N not taken up by the crop or cropping system may be subject to storage in the soil or loss from the system. Use of economically optimum N rates can reduce the build-up of residual soil profile nitrate-N (Hong et al. 2007). A long-term study on the North American Great Plains comparing maize response to N rates with and without P, showed that adequate P fertilization for improved crop nutrition increased yields 42%, improved economic returns, and reduced soil profile $NO_3$-N levels by 66% (Schlegel et al. 1996). It has been shown that proper K nutrition can also help improve $RE_N$ and reduce the loss of $NO_3$-N (Johnson et al. 1997). High yield management research with maize by Gordon (2005) in the state of Kansas in the U.S. showed that proper rates of the principal essential nutrients including sulfur (S) can significantly increase crop yield and $RE_N$. There may be considerable opportunities for improved nutrient management, particularly with balanced and optimum levels of all nutrients, to recover lost efficiencies in many regions of the world.

## Conclusion

Nitrogen management for cropping system production should be based on science-based principles. These principles – right N source, at the right rate, right time, and right place (4R Nutrient Stewardship) should form the foundation of every nutrient input decision and goal: in developed and developing countries alike. University researchers, extension leaders, government agencies, crop advisers, fertilizer industry representatives and leading farmers need to work more closely to implement a strategy of improved N stewardship. Crop N use efficiency can be improved through the appropriate '4R' approach to help raise global $RE_N$ values from the typical <50% range to the 60-70% range, or higher for cereal crops. These N management improvement efforts may simultaneously result in decreased losses of N to the environment. As population-driven encroachment leads to a reduction in natural areas, and as land most suitable for crop production becomes more limited, site-specific nutrient management using the '4R" approach will become increasingly important.

## References


Adviento-Borbe, M.A.A., M.L. Haddix, D.L.Binder, D.T. Walters, and A. Dobermann. 2007. Soil greenhouse gas fluxes and global warming potential in four high-yielding maize systems. Glob. Change Biol. 13:1972-1988

Balasubramanian, V., B. Alves, M. Aulakh, M. Bekenda, Z. Cai, L. Drinkwater, D. Mugendi, C.van Kessel, andO Oenema. 2004. Ch. 2, pp. 19-43. Crop environmental, and management factors affecting nitrogen use efficiency. In: Mosier, A.R., J.K. Syers and J.R. Freney (eds.). Agriculture and the Nitrogen Cycle: Assessing the impacts of fertilizer use on food production and the environment. Scientific Committee on Problems of the Environment (SCOPE), of the International Council for Science. Island Press. Washington, DC, USA.

Baumert, K.A., T. Herzog, and J. Pershing. 2005. Navigating the Numbers: Greenhouse Gas Data and International Climate Policy. World Resources Institute. Washington, DC. 122 pp. http://www.wri.org

Bellarby, J., B. Foreid, A. Hastings, and P. Smith. 2008. Cool Farming: Climate impacts of agriculture and mitigation potential. Greenpeace. Amsterdam, The Netherlands., 43 pp.

Beman, M. J., K.R. Arrigo, and P.A. Matson. 2005. Agricultural runoff fuels large phytoplankton blooms in vulnerable areas of the ocean. Nature 434:211-214

Bouwman, A. F., L. J. M. Boumans, and N. H. Batjes. 2002. Estimation of global NH3 volatilization loss from synthetic fertilizers and animal manure applied to arable lands and grasslands. Global Biogeochem. Cycles 16 (2):1024, doi:10.1029/2000GB00138

Bouwman, A. F., G. Van Drecht, J. M. Knoop, A. H. W.

Beusen, and C. R. Meinardi. 2005. Exploring changes in river nitrogen export to the world's oceans, Global Biogeochem. Cycles, 19, GB1002, doi:10.1029/2004GB002314

Boyer, E.W., R.W. Howarth, J.N. Galloway, F.J. Dentener, P.A. Green, and C.J. Vorosmarty. 2006. Riverine nitrogen export from the continents to the coasts. Global Biogeochem. Cycles. 20: GB1S91. doi:10.1029/2005GB002537

Bruulsema, T.W., C. Witt, F. Garcia, S. Li, T.N. Rao, F. Chen, S. Ivanova. 2008. A global framework for fertilizer BMPs. Better Crops 92(2):13-15

Bruulsema, T., J. Lemonyon, B. Herz. 2009. Know your fertilizer rights. Crops & Soils March-April 2009. American Society of Agronomy. Madison, WI. pp. 13-18

Buresh, R.J. and C. Witt. 2008. Balancing fertilizer use and profit in Asia's irrigated rice systems. Better Crops 92(1):18-22

Cassman, K.G., A. Dobermann and D.T.Walters. 2002. Agroecosystems, Nitrogen-use Efficiency, and Nitrogen Management. Ambio 31(2):132-140

Dobermann, A. 2007. Nutrient use efficiency – measurement and management. In: Fertilizer Best Management Practices: General Principles, Strategy for their Adoption and Voluntary Initiatives vs Regulations. 259 pp. Proc. IFA International Workshop on Fertilizer Best Management Practices. 7-9 March 2007. Brussels, Belgium. International Fertilizer Industry Association. Paris, France. pp. 1-28

Dobermann, A. and K.G. Cassman. 2002. Plant nutrient management for enhanced productivity in intensive grain production systems of the United States and Asia. Plant Soil 247:153–175

Dobermann, A. and T.H. Fairhurst. 2000. Rice: Nutrient Disorders and Nutrient Management. 191 pp. International Rice Research Institute and Potash & Phosphate Institute

EPA. 2006. Global Anthropogenic non-CO2 greenhouse gas emissions: 1990-2020. United States Environmental Protection Agency. EPA 430-R-06-003. June 2006 revised. Washington, DC, Available at http://www.epa.gov/nonco2/econ-inv/downloads/GlobalAnthroEmissionsReport.pdf

EPA SAB. 2008. Hypoxia in the northern Gulf of Mexico: an update by the EPA Science Advisory Board. 275 pp. Available on-line at: http://yosemite.epa.gov/sab/sabpeople.nsf/Search?ReadForm&Query=hypoxia&committee=BOARD .

EPA. 2009. Inventory of U.S. Greenhouse Gas Emissions and sinks: 1990-2007. U.S. Environmental Protection Agency. 15 April 2009. EPA 430-R-09-004. Available at http://epa.gov/climatechange/emissions/usinventoryreport.html

Fixen, P.E., J.Jijun, K.N. Tiwari, and M.D. Stauffer. 2005. Capitalizing on multi-element interactions through balanced nutrition – a pathway to improve nitrogen use efficiency in China, India and North America. Science in China Ser. C Life Sciences Special Issue 48:780-790

Follett, R.F. 2001. Nitrogen transformation and transport processes. Ch. 2, pp. 17-44 In: Follett, R.F. and J.L. Hatfield (eds.) Nitrogen in the Environment: Sources, Problems, and Management. Elsevier, Amsterdam, The Netherlands.

Galloway, J.N., E.B. Cowling, S.S. Seitzinger, and R.H. Socolow. 2002. Reactive Nitrogen: Too Much of a Good Thing? Ambio 31(2):60-63

Galloway, J.N. and E.B. Cowling. 2002. Reactive nitrogen and the world: 200 years of change. Ambio 31(2):64-71

Galloway, J.N., J.D. Aber, J.W. Erisman, S.P. Seitzinger, R.W. Howarth, E.B. Cowling, and B.J. Cosby. 2003. The nitrogen cascade. BioScience 53:341-356

Galloway, J.N., F.J. Denter, D.G. Capone, E.W. Boyer, R.W. Howarth, S.P. Seitzinger, G.P. Asne, C.C. Cleveland, P.A. Green, E.A. Holland, D.M. Karl, A.F. Michaels, H. Porter, A.R. Townsend, and C.J. Vorosmarty. 2004. Nitrogen cycles: past, present, and future. Biogeochem 70:153–226

Galloway, J.N., N. Raghuram, and Y.P. Abrol. 2008a. A perspective on reactive nitrogen in a global, Asian and Indian context. Curr. Sci. 94(11):1375-1381

Galloway, J.N., A.R. Townsend, J.W. Erisman, M. Bekunda, Z. Cai, JR.. Freney, L.A. Martinelli, S. P. Seitzinger, and M. A. Sutton. 2008 b. Transformation of the Nitrogen Cycle:

Recent Trends, Questions, and Potential Solutions. Science 320:889-892

Goolsby, D.A., W.A. Battaglin, G.B. Lawrence, R.S. Artz, B.T. Aulenbach, R.P Hooper,

D.R. Keeney, and G.S. Stensland. 1999. Flux and sources of nutrients in the

Mississippi–Atchafalaya River basin—Topic 3, Report for the integrated assessment

of hypoxia in the Gulf of Mexico: National Oceanic and Atmospheric Administration

Coastal Ocean Program Decision Analysis Series 17, 128 pp.

Gordon, B. 2005. Maximizing irrigated corn yields in the Great Plains. Better Crops 89(2):8-10

Griggs, B.R. R.J. Norman, C.E. Wilson, Jr., and N.A. Slaton. 2007. Ammonia volatilization and nitrogen uptake for conventional and conservation tilled dry-seeded, delayed-flood rice. Soil Sci. Soc. Am. J. 71:745–751

Gruber, N. and J.N. Galloway. 2008. An Earth-system perspective of the global nitrogen cycle. Nature 451(17): 293-296

Hong, N., P.C. Scharf, J.G. Davis, N.R. Kitchen, and K.A. Sudduth. 2007. Economically optimal nitrogen rate reduces soil residual nitrate. J. Environ. Qual. 36:354–362.

IFA. 2007. Fertilizer Best Management Practices: General Principles, Strategy for their Adoption and Voluntary Initiatives vs. Regulations, Proc IFA International Workshop on Fertilizer Best Management Practices. 7-9 March 2007. Brussels, Belgium. International Fertilizer Industry Association., Paris, France. 259 pp.

IPCC. 2001. Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change. In: Houghton, J.T., Y. Ding, D.J. Griggs, M. Noguer, P.J. van der Linden, X. Dai, K. Maskell, and C.A. Johnson (eds.). Cambridge University Press. Cambridge, UK and New York, NY. USA. 881 pp.

Johnson, J.W., T.S. Murrell, and H.F. Reetz. 1997. Balanced fertility management: a key to nutrient use efficiency. Better Crops 81:3-5

Kissel, D. 1988. Management of urea fertilizers. NCR 326, North Central Regional Extension Publication. Kansas State University. Manhattan, Kansas

Kitchen, N.R., and K.W.T. Goulding. 2001. On-farm technologies and practices to improve nitrogen use efficiency. In: Follett, R.F. and J.L. Hatfield (eds.) Nitrogen in the Environment: Sources, Problems, and Management. Elsevier. Amsterdam, The Netherlands. Ch. 13, pp. 335-370

Krupnik, T.J., J. Six, J.K. Ladha, M.J. Paine, and C. van Kessel. 2004. An assessment of fertilizer nitrogen recovery efficiency by grain crops. Ch. 14, pp. 193- 207. In: Mosier, A.R., J.K. Syers and J.R. Freney (eds.). Agriculture and the Nitrogen Cycle: Assessing the impacts of fertilizer use on food production and the environment. Scientific Committee on Problems of the Environment (SCOPE), of the International Council for Science. Island Press. Washington, DC, USA.

Ladha, J.K., H. Pathak, and T.J. Krupnik. 2005. Efficiency of fertilizer nitrogen in cereal production: retrospects and prospects. Adv. Agron. 87:85-156

Rabalais, N.N., R.E. Turner, R.J., Díaz, and D. Justic. 2009. Global change and eutrophication of coastal waters. ICES Journal of Marine Science 66: 1528–1537

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

Rochette, P., J.D. MacDonald, D.A. Angers, M.H. Chantigny, M-O. Gasser, and N. Bertrand. 2009. Banding of urea increased ammonia volatilization in a dry acidic soil. J. Environ. Qual. 38:1383–1390

Schlegel, A.J., K.C. Dhuyvetter, and J.L. Havlin.1996. Economic and environmental impacts of long-term nitrogen and phosphorus fertilization. J. Produc. Agric. 9:114-118.

Schlesinger, W.H. 2009. On the fate of anthropogenic nitrogen. Proc. Natl. Academy Sci. 106(1):203-208

Snyder, C.S. 2008a. Fertilizer nitrogen BMPs to limit losses that contribute to global warming. Ref # 080507, International Plant Nutrition Institute. Norcross, GA, USA., 8 pp. http://www.ipni.net/ipniweb/portal.nsf/0/9bbc50427c6469ae852574f200162796/$FILE/Nitrogen%20BMP.pdf

Snyder, C.S. 2008b. Nutrients and Hypoxia in the Gulf of Mexico- An Update on Progress, 2008. Better Crops 92(2):16-22

Snyder, C.S., and T.W. Bruulsema. 2007. Nutrient Use Efficiency and Effectiveness in North America: Indices of Agronomic and Environmental Benefit. International Plant Nutrition Institute. June 2007. Ref # 07076. 4 pp. International Plant Nutrition Institute. Norcross, GA, USA. http://www.ipni.net/ipniweb/portal.nsf/0/D58A3C2DECA9D-7378525731E006066D5

Snyder, C.S., T.W. Bruulsema, T.L. Jensen, and P.E. Fixen. 2009. Review of greenhouse gas emissions from crop production systems and fertilizer management effects. Agric. Ecosyst. Environ. Agric. Ecosyst. Environ. 133 (2009) 247–266.

Subramanian, V. 2008. Nitrogen transport by rivers of south Asia, Curr. Sci. 94(11):1413-1418

Watson, C. 2005. Urease Inhibitors. IFA International Workshop on Enhanced-Efficiency Fertilizers Frankfurt, Germany. 28-30 June 2005. 8 pp. International Fertilizer Industry Association. Paris, France

# PRINCIPLES OF NUTRIENT USE EFFICIENCY OF PHOSPHORUS AND POTASSIUM

**T. Scott Murrell**

U.S. Northcentral Director, International Plant Nutrition Institute

## Abstract

Two measures of phosphorus (P) and potassium (K) efficiency that are of interest to producers are agronomic efficiency (*AE*) and partial nutrient balance (*PNB*). Agronomic efficiency considers crop response to a nutrient addition while *PNB* measures nutrient removal to nutrient use. Proper evaluation of *AE* requires long term monitoring. A single, large application of P or K can, over many years, result in an *AE* similar to smaller, annual applications. A larger initial dose will increase soil test levels higher than a smaller annual dose, which can result in higher crop yields sustained over a longer period of time, depending on initial fertility levels. Applications that replace the quantity of P and K removed by crop harvest are termed maintenance applications. It can be shown that for a maintenance application to at least break even economically in one crop season, *AE* must be equal to or greater than the nutrient to crop price ratio. For banded applications to have a constant improvement in *AE* over broadcast ones across a given set of nutrient rates, certain conditions must be met. Such conditions have seldom been reported. Improvements that have been reported do not present a complete picture of improved efficiency and are of limited use in production settings. Improvements in efficiency must be weighed against impacts on the long term sustainability of soil fertility levels.

## Definition of residual effects

Phosphorus and K are retained by soils and can therefore impact crop yields and soil fertility many seasons subsequent to their application. Such impacts are termed "residual." Consequently, the efficiency of an application can be evaluated for one season or many. Proper evaluations of residual effects require longer time periods to truly capture their full impact (Syers et al., 2008). This paper considers two measures of efficiency: agronomic efficiency and partial nutrient balance. They were selected because they are central to the aspects of P and K nutrient management of most concern to farmers and their advisers.

## Agronomic efficiency (*AE*)

Agronomic efficiency considers how much the yield of a crop is increased per unit of nutrient applied. It is defined as (Snyder and Bruulsema, 2007):

$$AE = (Y_F - Y_0) / F \qquad [1]$$

where $Y_F$ = the fertilized yield (kg ha$^{-1}$), $Y_0$ is the unfertilized yield (kg ha$^{-1}$), and $F$ is the rate of nutrient applied (kg ha$^{-1}$). Therefore, *AE* is a unitless quantity.

To demonstrate some of the different ways *AE* can be evaluated for nutrients like P and K, we consider a study comparing the effects on maize yield of a one-time application of 146 kg P ha$^{-1}$ to annual applications of 11.2 kg ha$^{-1}$ made on the same experimental unit over time (Webb et al., 1992). Both rates were broadcast and incorporated. The tillage practices consisted of chisel-plowing in the fall followed by disking in the spring. A check was included ($Y_0$), allowing the *AE* to be calculated for both P rates. A total of 13 years were considered so that the cumulative total of the smaller, annual application rates equaled the single, larger one, keeping the total amounts of P comparable in both treatments.

**Figure 1** shows the results of calculating *AE* in different ways. The top line with the greatest *AE* calculates efficiency using only the ($Y_F - Y_0$) observed in a given year and annual P application = 11.2 kg ha$^{-1}$. It therefore represents an annual efficiency that does not take into account the fertilization

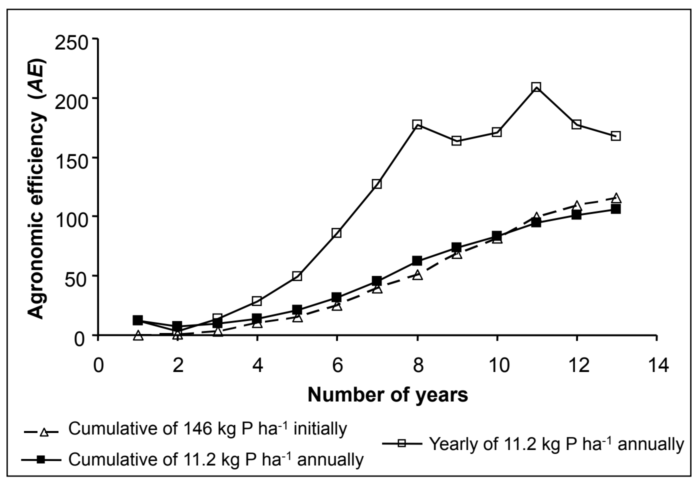



**Figure 1**. Agronomic efficiency (*AE*) for a one-time application of 146 kg P ha$^{-1}$ and annual applications of 11.2 kg P ha$^{-1}$. The *AE* of the annual application was evaluated two ways: 1) each year considered individually with no prior fertilization history (yearly of 11.2 kg P ha$^{-1}$ annually) and 2) *AE* based on the cumulative sum of annual rates up to and including the current year (cumulative of 11.2 kg P ha$^{-1}$ annually). (Webb et al., 1992).

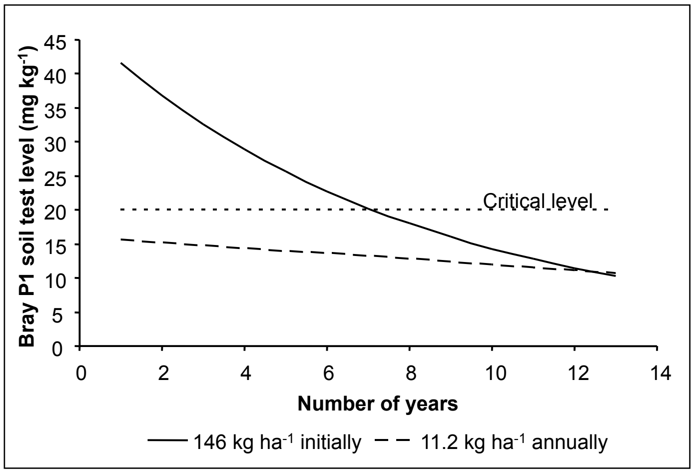



**Figure 2**. The effect on Bray P1 soil test levels of a single larger P application and a series of smaller, annual ones. The total applied over the time period considered was the same for both application rates (Webb et al., 1992).

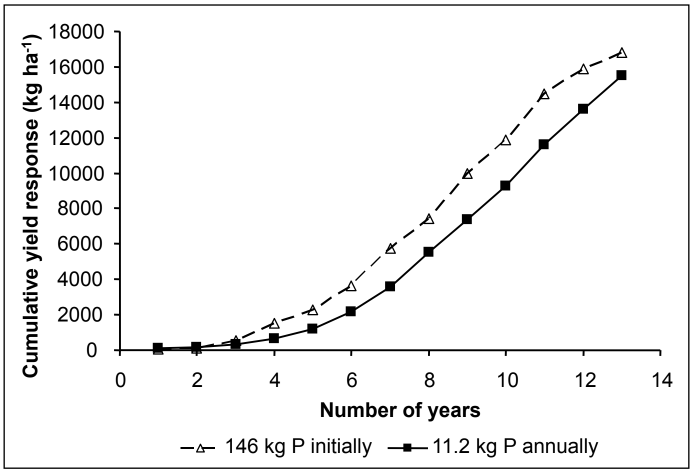



**Figure 3**. Cumulative yield response to a one time, larger dose of P and to smaller, annual doses of P (Webb et al., 1992).

or yield response history (short-term). In the remaining two cases, $(Y_F - Y_0)$ is a running total of yield response for all years up to and including the year of interest. Similarly, $F$ represents the sum of all rates up to and including the year of interest (long-term).

**Figure 1** points out that short-term evaluations that ignore fertilization history and historical yield responses may produce artificial values of *AE*. Additionally, it is demonstrated that a single, large application of P produced a long-term *AE* essentially equal to the same total P rate broken up into smaller, annual applications. Consequently, evaluating annual applications must consider fertilization history to be properly compared to larger, more periodic doses.

Another important difference between a single, larger P application and smaller, annual ones is their relative effects on soil test levels (**Figure 2**). In the same study cited above, the 146 kg ha$^{-1}$ dose initially increased soil test levels well above the critical level of 20 ppm Bray P1. This level was the point in the study below which greater probabilities existed that soil P levels were too low to fully supply crop needs. Over time, with no subsequent fertilization, soil test levels dropped in an exponential manner and by year 8 were below the critical level. Such exponential decreases have been observed by others (McCollum, 1991; Syers et al., 2008). Conversely, annual applications of 11.2 kg ha$^{-1}$ never did raise soil test levels higher than the critical level. Instead, they resulted in steady declines in soil fertility. By the end of the time period considered, both rates resulted in nearly identical and low final soil test levels.

An important difference between the two dosage distributions in Webb et al. (1992) arose in yield response. **Figure 3** shows that the larger, single rate resulted in higher cumulative yields by year 4 that remained higher during the rest of the 13 year period. Economic analysis in the study examined only short-term returns to annual applications. However, there are implications upon long-term profitability. Higher yields sustained earlier are capable of providing revenue that has a higher value when considered over the entire 13 year period, since currency tends to devalue over time. Additionally, a one time purchase of P could have been timed to match with favorable crop price and nutrient price conditions if sufficient capital were available and if the land were owned or under a long-term rental agreement. In some cases, a single, larger investment in fertilizer that is well timed in the market can be more profitable over the long term than smaller, annual purchases more subject to fluctuating economic conditions. Profitability analyses should examine such long-term factors to provide a complete picture of risk.

## Partial nutrient balance (*PNB*)

Partial nutrient balance is the ratio of the quantity of nutrient removed in harvested crop portions ($U_H$) to the quantity of nutrient applied (Snyder and Bruulsema, 2007):

$$PNB = U_H / F \quad [2]$$

Accuracy in determining *PNB* primarily entails 1) measuring, rather than estimating the concentration of nutrients in harvested crop portions and 2) accounting for all applications of nutrients, including manure and commercial fertilizer.

The primary goal of this measure of efficiency is to determine how close a system is to one. A *PNB* value close to one indicates that mass balance exists – nutrient applications to a unit of land approximately equal nutrient removal. Such a balance is necessary for the fertility level of a system to be sustained.

A *PNB* value of one does not guarantee that soil test levels will remain static, however. In a study of irrigated alfalfa, Fixen and Ludwick (1983) found that to maintain P soil test levels on the two soils studied, *PNB* values of 2.2 and 1.4 were needed. For K, these *PNB* values were 0.75 and 0.22. This study used larger broadcast and incorporated fertilizer rates initially, follow by annual applications that were broadcast but not incorporated. Moncrief et al. (1985) demonstrated that for the same total quantity of K applied to a tilled and untilled soil, an unincorporated application to the surface of the untilled soil resulted in higher soil tests when evaluated by a 15 cm deep sample. These two studies demonstrate that the distribution of nutrients within the soil can greatly affect whether or not soil test levels will remain constant or change when maintenance applications, those that keep *PNB* near one, are made.

## Agronomic efficiency of a profitable maintenance application

When efficiencies are examined, it is often difficult to know how to interpret them. How much efficiency can reasonably be expected? In this section, we examine the minimum *AE* to be expected for a profitable maintenance application.

As discussed above, a maintenance application rate is one that strives to maintain mass balance, keeping *PNB* close to one. This rate may be defined as:

$$F_{\text{maint}} = rY_F \quad [3]$$

where $F_{\text{maint}}$ is the maintenance rate, r is the rate of nutrient removal per harvested crop unit, and $Y_F$ is the fertilized crop yield.

To begin with, we consider a single season. For $F_{\text{maint}}$ to be profitable in that season, the revenue from the increase in yield due to the application must be at least equal to the nutrient cost. This can be expressed as:

$$P_c(Y_F - Y_0) \geq P_F(F_{\text{maint}})$$

where $P_c$ is the price of the crop, $Y_F$ and $Y_0$ are the fertilized and unfertilized yields, respectively, and $P_F$ is the price of the nutrient applied at the maintenance rate. Rearranging this equation and defining a new variable *R* to be the ratio of fertilizer price to crop price ($R = P_F / P_c$) which is a unitless quantity, we obtain the following:

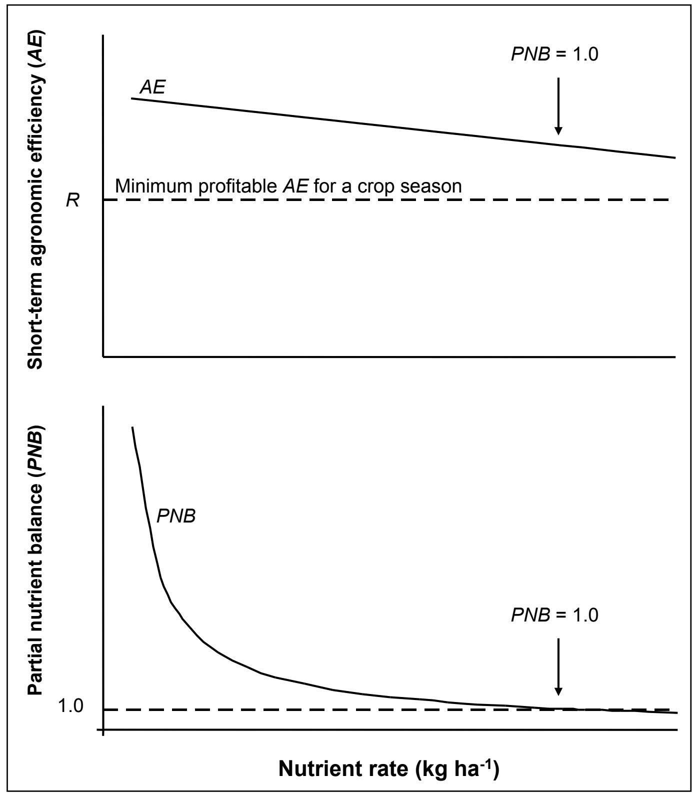



**Figure 4**. Theoretical relationships between agronomic efficiency (*AE*) and partial nutrient balance (*PNB*) for a situation where a maintenance rate of a nutrient (*PNB* = 1) is profitable in one crop season, resulting in an *AE* > *R*.

$$(Y_F - Y_0) / F_{\text{maint}} \geq R, \textbf{ or } AE \geq R \quad [4]$$

Thus, for a maintenance fertilizer application to be profit neutral, it must have an *AE* at least equal to *R*. An *AE* value greater than *R* is profitable within one crop season.

These relationships are demonstrated graphically in **Figure 4**. During the first increments of nutrient addition, *PNB* decreases rapidly as both $Y_F$ and the nutrient rate increase. As the rate approaches $F_{\text{maint}}$, *PNB* reduces to 1. Simultaneously, *AE* becomes smaller as both the rate increases and as the crop response begins to level off, but because a profitable scenario is depicted, *AE* remains above R by the time $F_{\text{maint}}$ is reached.

Maintenance applications are important for sustaining nutrient mass balance in soils. This discussion demonstrates that it is possible to define at least a minimum *AE* that may be expected if a maintenance application is to be profitable in a single season.

## Nutrient placement effects on *AE* and *PNB*

In many states in the western U.S. Corn Belt, recommendations exist for reducing fertilizer rates if they are applied in a band, rather than broadcast (Gerwing and Gelderman, 2002; Rehm et al., 2006; Shapiro et al., 2003). Sometimes the degree of reduction varies by soil test level (Rehm et al., 2006) and sometimes it does not (Shapiro et al., 2003). Often, banded rates are reduced to half of the broadcast rate.

The primary assumptions behind this recommendation are that banded applications (b) are generally more efficient than are broadcast applications (B) and that both produce essentially the same yield response. These assumptions are shown graphically in **Figure 5**. In this figure, the commonly used quadratic-plateau function ($Y_F = \beta_0 + \beta_1 F + \beta_2 F^2$ for $F \le F_{max}$; $Y_F = Y_{max}$ for $F > F_{max}$) was chosen to model crop response. The figure shows the case where a banded application has twice the *AE* as a broadcast application ($AE_b = 2AE_B$ in the bottom graph). This doubling in efficiency arises strictly from the half rate of banded fertilizer needed to produce maximum yield ($Y_{max}$) compared to a broadcast application ($F_{max\text{-}b} = 0.5F_{max\text{-}B}$ in the top graph). The higher efficiency of the banded application can be expressed by the ratio $F_{max\text{-}b} / F_{max\text{-}B}$ which equals, in this case, 0.5.

It can be demonstrated that under the crop response scenario described above, the following relationships hold. First, the intercepts ($\beta_0$) of the two equations are the same:

$$\beta_{0B} = \beta_{0b} \quad [5]$$

where $\beta_{0B}$ is the intercept of the broadcast response curve and $\beta_{0b}$ is the intercept of the banded one. Next, the coefficient of linear slope ($\beta_1$) for the crop response to the broadcast rates can be described as:

$$\beta_{1B} = (F_{max\text{-}b} / F_{max\text{-}B})\, \beta_{1b} \quad [6]$$

where $\beta_{1B}$ is the coefficient of linear slope for the broadcast rates and $\beta_{1b}$ is the same coefficient for the banded rates. Similarly, the coefficient of curvature ($\beta_2$) for the two response equations are related as follows:

$$\beta_{2B} = (F_{max\text{-}b} / F_{max\text{-}B})^2\, \beta_{2b} \quad [7]$$

As long as these relationships hold, then the improved *AE* of the banded rate relative to the broadcast one is a constant across all rates in the response. The practical implication of this relationship is that if farmers have to reduce rates below those producing maximum yield, banded rates will still have the same efficiency as those producing maximum yield.

The increased efficiency of banded applications compared to broadcast ones has been investigated previously (Welch et al., 1966a; Welch et al., 1966b, Peterson et al., 1981). All of these investigations compared broadcast to banded applications during one crop year and did not consider residual effects. All of these studies also reported crop response as a quadratic function, allowing the theoretical relationship described above to be tested.

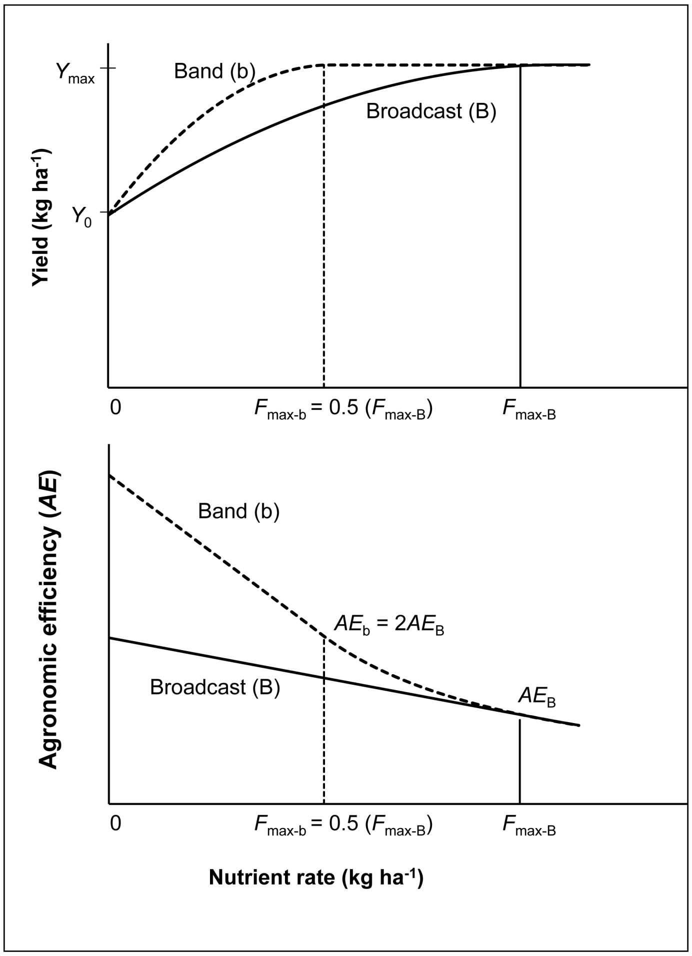



**Figure 5**. Theoretical relationship between a quadratic-plateau type of crop yield response to a broadcast application and to a banded application that is twice as efficient but which results in the same yield response and maximum yield as the broadcast application.

Across all three reported studies, 12 site-years of data existed – 9 investigating P and 3 investigating K. Of these 12, only one site-year conformed to the theoretical response described in **Figure 5**. The study showed that $F_{max\text{-}b} / F_{max\text{-}B} = 0.63$, demonstrating that at this site, which had a low soil test P level, banded applications could be slightly less than two-thirds of a broadcast application and produce the same yield response. At 5 of the remaining site-years, rates were not selected that maximized yield response to one or both of the placement methods. At 2 site-years, no significant difference existed between placement methods. At the remaining 4 site-years, maximum yields attained by placement methods differed, with banded applications producing higher maximum yields than banded ones at 3 of the site-years.

Investigators involved in these studies did not use the theoretical relationship in **Figure 5** to evaluate broadcast and banded applications. Instead, a yield level was selected, and broadcast and banded rates needed to attain that yield were compared. While a $F_b$ / $F_B$ ratio can be calculated in this manner for a given set of rates, such a ratio does not provide a complete picture of the crop responses involved and can be misleading. For instance, it is important for the farmer to know that regardless of the efficiency, a banded application will not equal the yield response of a broadcast one or vice versa. Additionally, if the improved efficiency of one application method over another is not constant across all rates, then unexpected results can occur if a rate is chosen that is not the one upon which the comparison was based.

Work by Anghinoni and Barber (1980) has demonstrated that when lower rates of fertilizer are applied to nutrient deficient soils, banded applications that fertilize a smaller soil volume produce higher yields than the same low rates mixed more thoroughly with a larger soil volume. However, as the application rate increases, fertilization of a greater soil volume is necessary to maximize yield, and the yield attained with that higher rate is greater than the yield attained with a lower, banded rate. Banded and broadcast applications used together may provide more complete nutrition than either one alone. Banded nutrients near the seed provide the early season positional availability of a concentrated supply needed to satisfy high nutrient influx rates early in the season (Mengel and Barber, 1974). More thoroughly incorporated broadcast rates increase the quantity of nutrients available to the more extensive root system developed later in the season.

In cases when one fertilizer placement method results in improved *AE*, the reduced rate must be examined carefully to determine how it compares to the *PNB* of 1.0 needed to sustain soil fertility levels. In cases where the more efficient rate is less than this *PNB* value, short-term efficiency gains need to be weighed against the longer-term implications on declining soil fertility should that rate be repeatedly implemented.

## References


Anghinoni, I. and S.A. Barber. 1980. Predicting the most efficient phosphorus placement for corn. Soil Sci. Soc. Am. J. 44:1016-1020.

Fixen, P.E. and A.E. Ludwick. 1983. Phosphorus and potassium fertilization of irrigated alfalfa on calcareous soils: I. Soil test maintenance requirements. Soil Sci. Soc. Am. J. 47:107-112.

Gerwing, J. and R. Gelderman. 2005. South Dakota fertilizer recommendations guide. Sep. 2005. EC750. South Dakota Coop. Ext. Serv., South Dakota State Univ., Brookings. Available online at http://agbiopubs.sdstate.edu/articles/EC750.pdf (verified 14 Aug. 2009).

McCollum, R.E. 1991. Buildup and decline in soil phosphorus: 30 year trends on a typic umprabuult. Agron. J. 83:77-85.

Mengel, D.B. and S.A. Barber. 1974. Rate of nutrient uptake per unit of corn root under field conditions. Agron. J. 66:399-402.

Moncrief, J.F., P.M. Burford, and J.B. Swan. 1985. The effect of tillage on interpretation and response to soil K. J. Fert. Iss. 2:17-25.

Peterson, G.A., D.H. Sander, P.H. Grabouski, and M.L. Hooker. 1981. A new look at row and broadcast phosphate recommendations for winter wheat. Agron. J. 73:13-17.

Rehm, G., G. Randall, J. Lamb, and R. Eliason. 2006. Fertilizing corn in Minnesota. FO-3790-C. Rev. 2006. Minnesota Coop. Ext. Serv., St. Paul., MN. Available online http://www.extension.umn.edu/distribution/cropsystems/DC3790.html (verified 14 Aug. 2009).

Shapiro, C.A., R.B. Ferguson, G.W. Hergert, A.R. Dobermann, and C.S. Wortmann. 2003. Fertilizer suggestions for corn. G74-174-A. Rev. Nov. 2003. Nebraska Coop. Ext. Serv., Univ. Nebraska, Lincoln. Available online at http://www.ianrpubs.unl.edu/epublic/pages/publicationD.jsp?publicationId=142 (verified 14 Aug. 2009).

Snyder, C.S., and T.W. Bruulsema. 2007. Nutrient use efficiency and effectiveness in North America: Indices of agronomic and environmental benefit. Ref # 07076. International Plant Nutrition Institute. Norcross, GA. Available at http://www.ipni.net/ipniweb/portal.nsf/0/D58A3C2DECA9D7378525731E006066D5 (verified 11 Aug. 2009).

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.

Webb, J.R., A.P. Mallarino, and A.M. Blackmer. 1992. Effects of residual and annually applied phosphorus on soil test values and yields of corn and soybean. J. Prod. Agric. 5:148-152.

Welch, L.F., P.E. Johnson, G.E. McKibben, L.V. Boone, and J.W. Pendleton. 1966a. Relative efficiency of broadcast versus banded potassium for corn. Agron. J. 58:618-621.

Welch, L.F., D.L. Mulvaney, L.V. Boone, G.E. McKibben, and J.W. Pendleton. 1966b. Relative efficiency of broadcast versus banded phosphorus for corn. Agron. J. 58:283-287.

# NUTRIENT USE EFFICIENCY IN BRAZIL

**Luís Ignácio Prochnow[1], Valter Casarin[2], Nand Kumar Fageria[3], and Milton Ferreira Moraes[4]**

## 1. Introduction

Brazil is the fourth largest market for fertilizers worldwide, which represents about 6% of world consumption. Projections from the International Fertilizer Industry Association (IFA) suggest an increase in the demand for fertilizers in Asia, Africa and the Americas. However, the largest potential area for agricultural expansion in the world is in Brazil (around 100 million hectares) where IFA projects an increase of 15 million ha by 2015, which could result in a market expansion of 30 million tons of fertilizer. To sustain the necessary increase in yield without degrading the environment, it will be necessary to utilize these fertilizers efficiently (Horowitz, 2007).

Farmers need to carefully consider several factors in order to increase crop yields These include options to manage water availability, diseases and insect control, weed control and others. Soil fertilization is one of the most important, but all the factors should be in equilibrium so plant growth can support high yields.

The effectiveness of nutrient acquisition, transport and use by plants is controlled mainly by: *(i) the soil's capacity to provide nutrients and (ii) the plant's ability to absorb and utilize these nutrients*. These factors vary with soil, crops, cultivars and climatic conditions (Baligar and Fageria, 1997). In Brazil, the effectiveness in the use of plant nutrients is strongly dependent on soil management factors which: *(i) control acidity, (ii) increase cation exchange capacity, (iii) decrease nutrient losses (especially through leaching and volatilization), and (iv) monitor the soil organic fraction* (Goedert et al., 1997).

The two main factors that limit crop yields in Brazil are water and nutrient stress. The newly cultivated soils of the savannah region provide a clear example of this as they have inherently low soil fertility, especially considering P (Fageria, 1998). Considering the first crop, average plant nutrient recoveries are only about 50%, 10% and 40% for N, P and K, respectively (Baligar and Bennet, 1986). Besides soil evaluation and control, the plant should also be considered in terms of efficiency in P acquisition (Machado, 1997). Cultivars have different nutrient absorbing capacities, which need to be taken into consideration for a more efficient and sustainable agriculture.

It is essential to understand all factors related to nutrient

**Table 1**. Area, total yield and average yield of main crops in Brazil.

| Crop | Area (ha) | Total Yield (t) | Average Yield (kg ha$^{-1}$) |
|---|---|---|---|
| Soybean | 21,271,762 | 59,916,830 | 2,817 |
| Corn | 14,443,337 | 59,011,703 | 4,086 |
| Sugarcane | 8,141,228 | 648,973,981 | 79,715 |
| Beans | 3,779,449 | 3,460,067 | 915 |
| Rice | 2,891,665 | 12,100,946 | 4,229 |
| Wheat | 2,373,572 | 5,886,009 | 2,480 |
| Coffee | 2,216,014 | 2,790,858 | 1,259 |
| Cotton | 1,057,032 | 3,971,090 | 3,757 |
| Orange | 833,409 | 18,394,719 | 22,072 |

**Source:** GCEA, IBGE (2008).

[1]IPNI Brazil Program Director. E-mail: lprochnow@ipni.net
[2]IPNI Brazil Program Deputy Director. E-mail: vcasarin@ipni.net
[3]Researcher at EMBRAPA Rice and Beans. E-mail: fageria@cnpag.embrapa.br
[4]Pos Doctor at the University of São Paulo. E-mail: moraesmf@yahoo.com.br

**Table 2**. Area, total yield and average yield of secondary crops in Brazil.

| Crop | Area (ha) | Total Yield (t) | Average Yield (kg ha$^{-1}$) |
|---|---|---|---|
| Cassava | 1,860,800 | 26,336,652 | 14,153 |
| Sorghum | 811,662 | 1,965,865 | 2,422 |
| Cacao | 655,009 | 208,537 | 318 |
| Potatoes | 144,829 | 3,676,046 | 25,382 |
| Oil seed | 156,412 | 120,499 | 770 |
| Peanuts | 113,085 | 296,600 | 2,623 |
| Oats | 111,208 | 232,175 | 2,088 |
| Barley | 79,270 | 236,911 | 2,989 |
| Triticale | 75,640 | 184,602 | 2,441 |
| Onion | 63,639 | 1,299,815 | 20,425 |

**Source:** GCEA, IBGE (2008).

use efficiency in tropical soils. This paper will elaborate on the the extent of crop production and fertilizer use in Brazil, with focus for improving nutrient use efficiency. It is expected that the same principles can apply to other tropical regions across the globe.

## 2. Agriculture in Brazil: area, crops, production and average yields

Total crop production in Brazil in 2008 was 145.8 million tons (IBGE, 2009), 9.5% higher than in 2007 (133.1 million tons). The percent distribution of total crop production by region in Brazil is as follows: south (61.3 million t), midwest (50.7), southeast (17.5), northeast (12.5) and north (3.8). Total crop area was 4.1% higher in 2008 compared to 2007. In particular, sugarcane showed a 19.2% increase in total production in 2008, as well as a 12.5% expansion in cropped area, primarily due to forecasts for increased demand of ethanol.

Soybean, corn and rice represented 89.7% of the total grain production in Brazil in 2008. Crops grown for export comprise the majority of the cultivated area (**Table 1**). Among the list of Brazil's secondary crops (**Table 2**), cassava holds a significant portion of cultivated area.

## 3. Fertilizer Use in Brazil

Brazil depends heavily on the international fertilizer market, with imports mainly from the USA (nitrogen), Russia (nitrogen and potash), Morocco (rock phosphate), and Canada (potash). Total fertilizer consumption in the country in 2008 was 22.429 million tons, which was 8.9% lower than in 2007. Mato Grosso is the leading state in terms of fertilizer consumption (16.6%), followed by São Paulo (14.5%), Parana (14.5%), Minas Gerais (12.4%) and Rio Grande do Sul (11.4%) (IEA, 2009). **Figure 1** illustrates fertilizer consumption by region. The midwest is the leading region with 31% of the total fertilizer consumption in the country.

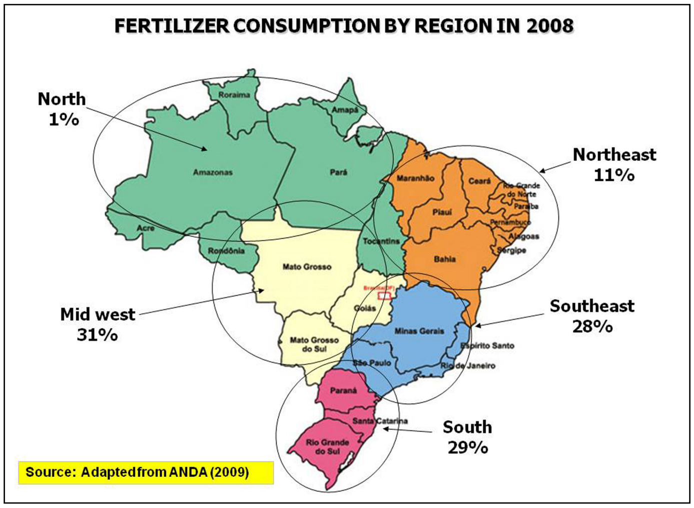



**Figure 1**. Fertilizer consumption by region in Brazil in 2008.

**Table 3** shows the evolution of crop-wise fertilizer consumption in Brazil from 1991 to 2008. Soybean continues to be the dominant crop and consumed about 33% of the total in 2008. Data on total N, $P_2O_5$ and $K_2O$ consumption during the past three decades is provided in **Figure 2** and **Tables 4** to **6**. Brazil has experienced a sharp increase in fertilizer consumption during this period. A decline in 2008 is associated with the effects of the world financial situation and the lack of credit available for fertilizer importation.

**Table 3**. Percent fertilizer consumption by main crops in Brazil (1991 – 2008).

| Crop | 1991 | 1996 | 2001 | 2006 | 2007 | 2008 |
|---|---|---|---|---|---|---|
| | | | % of total | | | |
| Soybean | 17.2 | 22.8 | 32.6 | 33.9 | 34.0 | 33.2 |
| Corn | 17.6 | 20.6 | 17.3 | 17.4 | 19.3 | 19.6 |
| Sugarcane | 20.4 | 17.5 | 12.6 | 14.9 | 14.0 | 13.0 |
| Coffee | 6.3 | 6.8 | 6.8 | 7.6 | 6.3 | 5.7 |
| Cotton | 3.6 | 1.5 | 3.7 | 5.0 | 5.0 | 3.9 |
| Total (1,000 t) | 8,510 | 12,248 | 16,737 | 20,982 | 24,609 | 22,429 |

**Source:** ANDA (2009).

**Table 4**. Nitrogen fertilizer – local production and importation (1981-2008).

| Year | Local | Importation | Total | % Imported |
|---|---|---|---|---|
| | | (1,000 t of N) | | |
| 1981 | 348.8 | 319.1 | 667.9 | 48 |
| 1986 | 714.2 | 275.7 | 989.9 | 28 |
| 1991 | 704.3 | 232.0 | 936.3 | 25 |
| 1996 | 779.0 | 502.8 | 1,281.8 | 39 |
| 2001 | 658.0 | 1,073.0 | 1,731.0 | 62 |
| 2006 | 847.0 | 1,491.0 | 2,338.0 | 64 |
| 2007 | 757.0 | 2,322.0 | 3,079.0 | 75 |
| 2008 | 686.0 | 1,903.3 | 2,589.3 | 74 |

**Source:** ANDA (2009).

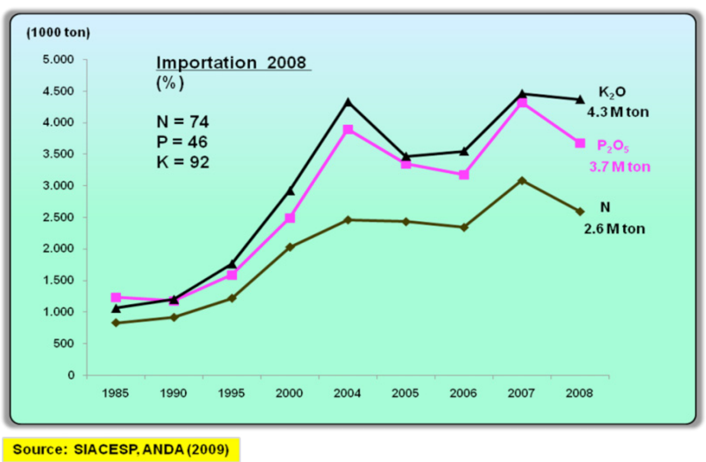



**Figure 2**. N, $P_2O_5$, and $K_2O$ consumption in Brazil (1985 – 2008).

## 4. Nutrient Balance in Brazilian Agriculture

A recently completed study on macronutrient balance in Brazilian agriculture indicates that 59%, 48% and 66% of added N, $P_2O_5$, and $K_2O$ are exported from Brazilian soils (**Table 7**). It is important to note that these nutrient exports did not necessarily originate from direct fertilizer applications to soil. Plants can take up nutrients from other sources (native to the soil or added as organic matter). However, these numbers create a general opportunity to verify nutrient use efficiency. Although reasonable, these efficiencies can be improved with better use and management of fertilizers.

## 5. Main Soil Fertility Constraints in Brazil

The soils in the tropical region of the globe are mainly poor in soil fertility, which leads to low yield potentials if not managed properly. According to Sanches and Salinas (1981), the main problems in tropical America are high amounts of toxic Al (more than 50% of total area) and extensive deficiencies in N, P, K, Ca, Mg, S and Zn. In Brazil

**Table 5**. Phosphate fertilizer – local production and importation (1981-2008).

| Year | Local | Importation | Total | % Imported |
|---|---|---|---|---|
| | ------------------------------- | (1,000 t of $P_2O_5$) | ------------------------------- | |
| 1981 | 1,084.4 | 136.5 | 1,220.9 | 11 |
| 1986 | 1,415.8 | 147.3 | 1,563.1 | 9 |
| 1991 | 1,096.8 | 179.8 | 1,276.6 | 14 |
| 1996 | 1,268.9 | 463.7 | 1,732.6 | 27 |
| 2001 | 1,445.0 | 1,147.0 | 2,592.0 | 44 |
| 2006 | 1,847.0 | 1,325.0 | 3,172.0 | 42 |
| 2007 | 2,107.4 | 2,208.4 | 4,315.8 | 51 |
| 2008 | 1,970.5 | 1,703.1 | 3,673.6 | 46 |

**Source:** ANDA (2009).

**Table 6**. Potassium fertilizer – local production and importation (1981-2008).

| Year | Local | Importation | Total | % Imported |
|---|---|---|---|---|
| | ------------------------------- | (1,000 t of $K_2O$) | ------------------------------- | |
| 1981 | - | 766.6 | 766.6 | 100 |
| 1986 | 10.5 | 1,280.1 | 1,290.6 | 99 |
| 1991 | 101.8 | 1,178.1 | 1,279.9 | 92 |
| 1996 | 240.7 | 1,828.5 | 2,069.2 | 88 |
| 2001 | 357.0 | 2,525.0 | 2,882.0 | 88 |
| 2006 | 424.0 | 3,122.0 | 3,546.0 | 88 |
| 2007 | 389.1 | 4,068.0 | 4,457.1 | 91 |
| 2008 | 352.0 | 4,014.1 | 4,366.1 | 92 |

**Source:** ANDA (2009).

**Table 7**. Nutrient balance in Brazilian agriculture (2007).

| Item | N | $P_2O_5$ | $K_2O$ |
|---|---|---|---|
| Exportation by main crops (t) | 5,506,516 | 1,616,368 | 2,647,697 |
| N deduction from the biological fixation of N by soybean and beans (t) [(1)] | 3,579,623 | - | - |
| N deduction considering 60 kg $ha^{-1}$ of this nutrient from soybean taken up by winter relay crops (t) | 423,898 | - | - |
| K deduction considering 20% of $K_2O$ coming from sugarcane industry by-products (t) | - | - | 92,422 |
| Total exportation (t) (A) | 1,502,995 | 1,616,368 | 2,555,276 |
| Input by fertilizers (t) (B) | 2,557,647 | 3,402,224 | 3,881,656 |
| **Relative Index (= A/B * 100)** | **59%** | **48%** | **66%** |

**Source:** Cunha (2009; unpublished data)
[(1)] 100% for soybean and 30% for beans.

**Table 8**. Comparison of average levels of soil fertility from the Midwest and Amazon regions of Brazil with adequate levels for crop cultivation.

| Soil Fertility Index | Adequate Levels | Soils of Midwest | Soils of Amazon |
|---|---|---|---|
| N (%) | 0.13-0.16 | 0.09 | 0.13 |
| pH in $H_2O$ | 6.0-6.5 | 5.0 | 4.5 |
| Available P, ppm[(1)] | 10-15 | 5.0 | 4.5 |
| $S\text{-}SO_4^{2-}$, ppm | 10-15 | 7 | not available |
| $K^+$ | 0.20-0.30 | 0.08 | 0.10 |
| $Ca^{2+}$ | 3-4 | 0.25 | 0.48 |
| $Mg^{2+}$ | 1.0-1.5 | 0.09 | 0.23 |
| $Al^{3+}$ | < 0.6 | 0.6 | 0.5 |
| $K^+$ (as % CEC) | 3.0-5.0 | 1.0 | 1.0 |
| $Ca^{2+}$ (as % CEC) | 50-60 | 10 | 6 |
| $Mg^{2+}$ (as % CEC) | 10-15 | 10 | 3 |
| Base Saturation (as % CEC) | 50-70 | 30 | 10 |
| Al Saturation | < 30 | 59 | 44 |
| B, ppm[(2)] | 0.5-1.0 | 0.10 | 0.53 |
| Cu, ppm[(1)] | 0.8-1.6 | 0.6 | 0.17 |
| Fe, ppm[(1)] | 30-40 | 32 | 148 |
| Mn, ppm[(1)] | 10-20 | 8 | 3.6 |
| Zn, ppm[(1)] | 1-5 | 0.6 | 0.4 |

**Source:** Adapted from Malavolta (1992).
[(1)] Mehlich 1. [(2)] Hot water.

these constraints are even more intense. Another common problem in the tropics, and especially Brazil, is high soil fixation capacity, which renders P unavailable for plants. In a study with 518 soil samples from the midwest, 92.1% were considered as very low in P (Lopes, 1983). **Table 8** shows the average soil fertility for the midwest and Amazonia region of Brazil in comparison to adequate indexes of soil fertility (Malavolta, 1992).

## 6. Nutrient Use Efficiency: Concepts and Some Agronomic Data from Brazil

The most common concept for nutrient use efficiency is one which relates the increase in yield per unit of nutrient applied to soil. Consequently, a low nutrient efficiency generally translates into low profitability (Lopes and Guilherme, 2002). In order to obtain high nutrient use efficiency farmers are advised to carefully consider the principles of the *4R nutrient stewardship concept* (i.e., *right source, right rate, right time and right place* – more details provided below). The correct definition of these principles requires knowledge of plant nutrition, soil chemistry, soil fertility, fertilizer characteristics, soil physics, soil classification and also economics (Yamada, 1989).

In literature one will find different formats for calculating nutrient use efficiency. According to Graham (1984) efficiency can be defined as the relative production of a genotype in a deficient soil in comparison with its production under an optimal level of nutrients. Cooke (1987) defined nutritional efficiency as the increase in yield per unit of nutrient applied. Israel and Rufty Junior (1988) defined nutritional efficiency as the relationship between total biomass and the amount of nutrient absorbed by plants. Maranville et al. (1980), Siddiqi and Glass (1981), Craswell and Godwin (1984) and Fageria (1992) have mentioned that nutritional efficiency can be expressed and calculated by five different formats: *(i) agronomic effectiveness (AE), (ii) physiological effectiveness (PE), (iii) grain yield efficiency (GYE), (iv) recovery efficiency (RE), and (v) utilization efficiency (UE).*

In Brazil, although other indexes of nutrient use efficiency (i.e., absorption efficiency and biomass conversion efficiency) have been used, the most common include the five indexes quoted above by Maranville et al. (1980) and others.

**Table 9**. Agronomic effectiveness (AE) of rice cultivars in soils of the Midwest of Brazil.

| Cultivar | ---------------------Grain Yield (kg ha$^{-1}$)--------------------- | | AE |
|---|---|---|---|
| | 15 kg ha$^{-1}$ N | 50 kg ha$^{-1}$ N | (kg grain per kg N) |
| IAC 114 | 2,319 | 2,800 | 14 |
| CNA 790124 | 3,208 | 4,075 | 25 |
| CNA 800160 | 2,929 | 3,142 | 6 |
| IAC 136 | 2,198 | 2,278 | 2 |
| IAC 165 | 1,232 | 1,578 | 10 |
| IR 20 | 1,040 | 1,330 | 8 |
| CN 770538 | 896 | 1,687 | 23 |
| IR 144 | 1,405 | 1,483 | 2 |
| IRAT 134 | 959 | 1,073 | 3 |

**Source:** FAGERIA et al. (1997).

Below are full definitions to these five indexes:

*(i) Agronomic effectiveness (AE):* relates the yield (grain for annual crops) to the amount of nutrient applied. AE is also named economic effectiveness. It can be estimated by the equation:

$$AE = \frac{\textit{Yield, in Kg, with fertilizer} - \textit{Yield, in Kg, with no fertilizer}}{\textit{Amount of nutrient applied, in Kg}}$$

In field experiments, AE is generally expressed as Kg of product per Kg of nutrient. **Table 9** shows the AE for N of some upland rice cultivars in Brazil.

*(ii) Physiological Effectiveness (PE):* relates the biological yield (grain + straw for annual crops) per unit of nutrient accumulated by plants. At times the PE is also named biological effectiveness. The PE can be calculated as:

$$PE\ (kg\ kg^{-1}) = \frac{\textit{Total dry matter yield with fertilizer (Kg)} - \textit{Total dry matter yield without fertilizer (Kg)}}{\textit{Nutrient uptake by plants with fertilizer (Kg)} - \textit{Nutrient uptake by plants without fertilizer (Kg)}}$$

*(iii) Grain Yield Effectiveness (GYE)*: relates the yield per unit of nutrient accumulated by plants and can be estimated by the following equation:

$$GYE = \frac{\textit{Grain Yield, in Kg, with fertilizer} - \textit{Grain Yield, in Kg, without fertilizer}}{\textit{Nutrient uptake by straw and grain, in Kg, with fertilizer} - \textit{Nutrient uptake by straw and grain, in Kg, without fertilizer}}$$

**Table 10** summarizes the GYE for upland rice cultivars in Brazil. It is possible to note large differences in terms of GYE among the different cultivars.

*(iv) Recovery Effectiveness (RE):* relates the amount of nutrient accumulated by the plants per unit of nutrient applied and can be estimated by the equation:

$$RE = \frac{\textit{Nutrient uptake by plants, in Kg, with fertilizer} - \textit{Nutrient uptake by plants, in Kg, without fertilizer}}{\textit{Amount of nutrient applied, in Kg}}$$

The RE is generally expressed on a percent basis and is also referred to as nutrient acquisition effectiveness.

*(v) Utilization efficiency (UE):* combines PE and RE into one equation:

$$UE = PE \times RE = Kg\ Kg^{-1}$$

Martinez et al. (1993 a, b) measured several nutrient efficiency indexes for three soybean cultivars under greenhouse conditions. Here the authors verified that the AE of the UFV1 variety was lower than Doko, and the Santa Rosa cultivar fell between these two. The most efficient varieties in terms of P utilization had lower ratios between above ground tissue and the roots at low levels of P, and suggested a higher efficiency in terms of root development (**Table 11**).

## 7. General Guidelines for Management Practices to Increase Nutrient Use Efficiency in Tropical Soils

**Table 10**. Grain Yield Effectiveness (GYE) for rice cultivars in soils of in midwestern Brazil.

| Genotipes | ----------- GYE (kg of grain per kg nutrient accumulated by the plants) ----------- | | |
|---|---|---|---|
| | N | P | K |
| CNA 7013-D | 62 | 376 | 52 |
| Araguaia | 24 | 413 | 16 |
| IAC 84-198 | 51 | 503 | 99 |
| IAC 1175 | 47 | 458 | 33 |
| CNA 6710 | 34 | 376 | 48 |
| CNA 7024 | 37 | 858 | 38 |
| CNA 7066 | 25 | 395 | 303 |
| IAC 1176 | 41 | 288 | 46 |
| Média | 40 | 458 | 79 |

**Source:** FAGERIA et al. (1994).

**Table 11**. Agronomic (AE), recovery (RE), absorption (AbE) and root development effectiveness (RDE) of three soybean cultivars in different rates of P applied.

| Rates of P (mg) | Cultivars | | |
|---|---|---|---|
| | Santa Rosa | Doko | UFV1 |
| | | AE (mg DMY $mg^{-1}$ P applied) | |
| 30.4 | 275.22 aAB[1] | 280.15 aA | 253.40 aB |
| 54.6 | 169.36 Ba | 164.16 bA | 148.15 bA |
| 78.9 | 112.00 Ca | 120.62 cA | 98.99 cA |
| | | RE (mg P absorbed $mg^{-1}$ P applied) | |
| 30.4 | 0.697 Aa | 0.673 aA | 0.603 aA |
| 54.6 | 0.715 aA | 0.726 aA | 0.657 aA |
| 78.9 | 0.691 aAB | 0.744 aA | 0.619 aB |
| | | AbE (mg P absorbed $mg^{-1}$ root DMY) | |
| 30.4 | 0.011 cA | 0.009 cA | 0.012 cA |
| 54.6 | 0.024 bA | 0.024 bA | 0.026 bA |
| 78.9 | 0.034 aA | 0.036 aA | 0.034 aA |
| | | RDE (mg root DMY $mg^{-1}$ P absorbed) | |
| 30.4 | 65.57 aA[2] | 71.60 aA | 53.62 aB |
| 54.6 | 30.31 Ba | 30.74 bA | 25.18 bB |
| 78.9 | 19.90 cA | 20.95 cA | 18.21 cA |

[1] Average result followed by the same capital letter, in the lines, or some low case letters, in the column, do not differ by the Duncan test at 5% probability.
[2] Comparisons based on results submitted to mathematical transformations.
**Source:** Adapted from Martinez et al. (1993 a,b).

In order to increase nutrient use efficiency, native to the soil or added through fertilizers, it is necessary to examine the many variables that interact with fertilizer application. Soil, crop, expected climatic conditions, cropping systems and general crop management are decisive factors that should be carefully studied to obtain not just the desired nutrient efficiency, but also the desired profit.

**Table 12**. Management practices to increase nutrient use efficiency.

| Fertilizer | Practice | Effect |
|---|---|---|
| NPK | (1) Soil chemical analysis (surface and subsurface) | (1) Determination of right rate |
| | (2) Plant tissue analysis | (2) Adjustment of fertilizer recommendation and tracking of plant nutritional status |
| | (3) Soil erosion control | (3) Avoid soil and nutrient losses |
| | (4) Use of cultivars with higher nutrient use efficiency and more responsive to fertilizer application | (4) Facilitate nutrient absorption at low levels in the soil, increase plant response to nutrient applied, convert nutrient from fertilizer into production |
| N | (1) Liming and phosphogypsum application | (1) More roots development, higher nutrient uptake |
| | (2) Fractionation of rates at different times | (2) Lower losses by leaching and volatilization, higher nutrient uptake |
| | (3) Urease or nitrification inhibitors | (3) Lower losses by leaching and volatilization, higher nutrient uptake |
| | (4) Slow release fertilizer | (4) Lower losses by leaching and volatilization, higher nutrient uptake |
| | (5) Crop rotation and cycling of residues | (5) Avoid nutrient wastes, save in regular fertilizer, increase soil physical properties |
| P | (1) Liming | (1) Lower P fixation, lower rates |
| | (2) Phosphogypsum application | (2) More roots development, higher nutrient uptake |
| | (3) Placement | (3) Increase contact with plant roots and not with soil sesquioxides |
| | (4) Mycorrhizae | (4) Increase contact with P |
| K | (1) Liming | (1) Increase cation exchange capacity in soils with variable charge, decrease K leaching |
| | (2) Phosphogypsum | (2) More root development, higher nutrient uptake |
| | (3) Placement | (3) Avoid/decrease effect of fertilizer salinity |
| | (4) Fractionation of rates | (4) Increase nutrient uptake |

**Source:** Adapted from Malavolta (1996).

**Table 12** summarizes, according to Malavolta (1996), management practices that should be adopted to increase nutrient use efficiency in Brazilian soils. These general factors can be used under other tropical conditions, but should be adjusted to fit local conditions.

Recently IFA and IPNI have been emphasizing the use of the *4R nutrient stewardship concept* as a general guideline for good practices related to nutrient use. It primarily considers that nutrients have to be applied at the *right source, right rate, right time and right place*. Again, these four fundamentals have to be adapted according to local research and farmer practice.

The *right source* of nutrient is specific for the region and crop. The chemical form of the nutrient in fertilizer also has to be considered. For example, mechanically harvested sugarcane creates large amounts of plant residue on the soil surface. Regular use of surface applied urea, the most utilized source of N in Brazil, will dramatically increase the risk for volatilization of N within this system due to rapid enzymatic conversion to ammonia resulting from prolonged contact with these crop residues. In a situation like this consultants and farmers have to look for alternatives, some being: *(i) incorporation of urea into the soil, (ii) other sources of N such as ammonium sulfate or ammonium nitrate, (iii) coated urea, and (iv) urea with a urease inhibitor such as NBPT (N-(n-butyl)thiophosphoric triamide)*.

The *right rate* of nutrient also depends on local research. Generally a methodology of soil analysis is selected based on *correlation studies*. This methodology is then calibrated

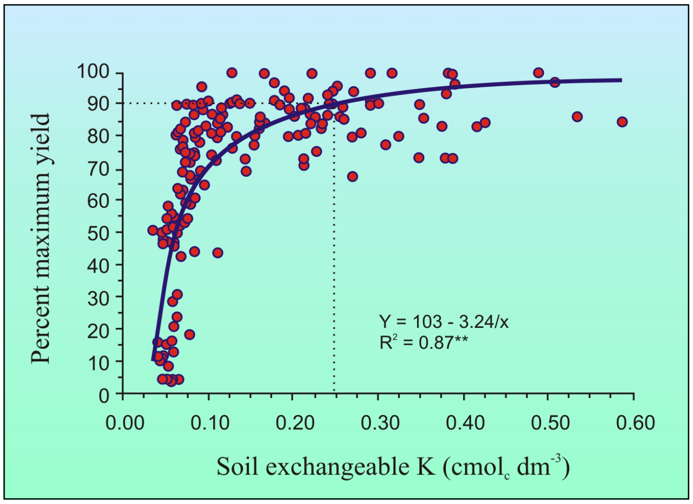



**Figure 3**. Calibration study relating soybean yield in percent basis with soil exchangeable K (Borket et al., 2005).

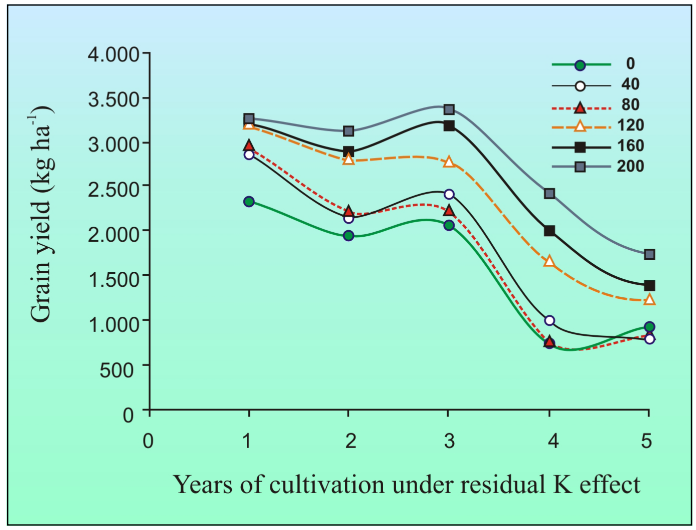



**Figure 4**. Soybean grain yield with time after suspension of different levels of K fertilization in previous years (0 to 200 Kg ha$^{-1}$ of $K_2O$).

for several crops under field conditions, or *calibration studies* – defining the nutrient level ranges in very low, low, medium, high and very high soil fertility conditions. Finally the research in *response curves* leads to an adequate and economic nutrient recommendation in terms of amounts to be used at each level of soil fertility. An example K calibration study in Brazil is shown in **Figure 3**. The appropriate rate used is specific to the region, crop and methodology. Alternative forms of nutrient rate definition exist, but regional studies are always necessary. One important aspect of the *right rate* concept relates to its correct application. There is no good in carefully defining the right rate to apply and then improperly applying it in the field. Many Brazilian farmers simply do not have the correct equipment or do not spend enough time calibrating their machines.

The same total amount of fertilizer applied in different strategies can lead to very different yields. The *right time* of nutrient application often leads to an increase in yield. As an example, soybean yield increases of up to 500 kg ha$^{-1}$ have been achieved by splitting the K application (½ at planting and ½ in top dressing) instead of applying all the K at planting.

The *right place* is also very important. Enormous gains in initial plant development can be obtained in corn when fertilizer is applied five cm below and five cm to the side of the seed row. This effect is directly related to the fertilizer salinity index, which if high can lead to lower amounts of available water and seedling damage.

On top of these four important factors (*source, rate, time and place*) there are many others that can influence nutrient use efficiency. For tropical soils the most important are: *(i) soil acidity control, (ii) phosphogypsum application, (iii) cropping system diversity, and (iv) organic matter evaluation and control*. Soils of the tropics are generally acidic and need to be ameliorated with liming materials to favor root and plant development. Liming can improve many soil properties including improved Ca and Mg content, decreased Al activity and increased nutrient availability. Phosphogypsum, which is applied in many soils as a by-product of the phosphoric acid industry, can also improve subsurface soil conditions (i.e., increased Ca and decreased Al activity) where lime, due to its low solubility, can't generally reach and react. The use of phosphogypsum has been extensively studied in Brazil and many farmers have benefited from its application. In terms of cropping system diversity, recent studies in Brazil have reinforced the importance of establishing real crop rotations, but these cropping systems have to be defined locally. The introduction of Brachiaria grass into crop rotations has been very advantageous in terms of improving nutrient uptake and system profitability. Data from Borghi et al. (2007) shows increases in agronomic effectiveness of up to 34% with the introduction of Brachiaria grass into a traditional cropping system.

Most Brazilian soils require routine applications of nutrients when aiming at high yields due to low soil cation exchange capacity. This is exemplified in **Figure 4**, which summarizes the results of a study on the residual effect of K in soybean (Borket et al., 2005). Yields dropped sharply after the second year of cultivation with no K added to the soil. Routine soil chemical analysis provides the guidance required to know when and how much nutrient should be applied.

## 8. Final Considerations

This manuscript summarizes: *(i) the situation in Brazil regarding crops, yields and fertilizer consumption, (ii) concepts used for assessing nutrient use efficiency, and (iii) guidelines for proper management of Brazilian soils.* All concepts and fundamentals discussed have to be adjusted for local conditions. It is expected that similar concepts can be applied with success in other tropical regions.

## References


ANDA. ASSOCIAÇÃO NACIONAL PARA DIFUSÃO DE ADUBOS. Anuário estatístico do setor de fertilizantes 2009. São Paulo, 2009. 160 p.

BALIGAR, V. C.; BENNETT, O. L. NPK-fertilizer efficiency - a situation analysis for the tropics. Fertilizer Research, Dordrecht, v. 10, p. 147-164, 1986.

BALIGAR, V. C.; FAGERIA, N. K. Nutrient use efficiency in acid soils: nutrient management and plant use efficiency. In: INTERNATIONAL SYMPOSIUM ON PLANT-SOIL INTERACTIONS AT LOW pH, 4., 1996, Belo Horizonte. Proceedings... Belo Horizonte : Brazilian Soil Science Society, 1997. p. 76-95.

BORGHI, E.; CRUSCIOL, C.A.  Produtividade de milho, espaçamento e modalidade de consorciação com Brachiarai brizantha no sistema plantio direto. Pesquisa Agropecuária Brasileira, Brasília, v.42, p.163-171, 2007.

BORKERT, C. M.; CASTRO, C.; OLIVEIRA, F. A.; KLEPKER, D.; OLIVEIRA JUNIOR, A. O potássio na cultura da soja. In: Potássio na Agricultura Brasileira. Piracicaba: POTAFOS, 2005. p. 671-722.

COOKE, G. W. Maximizing fertilizer efficiency by overcoming constraints to crop growth. Journal of Plant Nutrition, New York, v. 10, p. 1357-1369, 1987.

CRASWELL, E. T.; GODWIN, D. C. The efficiency of nitrogen fertilizers applied to cereals in different climates. In: TINKER, P. B.; LAUCHI, A. (Eds.) Advances in plant nutrition. New York: Praeger, 1984. p. 1-55.

FAGERIA, N. K. Maximizing crop yields. New York: Marcel Dekker, 1992. 274 p.

FAGERIA, N. K. Otimização da eficiência nutricional na produção das culturas. Revista Brasileira de Engenharia Agrícola e Ambiental, Campina Grande, v. 2, p. 6-16, 1998.

FAGERIA, N. K.; BALIGAR, V. C.; JONES, C. A. Rice. In: FAGERIA, N. K.; BALIGAR, V. C.; JONES, C. A. Growth and mineral nutrition of field crops. 2.ed. New York : M. Dekker, 1997. p. 283-343.

FAGERIA, N. K.; SANTANA, E. P.; CASTRO, E. M. de; MORAIS, O. P.; MOURA NETO, F. P. de. Resposta diferencial de linhagens de arroz de sequeiro à fertilidade do solo. In: CONFERÊNCIA INTERNACIONAL DE ARROZ PARA AMÉRICA LATINA E O CARIBE, 9., 1994, Goiânia. Resumos... Goiânia: EMBRAPA-CNPAF/CIAT, 1994.

GCEA. Grupo de Coordenação de Estatísticas Agropecuárias. Systematic Analyses of Brazilian Agriculture Production, 2008. GCEA/IBGE, 2008.

GOEDERT, W. J.; LOBATO, E.; LOURENÇO, S. Nutrient use efficiency in Brazilian acid soils: Nutrient management and plant efficiency. In: MONIZ, A. C.; FULANI, A. M. C.; SCHAFFERT, R. E.; FAGERIA, N. K.; ROSOLEM, C. A.; CANTARELLA; H. Plant-soil interactions at low pH: sustainable agriculture and forestry production. Brasília: SBCS, 1997. p. 97-104.

GRAHAM, R. D. Breeding for nutritional characteristics in cereals. In: TINKER, P. B.; LAUCHI, A. (Eds.). Advances in plant nutrition. New York: Praeger, 1984. p. 57-102.

HOROWITZ, N. Desafios e perspectivas do uso de fertilizantes no Brasil. In: CONGRESSO BRASILEIRO DE CIÊNCIA DO SOLO, 31., 2007, Gramado. Anais... Porto Alegre: UFRGS/SBCS, 2007. CD-ROM

IBGE. Instituto Brasileiro de Geografia e Estatística. Em 2009, safra deve atingir 137,3 milhões de toneladas. Disponível em <http://www.ibge.gov.br/home/presidencia/noticias/noticia_visualiza.php?id_noticia=1298&id_pagina=1>. Acesso em: 10 de jul. 2009.

IBGE. Instituto Brasileiro de Geografia e Estatística. Levantamento sistemático da produção agrícola. Pesquisa Mensal de Previsão e Acompanhamento das Safras Agrícolas no Ano Civil, 2008. Disponível em: <http://www.ibge.gov.br/home/default.php>. Acesso em: 10 de jul. 2009.

IEA. Instituto de Economia Agrícola. Fertilizantes: reversão dos excessos. Disponível em < http://www.iea.sp.gov.br/out/verTexto.php?codTexto=10493>. Acesso em: 10 de jul. 2009.

ISRAEL, D. W.; RUFTY JUNIOR, T. W. Influence of phosphorus nutrition on phosphorus and nitrogen utilization efficiencies and associated physiological response in soybean. Crop Science, Madison, v. 28, p. 954-960, 1988.

LOPES, A. S. Solos sob "Cerrado": características, propriedades e manejo. Piracicaba: POTAFOS, 1983. 162 p.

LOPES, A. S.; GUILHERME, L. R. G. Uso eficiente de fertilizantes e corretivos agrícolas: aspectos agronômicos. 3 ed. rev. São Paulo: ANDA, 2000. 72 p. (Boletim Técnico, 4).

MACHADO, A. T. Perspectiva do melhoramento genético em milho (*Zea mays* L.) visando eficiência na utilização do nitrogênio. 1997. 219 p. Tese (Doutorado em Genética e Melhoramento de Plantas) - Curso de Pós-Graduação em Genética e Melhoramento, Universidade Federal do Rio de Janeiro, Rio de Janeiro, 1997.

MALAVOLTA, E. Adubação e seu impacto ambiental. In: XIII Congresso Latinoamericano de Ciência do Solo. Águas de Lindóia: Sociedade Brasileira de Ciência do Solo, 1996.

MALAVOLTA, E. Fertilizantes, corretivos e produtividade - mitos e fatos. In: DECHEN, A. R.; BOARETTO, A. E.; VERDADE, F. C. (Coords.). XX Reunião Brasileira de Fertilidade do Solo e Nutrição de Plantas. Campinas: Fundação Cargill, 1992. p. 89-153.

MARANVILLE, J. W.; CLARK, R. B.; ROSS, W. M. Nitrogen efficiency in grain sorghum. Journal of Plant Nutrition, New York, v. 2, p. 577-589, 1980.

MARTINEZ, H. E. P.; NOVAIS, R. F.; RODRIGUES, L. A.; SACRAMENTO, L. V. S. do. Comportamento de variedades de soja cultivadas em diferentes doses de fósforo. I. Cinética de absorção de fósforo e ajustes morfológicos da planta. Revista Brasileira de Ciência do Solo, Campinas, v. 17, p. 231-238, 1993a.

MARTINEZ, H. E. P.; NOVAIS, R. F.; SACRAMENTO, L. V. S. do; RODRIGUES, L. A. Comportamento de variedades de soja cultivadas sob diferente níveis de fósforo: II. Translocação do fósforo absorvido e eficiência nutricional. Revista Brasileira de Ciência do Solo, Campinas, v. 17, p. 239-244, 1993b.

SANCHEZ, P.; SALINAS, J. G. Low-imput technology for managing Oxisols and Ultisols in tropical America. Advances in Agronomy, v. 34, p. 279-406, 1981.

SIDDIQI, M. Y.; GLASS, A. D. M. Utilization index: a modified approach to the estimation and comparison of nutrient utilization efficiency in plants. Journal of Plant Nutrition, New York, v. 4, p. 289-302, 1981.

YAMADA, T. Uso eficiente de fertilizantes. Palestra apresentada no Curso de Atualização de Fertilidade do Solo, promovido pela FFALM, POTAFOS e ANDA. Bandeirantes, PR, 23 a 27/outubro/1989. 27 p. (mimeografado).

# NUTRIENT USE EFFICIENCY OF CROPPING SYSTEMS IN THE SOUTHERN CONE OF LATIN AMERICA

**Fernando O. Garcia[1] and Fernando Salvagiotti[2]**

## 1. Introduction: Crop production in the countries of the Southern Cone

The Southern Cone region of Latin America includes five countries: Argentina, Bolivia, Chile, Paraguay and Uruguay. Approximately 65 million ha are devoted to agriculture, from which ca. 57% include grain crops, mainly soybean, wheat, maize, sunflower and rice. A large area (ca. 34%), is under pastures and forages, mainly dedicated to beef and dairy cattle production. Fruits, vegetables and forestry occupy the rest of the area and have a significant role in economy because of the high value of the production.

The global demand for food, feed, fiber, and biofuels in the last years has driven a strong increase in grain production in the region. In 2007, grain crops occupied 37 million ha in the Southern Cone, from which 55%, 18% and 14% were planted with soybean, wheat, and maize, respectively (**Table 1**). Argentina leads grain crop production in the region with 82% of the harvested area and 84% of the production. This country has shown a steady increase in crop production during the last 18 years (from 40 million ton in 1990 to 95 million ton in 2007). In this period, a 20-30% increase in grain yield per unit area was observed, attributed to improvements not only in genetics (new hybrids and varieties, glyphosate-resistant soybean, Bt maize), but also in crop management (planting dates, populations, pest control), no-tillage adoption and fertilizer use. However, the expansion of planted area with soybean explains most of the increase

**Table 1**. Area (thousand ha), production (thousand ton) and average yield (kg/ha) of the main field crops in the five countries of the Southern Cone region.

| Country<br>Source & year of data | | Soybean | Wheat | Maize | Sorghum | Sunflower | Barley | Total |
|---|---|---|---|---|---|---|---|---|
| Argentina<br>SAGPyA 2007 | Area | 16500 | 5850 | 4000 | 825 | 2650 | 436 | 30261 |
| | Production | 46500 | 16000 | 20400 | 3000 | 4630 | 1460 | 91990 |
| | Yield | 2818 | 2735 | 5100 | 3636 | 1747 | 3349 | 3040 |
| Bolivia<br>INE 2007 | Area | 959 | 144 | 354 | 110 | 162 | 93 | 1822 |
| | Production | 1596 | 165 | 770 | 372 | 173 | 73 | 3149 |
| | Yield | 1665 | 1147 | 2175 | 3385 | 1070 | 778 | 1729 |
| Chile<br>ODEPA 2007 | Area | - | 271 | 135 | - | 3.6 | 21 | 431 |
| | Production | - | 1238 | 1365 | - | 7.6 | 96 | 2707 |
| | Yield | - | 4570 | 10140 | - | 2110 | 4640 | 6286 |
| Paraguay<br>CAPECO 2007 | Area | 2430 | 320 | 450 | 23 | 109 | - | 3332 |
| | Production | 5581 | 800 | 2048 | 27 | 183 | - | 8640 |
| | Yield | 2297 | 2500 | 4552 | 1172 | 1679 | - | 2593 |
| Uruguay<br>DIEA 2007 | Area | 578 | 243 | 87 | 68 | 55 | 138 | 1169 |
| | Production | 1029 | 697 | 270 | 324 | 51 | 310 | 2681 |
| | Yield | 1780 | 284 | 3085 | 4764 | 918 | 2245 | 2293 |
| Total region | Area | 20467 | 6828 | 5026 | 1026 | 2980 | 688 | 37015 |
| | Production | 54706 | 18900 | 24853 | 3723 | 5045 | 1939 | 109166 |
| | Yield | 2673 | 2768 | 4945 | 3628 | 1693 | 2820 | 2949 |

[1]IPNI Latin America Southern Cone Program, fgarcia@ipni.net
[2]EEA INTA Oliveros (Santa Fe, Argentina), fsalvagiotti@correo.inta.gov.ar

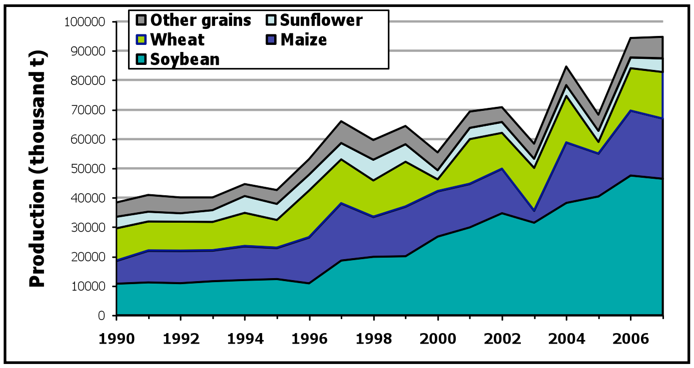



**Fig. 1**. Grain production in Argentina, 1990-2007. Source: Secretary of Agriculture (SAGPyA). http://www.sagpya.mecon.gov.ar/.

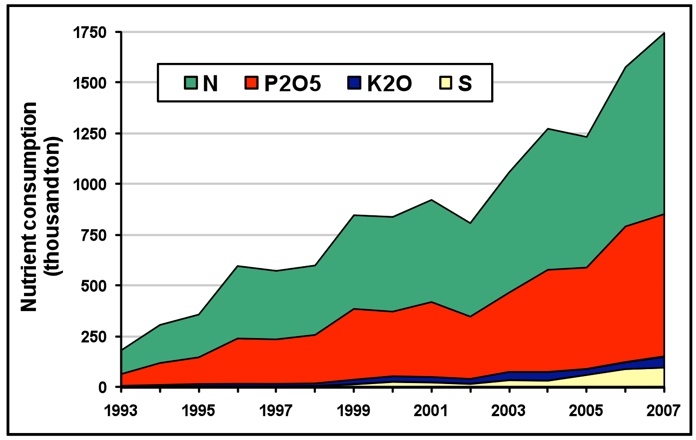



**Fig. 2**. Nutrient consumption in Argentina (1993-2007). Ellaborated from data of SAGPyA and Fertilizar AC.

in grain production in the last years (60-70% increase in the same period), including the opening of fragile ecosystems, particularly since 1996 when glyphosate-resistant varieties were adopted. Soybean currently occupies ca. 51% of the total cropped area (**Fig. 1**).

Since the possibilities for the expansion of agricultural area in the Southern Cone are scarce, total grain production in this region will rely on a sustainable intensification of the cropping systems, i.e. looking for higher yields avoiding the expansion of agriculture into fragile ecosystems. This intensification requires a continuous improvement in the use of resources and inputs, in which nutrients play an essential role. The objective of this paper is to discuss nutrient use efficiency in field crop systems in temperate areas of the Southern Cone region with emphasis in the Pampas region of Argentina, the main producing area.

## 2. Fertilizer use in the Southern Cone

Fertilizer consumption in the region is close to 2.83 million metric tons of $N+P_2O_5+K_2O$ (**Table 2**). The $N:P_2O_5:K_2O$ ratio is 6:5:1. Argentina consumes approximately 58% of this total, followed by Chile (19%), Uruguay (12%), Paraguay (10%), and Bolivia (1%). A sharp increase in fertilizer consumption has been observed in Argentina and, to a lesser extent in Paraguay and Uruguay in the last years. Most of this increase has been driven by the expansion of agricultural area and increased fertilizer rates in field crops. Chile is considered a mature fertilizer market while Bolivia a small fertilizer consumer. In Argentina, fertilizer use is close to 1.75 million metric tons of $N+P_2O_5+K_2O+S$ (**Fig. 2**). Grain crops (wheat, maize, soybean, and sunflower) ex-

**Table 2**. Estimated nutrient consumption (N, $P_2O_5$ and $K_2O$) in the five countries of the Southern Cone region. Source: Fertilizar AC (Argentina); APIA (Bolivia); SQM (Chile); CAPASAGRO (Paraguay); y DF-DSA-MGAP (Uruguay).

| Country | Year | Consumption (thousand ton) | | | |
|---|---|---|---|---|---|
| | | N | $P_2O_5$ | $K_2O$ | Total $N+P_2O_5+K_2O$ |
| Argentina | 2007 | 894 | 702 | 54 | 1650 |
| Bolivia | 2007 | 13 | 12 | 4 | 29 |
| Chile | 2003 | 270 | 180 | 81 | 532 |
| Paraguay | 2007 | 42 | 167 | 82 | 328 |
| Uruguay | 2007 | 128.4 | 178.4 | 21 | 328 |
| Total | | 1347 | 1241 | 242 | 2829 |

**Table 3**. Estimated nutrient use for the main four field grain crops of Argentina in 2007.

| Crop | | N | P | S |
|---|---|---|---|---|
| Wheat | kg/ha | 46 | 15 | 10 |
| | % fertilized area | 95 | 95 | 50 |
| Maize | kg/ha | 57 | 14 | 7 |
| | % fertilized area | 90 | 90 | 40 |
| Soybean | kg/ha | - | 15 | 10 |
| | % fertilized area | - | 50 | 50 |
| Sunflower | kg/ha | 15 | 9 | 5 |
| | % fertilized area | 60 | 40 | 10 |

plain 75% of total nutrient fertilizer consumption (Melgar, 2005). Current estimations indicate that 95%, 90%, 50%, and 60% of wheat, maize, soybean, and sunflower area, receive some kind of fertilization, respectively (**Table 3**). Urea and UAN are the main fertilizer N sources, while ammonium nitrate, calcareous ammonium nitrate (CAN), and ammonium sulfate are also used, but to a lesser extent. Among P fertilizers, diammonium phosphate (DAP), monoammonium phosphate (MAP), triple superphosphate (TSP) and single superphosphate (SSP) are the most common sources. In the last years, bulk blending has become a common practice in the Pampas. NP fertilizers and blends are commonly applied at planting, and N fertilization is commonly performed at planting, but sometimes is carried out pre-plant, or top-dressed at wheat tillering or surface-banded at V5-6 maize stage. Sulfur is applied as calcium sulfate (gypsum), single superphosphate, UAN-ATS liquid solution, or ammonium sulfate among other alternatives. Applications of S are done in bulk blends at planting, broadcasting at pre-plant, or topdressing.

## 3. Nutrient budgets in temperate regions of the Southern Cone

Nutrient budgets for field crops vary among countries because of differences in soils, crops, management practices, crop yields, and technology adoption. A common characteristic for the region, with exceptions in some areas of Chile, Paraguay, and Uruguay, is the high original soil K levels, which results in low or null response to K fertilization. Continuous agriculture under intensive tillage without any fertilization, that was usual in the Pampas until the end of the last century, have depleted soil organic matter and soil nutrient reserves (Andriulo and Cordone, 1998; Urricarriet and Lavado, 1999). In Argentina, the application/removal ratios for nitrogen (N), phosphorus (P), potassium (K), and sulfur (S) in field crops have improved during the last years (**Fig. 3**), but nutrient budgets are still negative. Estimations for 2007 indicate that 48%, 59%, 42%, and less than 2% of the N, P, S, and K, respectively, removed in grains were applied as fertilizer. On the other hand, in Bolivia, low adoption of fertilization practices in field crops resulted in low application/removal rates: 0.16, 0.30, and 0.05 for N, P, and K, respectively. Therefore, intense soil degradation is expected in this country, if agriculture continues in this direction..

Most of field crop production of Paraguay is carried out in the eastern half of the country on lateritic soils, characterized by low original P levels and high P retention. These conditions explain the high P application/removal ratio estimated on 1.38. However, ratios for N and K are 0.19 and 0.49, respectively, showing a low replenishment of soil N and K.

In Uruguay, nutrient budgets showed large variations because of the high variability on soils and management conditions. Cano et al. (2006) have estimated P balances that

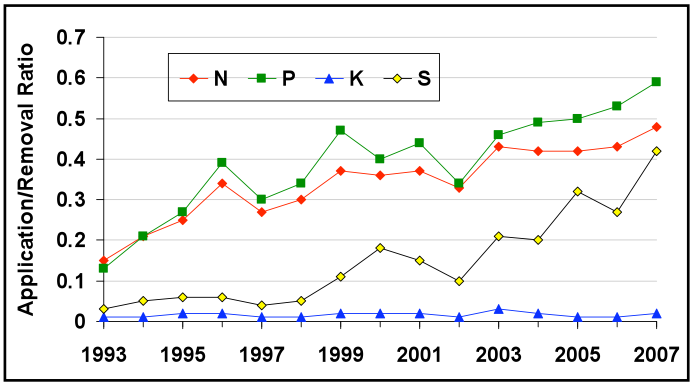



**Fig. 3**. Application/removal ratios for N, P, K, and S in Argentina. 1993-2007.

**Table 4**. Phosphorus balance in different farms grouped according to technology and management at western Uruguay (Cano et al., 2006).

| Group | Characteristics | Number of farms | Crops per year | Crops fertilized (%) | P rotation balance (kg P/ha) |
|---|---|---|---|---|---|
| A | High fertilization frequency | 7 | 1.13 | 91.1 | 24.5 |
| B | High fertilization frequency, double crop, long rotations | 6 | 1.97 | 86.7 | 11.0 |
| C (a) | Low P removal, short rotations | 6 | 1.22 | 71.4 | 4.5 |
| C (b) | No fertilization in double crops | 7 | 1.48 | 62.2 | -9.6 |
| D | High Bray P levels, low fertilization rates | 5 | 1.82 | 42.5 | -40.2 |

**Table 5**. Partial nutrient budget (PNB) and partial factor productivity (PFP) for nitrogen and phosphorus in the main four grain crops of Argentina. Estimations for the 2007/08 growing season.

| Crop | PNB | | PFP | |
|---|---|---|---|---|
| | kg removed N / kg applied N | kg removed P / kg applied P | kg grain / kg applied N | kg grain / kg applied P |
| Maize | 1.14 | 0.78 | 87 | 296 |
| Wheat | 0.86 | 0.61 | 48 | 174 |
| Soybean | - | 5.46 | - | 1011 |
| Sunflower | 1.50 | 1.23 | 69 | 201 |

PNB: Input= fertilizer; Output: crop N or P removal with grain. PFP: National grain production/ Estimated national nutrient applications for each crop. Estimations based on 2007/08 data from SAGyP and Fertilizar AC.

ranged from -40.2 to 24.5 kg P/ha for different groups of farms in the western area of the country, depending on the rotations and fertilizer use (**Table 4**).

## 4. Nutrient use efficiency in agricultural systems of the Southern Cone

Several indices exist to address short- and/or long-term nutrient use efficiency (NUE) (Dobermann, 2007: Snyder and Bruulsema, 2007). Management strategies aimed at optimizing fertilizer use should evaluate several of these indices simultaneously in order to understand the future impact of fertilization strategies. Thus, NUE should take into account not only nutrient use in a particular crop, but also the evolution of soil nutrient status in a rotation in which this crop is included. In the next sections, estimations in the region for different NUE indices are presented for N and P.

***a. Regional analysis of NUE for grain crops in Argentina.***

**Table 5** shows estimations of the partial nutrient budget (PNB) and partial factor productivity (PFP) for N and P in the main grain crops of Argentina. For maize and wheat, PNB of N is close to 1 indicating that fertilizer applications are close to N removal in both crops. In contrast, PNB for N in sunflower shows larger values, indicating that N fertilization rates are below removal. Indices other than PNB should be included in order to evaluate NUE of N since optimum N rates varies widely in a region depending on the soil capacity for supplying N, and the synchronization between crop uptake and N fertilizer application. In maize, PFP for N in Argentina is 87 kg grain per kg of applied N, ca. 30% greater than values reported in USA (Dobermann and Cassman, 2002). Therefore, this large PFP and a PNB above 1 indicate that N supply to maize is still depending on soil N supply.

PNB for P is well below 1 in wheat and maize, and PFP values in maize are approximately 20% lower than those reported in USA (Dobermann and Cassman, 2002). These numbers suggest soil P replenishment in wheat and corn,

**Table 6**. Soybean: Agronomic efficiency (AE), partial nutrient budget (PNB), and partial factor productivity (PFP) for P in three experimental networks in Argentina and Bolivia. Adapted from Ferrari et al. (2005); H. Fontanetto et al. (pers. comm.); and J. Terrazas et al. (pers. comm.).

| P rate | Grain yield | AE | PNB | PFP |
|---|---|---|---|---|
| kg P/ha | kg/ha | kg grain/ kg applied P | kg removed P / kg applied P | kg grain / kg applied P |
| | | *A. North-central Pampas region of Argentina 2003/04 – 15 trials* | | |
| 0 | 3135 | - | - | - |
| 10 | 3372 | 24 | 1.81 | 337 |
| 20 | 3557 | 21 | 0.96 | 178 |
| 30 | 3695 | 19 | 0.67 | 123 |
| | | *B. Northern Santa Fe province in the Pampas 2002-2006 (Argentina) – 28 trials* | | |
| 0 | 3230 | - | - | - |
| 10 | 3465 | 24 | 1.89 | 347 |
| 20 | 3680 | 23 | 0.99 | 184 |
| 30 | 3735 | 17 | 0.67 | 125 |
| 40 | 3715 | 12 | 0.50 | 93 |
| | | *C. Northern region of Santa Cruz 2005 (Bolivia) – 4 trials* | | |
| 0 | 2754 | - | - | - |
| 20 | 3263 | 25 | 0.88 | 163 |

**Table 7**. Critical levels of available N at planting ($NO_3^-$-N, 0-60 cm depth) for wheat and maize in different areas of the Pampas with different expected yields.

| Area | Critical level ($NO_3^-$-N, 0-60 cm + fertilizer) | Expected yield | Reference |
|---|---|---|---|
| | -------- kg ha$^{-1}$ -------- | | |
| | *Wheat* | | |
| Southeastern Buenos Aires | 125 | 3500 | González Montaner et al., 1991 |
| Southeastern Buenos Aires | 175 | 5000-5500 | González Montaner et al., 2003 |
| Central and South Santa Fe | 92 | 3500-4000 | Salvagiotti et al., 2004a |
| Southern Santa Fe and Córdoba | 100-150 | 3200-4400 | García et al., 2006 |
| | *Maize* | | |
| Northern Buenos Aires | 150 | 9000 | Ruiz et al., 2001 |
| Northern Buenos Aires | 150-170 | 10000 | Alvarez et al., 2003 |
| Central and South Santa Fe | 135<br>162 | < 9500<br>> 9500 | Salvagiotti et al., 2004b |
| Southern Santa Fe and Córdoba | 150-200 | 10000-11000 | Nutrition network CREA Southern Santa Fe, 2009 |

and/or low P use efficiency. However, soybean, the dominating crop in agricultural systems of Argentina, show larger PNB and PFP values than maize or wheat, above 5 and 1000, respectively. Thus, considering the magnitude of soybean production area in Argentina, soil P replenishment in the region is still negative and crop production rest on soil P supply. Since P is a nutrient with high residuality in these soils, fertilizer best management practices (FBMP) for P should take into account nutrient use efficiency not only in the crop that is currently fertilized, but also in the soil P balance. This will give a better estimation of P use efficiency in the cropping system.

***b. Phosphorus use efficiency in field experiments in Argentina and Bolivia***

**Table 6** shows P use efficiency indices for three experimental networks of soybean: i) north-central Pampas region of Argentina (Ferrari et al., 2005); ii) northern Santa Fe province in the Pampas (H. Fontanetto et al., pers. comm.), and iii) northern region of Santa Cruz in Bolivia (J. Terrazas et al., pers. comm.). In all cases, soil P was below critical levels (Bray P and Olsen P below 20 and 15 mg/kg, respectively).

Similar P use efficiency indices were observed in the two experimental networks in Argentina. The lowest P rate (P10), commonly used by farmers, resulted in the greatest agronomic efficiency (AE), but also a larger PFP and PNB. This situation is very common in soybean-based cropping systems in Argentina, which usually result in negative soil P balance as previously discussed (see **Table 5**). Farmers emphasize immediate return to the investment (high AE), and do not consider system effectiveness and medium and long-term effects of low mobility nutrients. These decisions drive to a reduction in soil P fertility, which might reduce the sustainability of the cropping system in the long term. On the other hand, larger P fertilizer rates may improve PNB, either with neutral (P20) or positive (P30) P balances, maintaining adequate AEs. On the other hand, P rates above 40 kg ha$^{-1}$ (network in northern Santa Fe, (see **Table 6**) showed the lowest PNB (i.e. for the greater soil P replenishment) but with a strong reduction in AE.

Data from the experimental network in Bolivia show similar P use efficiency indices to those observed in the experimental networks in the Pampas region, suggesting these indices as preliminary references for P use in soybean in the Southern Cone region.

## 5. Fertilizer best management practices to maximize NUE in temperate regions of the Southern Cone

FBMP are based on scientific principles, and can be described as the selection of the right source to be applied, using the right rate at the right time, and in the right place (Bruulsema et al., 2008). Fertilizer source, rate, timing and placement are interdependent, and are also interlinked with a set of best agronomic management practices applied in the cropping system.

***a. Diagnosis of nutrient deficiencies and nutrient use efficiency***

Maximum nutrient use efficiency is reached when nutrient supply (soil plus fertilizer) is optimized with the purpose of maximizing grain yield. Therefore, the evaluation of soil nutrient status and crop yield levels are crucial to understand NUE in the short and long term. In order to estimate the right nutrient rate, many supporting tools have been evaluated in Argentina for deciding the right nutrient (N, P and S) rate in maize, wheat and soybean.

Soil testing has proved to be a practical way to recommend N fertilization needs in contrast to plant analysis which showed little success. Nitrogen balances are frequently used in the Pampas as a first approximation to determine N fertilization needs in wheat and maize in the region (Barberis et al., 1983; Berardo, 1994; Melchiori, 2002). This approach quantifies the main components of the N cycle in soil; however, sometimes it is difficult to quantify N fertilizer needs because of the lack of information regarding N mineralization or the N use efficiency of different N pools in soil.

In the last years, several researchers from different areas of the Pampas region of Argentina have calibrated critical levels of soil available (inorganic) N at planting ($NO_3$-N at 0-60 cm at planting + N fertilizer) above which no response to fertilizer N is expected for wheat and maize (**Table 7**). Critical N levels show different values according to the crop (wheat or maize), yield goal and soil and climate conditions of the area (**Table 7**). Nitrogen fertilizer rates are estimated from the difference between the critical level and the amount of $NO_3$--N determined before planting. Agronomic efficiencies ranged from 10 to 25 kg wheat/kg N and 20 to 35 kg maize/kg N, when fertilizer N applications are below the critical level.

The calibration of in-season methodologies for diagnosing N fertilizer rate may contribute to increase N use efficiency because fertilizer applications are synchronized with crop demand. These determinations include the estimation of critical levels of soil available N at tillering in wheat (Barbieri et al, 2008) or the calibration of the presidedress nitrate test  in maize. (Garcia et al., 1997; Sainz Rozas et al., 2000, Salvagiotti, 2004a). In line with this objective, on-going research is validating the performance of crop canopy sensors/fertilizer applicators in Argentina, and developing algorithms for its use in wheat and corn (Melchiori, 2007).

In addition to soil N testing, crop simulation models are used to predict grain yield goal and response to N fertilization with different management strategies based on

**Table 8**. Critical levels of soil P Bray 1 (0-20 cm) for wheat, soybean, sunflower and maize in the Pampas region of Argentina.

| Crop | Critical level (mg/kg) | Reference |
|---|---|---|
| Wheat | 15-20 | Echeverría and García, 1998; García, 2007 |
| Soybean | 9-14 | Echeverría and García, 1998; Gutiérrez Boem et al., 2002; Díaz Zorita et al., 2002; Fontanetto, 2004 |
| Sunflower | 10-15 | Díaz Zorita, 2004 |
| Maize | 13-18 | García et al., 1997; Ferrari et al., 2000; Berardo et al., 2001; Garcia et al., 2006 |

calibrated versions of CERES-Wheat and CERES-Maize (Satorre et al., 2001; FAUBA-AACREA, 2005; Satorre et al. 2005).

The efficiency with which low mobility nutrients (e.g. P) are used should be evaluated not only in a particular crop, but also in the sequence, because of residual effects of current fertilization on successive crops in a sequence. Phosphorus fertilization is recommended based on soil P-Bray 1 levels in the upper 20 cm soil before planting. Critical levels vary according to the crop (**Table 8**) and agronomic efficiencies ranged between 25 to 60 kg wheat/kg P, 30 to 70 kg maize/kg P, and 20 to 40 kg soybean/kg P, with P applications below the critical level. Studies in different soils in Argentina indicated rates of 3 to 10 kg P/ha in order to increase soil P-Bray 1 by 1 mg/kg (Rubio et al., 2007; Ciampitti et al., 2009), depending on the initial soil P-Bray 1 level, soil texture, grain or forage P removal, and time from fertilization. This information is important for estimating the effects of P fertilization on P use efficiency for a rotation.

Moderate sulfur deficiencies have been detected in the mid 90's in soils with low soil organic matter content, under long cropping history, high soybean frequency, no-tillage management and adequate N and P fertilization (Martínez and Cordone, 2005). Few tools exist to diagnose S fertilization. In wheat, recent work has shown that S concentration and N/S ratio in grain and in plant could be used to characterize S deficient fields (Reussi Calvo and Echeverria, 2009). Some studies have shown no yield increases when S fertilizer rates were above 10 kg S $ha^{-1}$ in maize and soybean (Salvagiotti, 2004b; Ferraris et al., 2005). Agronomic efficiencies were 47-93 kg soybean/kg S and 30-200 kg maize/kg S below this S rate. Studies in wheat showed that S fertilization improves nitrogen use efficiency by increasing the recovery efficiency of N uptake, and thus reducing the risk of N loss when fertilization is balanced **(Table 9)** (Salvagiotti et al, 2009).

Research in the Pampas has shown high residual effects of

**Table 9**. Nitrogen use efficiency (NUE), N recovery efficiency (RE) and N internal efficiency (IE) of wheat crops fertilized only with N (N100) and N + S (N100+S20). Each value is the average of 2 genotypes in 3 experimental sites (Salvagiotti et al., 2009).

| Variable | Units | N100 | N100 +S20 |
|---|---|---|---|
| NUE | kg grain per kg applied N | 8.4 | 10.7 |
| RE | kg N uptake per kg applied N | 0.35 | 0.47 |
| IE | kg grain per kg N uptake | 22.7 | 22.5 |

P and S applications. These residual effects may be managed to improve and/or maintain soil fertility conditions, and to design BMPs for high NUE not only for the crop that is currently fertilized, but also for the rotation. As an example, application of P and S for both, wheat and soybean, at wheat planting, results in similar P and S use efficiency as if both nutrients are applied for each crop (Salvagiotti et al., 2004c). Long-term research has also showed the effects of nutrient management for different crop rotations in the Pampas. The CREA Nutrition Network in Southern Santa Fe province (Argentina) showed cumulative effects of fertilization on grain yield along the years (**Fig. 4**) (Garcia et al., 2006). Relative differences between the NPS and the Check increased from 43% to 87%, 58% to 208%, and 6% to 89% for maize, wheat, and double cropped soybean, respectively. In addition, soil fertility indicators such as residue cover, soil organic matter, and soil Bray P were improved under balanced NPS fertilization. Soil Bray P was only increased when P fertilization rates were above grain P removal, but this relative increase in response to P fertilization depended on initial Bray P levels in each experiment (Ciampitti, 2009). Maintaining adequate soil Bray P levels, either by increasing in low P soils or by balancing in optimum P soils, contributes to cropping system sustainability by avoiding P limitations for crop yield, facilitating P annual management (application), optimizing productivity, ensuring profitability, and reducing soil degradation.

### *b. Fertilizer management and nutrient use efficiency*

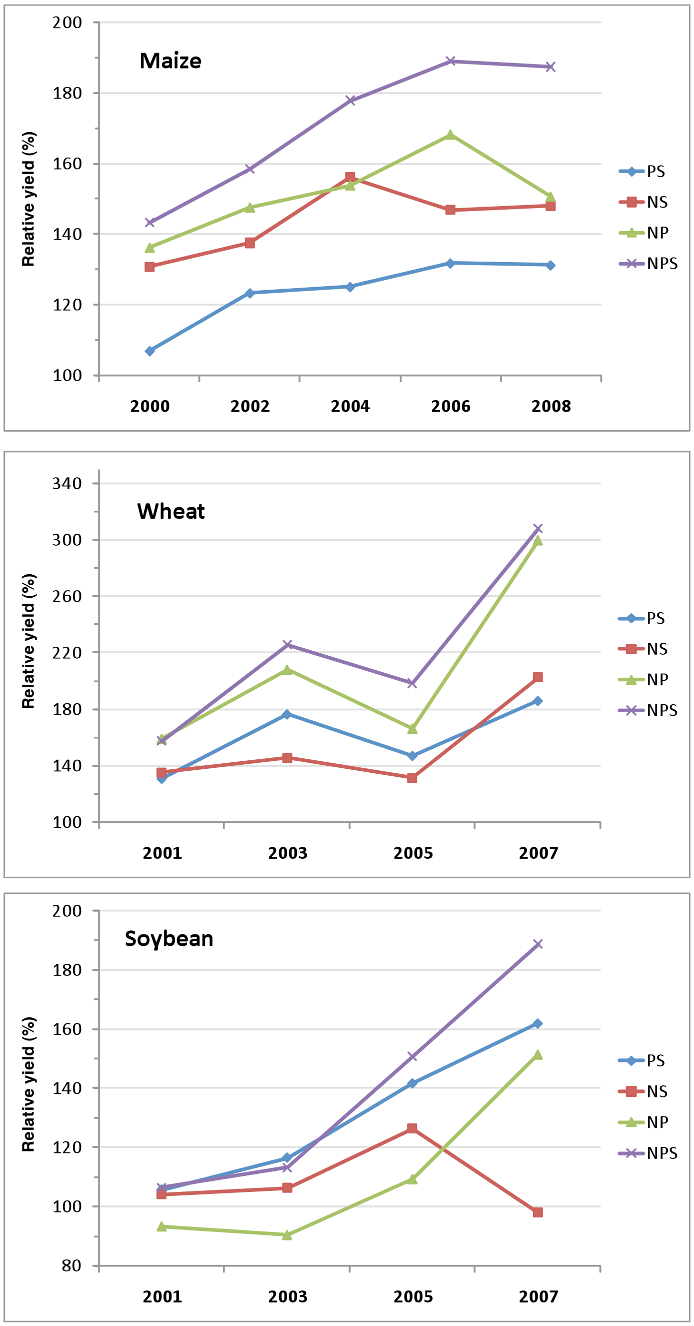



**Fig. 4**. Evolution of relative grain yields of maize, wheat and soybean for different NPS fertilization treatments in a corn-wheat/ soybean rotation. Averages for five sites of the Nutrition Network CREA Southern Santa Fe (Argentina), 2000-2008. Relative yields relative to the Check as 100.

Once nutrient fertilizer rate is determined, fertilizers must be managed with the objective of avoiding losses in order to maximize nutrient use efficiency. The period from planting to the end of tillering is usually dry for most of the wheat producing area of Argentina. Therefore, early N applications usually result in high N use efficiencies (Melchiori and Paparotti, 1996; Díaz Zorita, 2000). However, in areas in the southeast of the Pampas, winter precipitation may increase nitrate leaching, and in several years N use efficiency would be improved by N topdressing at tillering compared to pre-plant or planting applications (Barbieri et al., 2008). Similar efficiencies have been observed when N was applied as urea, CAN or UAN, on surface-before planting, at planting or at tillering in wheat. Some reports in the Pampas region showed that ammonia volatilization losses from surface-applied urea or dribbled UAN were less than 10% (Garcia et al., 1999; Fontanetto et al., 2006).

In maize, N applications are carried out before planting, at planting, or up to V5-6 stage. Research has shown that fertilization around V5-6 usually have greater N use efficiency than early applications (Sainz Rozas et al., 1999). Differences in N use efficiency among N fertilizers have been observed under surface applications, especially at V5-6, because of $NH_3$-N volatilization losses from surface-applied urea (García et al., 1999; Sainz Rozas et al., 1999; Salvagiotti and Vernizzi, 2006). Ammonia-N losses are lower with dribble UAN than surface-applied urea improving N use efficiency. However, all N fertilizer sources show similar efficiencies when they are incorporated in the soil (**Fig. 5**) (Fontanetto, 2004).

Phosphorus fertilization is generally carried out at planting, banding the fertilizer with or close to the seed, depend-

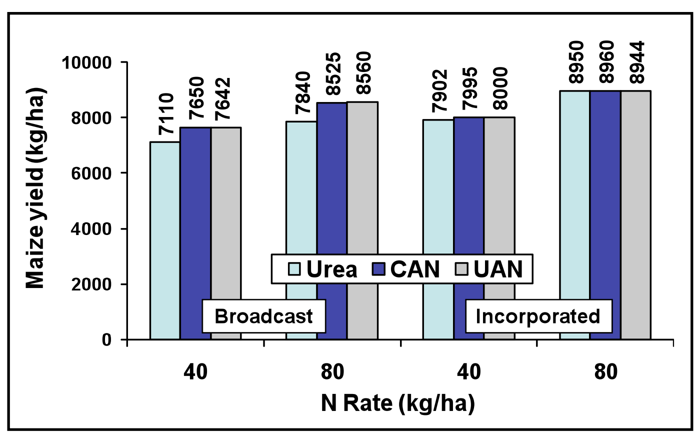



**Fig. 5**. Effect of N source and application method on maize yield at San Carlos (Santa Fe, Argentina). Applications were carried out at V5 stage. Yield without N was 6720 kg/ha (Fontanetto, 2004).

ing on planting equipment. In recent years, research has shown that pre-plant broadcast of P fertilizers would be an efficient alternative under no-tillage systems (Bianchini, 2003; Echeverría et al., 2004) (**Fig. 6**). The most common P fertilizers used by farmers (DAP, MAP, TSP or SSP), present similar P use efficiencies (Ciampitti et al., 2009).

Sulfur fertilizer sources such as ammonium sulfate, single superphosphate, magnesium-potassium sulfate, ammonium tiosulfate (ATS), and magnesium sulfate, have shown similar S use efficiencies. These sources are applied before planting or at planting in a single application or blended with P or N fertilizers. Gypsum is the most common source and its efficiency highly depends on particle size. Prilled or standard (2-4 mm) gypsum has shown similar S efficiency as other sulfate sources, but when applied in large particles, the low solubility of calcium sulfate results in a low S use efficiency. These sources are suitable for long-term S fertilization programs.

## 6. Prospects and research needs for improving NUE in the Southern Cone

Nutrient management is crucial for increasing the overall production of grain crops in the Southern Cone because nutrient reserves are being depleted as agriculture is intensified, and the region present ecological conditions able to produce grain yields larger than current national averages. Therefore, nutrient management based on scientific principles (FBMPs) will be the baseline for pushing yields higher and recovering nutrient fertility of chemically degraded soils. Improvement in NUE is an obligated goal in order to meet multiple goals in crop production: sustainable cropping systems that enhance productivity (food, fiber, biofuels) and profitability, while simultaneously avoid negative effects on the environment.

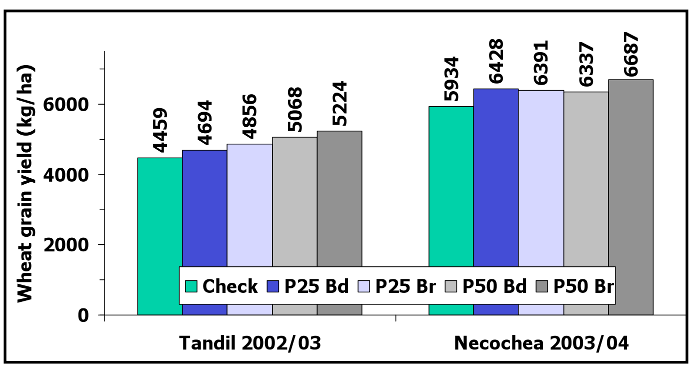



**Fig. 6**. Wheat grain yield for different P placement methods under no-tillage at two field experiments of the southern Pampas of Argentina. Rates are indicated as kg P/ha. Bd indicates banded at planting, and Br broadcasted 45-60 days before planting (Echeverria et al., 2004).

The evaluation of NUE by using different indices not only allows an analysis of regional and local trends in nutrient use, but also gives some insight into the likely processes and mechanisms involved. There are gaps in the values of different indicators of NUE in the countries of the Southern Cone as compared to those observed in similar cropping systems in other countries. These gaps give the opportunity to increase NUE in the region.

Tools for deciding the right rate, source, time, and placement of fertilizer have been developed. Future research should be oriented at exploring causes that may increase NUE: grain yield gaps and constraints for grain production in different cropping systems. Nutrient recommendations should be based in more mechanistic approaches, i.e. an integration of the physiological principles behind crop response to fertilizers, the capacity of soils to provide nutrients to the crop and the efficiency with which fertilizers are used by the crop or a sequence of crops, depending on the mobility and residual effects of each particular nutrient. It is also important to highlight the importance of looking the impact of nutrient management on the whole system effectiveness not only in the short- but also in the long-term by watching not only the direct effects of nutrient addition, but also the indirect effects through increasing organic matter in soils.

## References


Alvarez R., H. Steinbach, C. Alvarez and S. Grigera. 2003. Recomendaciones para la fertilización nitrogenada de trigo y maíz en la pampa ondulada. Informaciones Agronómicas 18:14-19. INPOFOS Cono Sur. Acassuso, Buenos Aires, Argentina.

Andriulo A. and G. Cordone. 1998. Impacto de labranzas y rotaciones sobre la material orgánica de suelos de la región pampeana húmeda. *In* Siembra directa. J. Panigatti, H. Marelli, D. Buschiazzo and R. Gil (Eds.). Ed. Hemisferio Sur. Buenos Aires, Argentina. pp.65-96.

Barberis L., A. Nervi, H. del Campo, S. Urricariet, J. Sierra, P. Daniel, M. Vazquez and D. Zourarakis. 1983. Análisis de la respuesta del trigo a la fertilización nitrogenada en la Pampa Ondulada y su predicción. Ciencia del suelo 1:51-64.

Barbieri P. A., H. E. Echeverría, and H. R. Sainz Rozas. 2008. Nitratos en el suelo a la siembra o al macollaje como diagnostico de la nutrición nitrogenada en trigo en el sudeste bonaerense. Actas CD XXI Congreso Argentino de la Ciencia del Suelo. San Luis. AACS.

Berardo A. 1994. Aspectos generales de fertilización y manejo de trigo en el área de influencia de la Estación Experimental INTA-Balcarce. Boletín Técnico No. 128. EEA INTA Balcarce. Argentina.

Berardo A., S. Ehrt, F. Grattone and F. García. 2001. Corn yield response to phosphorus fertilization in the southern Pampas. Better Crops International 15(1): 3-5.

Bianchini A. 2003. Localizacion de fosforo en siembra directa. Actas XI Congreso Nacional de AAPRESID. Rosario, Santa Fe. Pp. 309-314.

Bruulsema T., C. Witt, F. Garcia, S. Li, T.N. Rao, F. Chen and S. Ivanova. 2008. A Global Framework for Fertilizer BMPs. Better Crops 92 (2): 13-15. IPNI. Norcross, GA. USA.

Cano J., O. Ernst, and F. Garcia. 2006. Balance aparente de fósforo en rotaciones agrícolas del litoral oeste del Uruguay. Informaciones Agronómicas 32:8-11. INPOFOS Cono Sur. Acassuso, Buenos Aires, Argentina.

CAPECO. 2007. Available at http://www.capeco.org.py/

Ciampitti I. 2009. Dinámica del fósforo del suelo en rotaciones agrícolas en ensayos de nutrición a largo plazo. M.Sc. thesis. FA-UBA. Buenos Aires, Argentina. XX pag.

Ciampitti I., G. Rubio, L. Picone and F. Garcia. 2009. El fosforo en la agricultura: Mejores practicas de manejo. *In* F. Garcia e I. Ciampitti (ed.). Simposio Fertilidad 2009: Mejores prácticas de manejo para una mayor eficiencia en la nutrición de cultivos. IPNI Cono Sur. Acassuso, Buenos Aires, Argentina. pag. 35-51. ISBN 978-987-24977-1-2.

Diaz-Zorita, M. 2000. Urea fertilization timing effect on wheat grain yields in Drabble, Buenos Aires, Argentina. Ciencia del Suelo 18[2], 125-131...

Díaz Zorita M. 2004. Importancia del fósforo en la nutrición mineral del girasol. En: www.fertilizar.org

Díaz Zorita M., F. García and R. Melgar. 2002. Fertilización en soja y trigo-soja: Respuesta de la fertilización en la región pampeana. Boletín Proyecto Fertilizar. EEA INTA Pergamino. 44 pág.

DIEA. 2007. Available at http://www.mgap.gub.uy/DIEA/.

Dobermann A. 2007. Nutrient Use Efficiency – Measurement and management. IFA Internacional Workshop on fertilizer best management practices. 7-9 March, Brussels, Belgium.

Dobermann A. and K.G. Cassman. 2002. Plant nutrient management for enhanced productivity in intensive grain production systems of the United States and Asia. Plant Soil 247: 153-175.

Echeverría H. and F. Garcia. 1998. Guía para la fertilización fosfatada de trigo, maíz, girasol y soja. Boletín Técnico No.149. EEA INTA Balcarce.

Echeverría H., H. Sainz Rozas, A. Bianchini and F. García. 2004. Utilización y residualidad de fósforo bajo siembra directa en la región pampeana. Actas XIX Congreso Nacional de la Ciencia del Suelo. Paraná, Entre Ríos. AACS.

FAUBA-AACREA. 2005. Software *Triguero* (CD). Facultad de Agronomía (UBA)-AACREA. Buenos Aires, Argentina. Available at www.aacrea.org.ar. Accessed January 22, 2007.

Ferrari M., J. Ostojic, L. Ventimiglia, H. Carta and G. Ferraris. 2000. Fertilización de maíz: buscando una mayor eficiencia en el manejo del nitrógeno y el fósforo. Actas: "Fertilidad 2000" (IPNI Cono Sur) Rosario, pp. 23-37.

Ferraris, G., Gutierrez Boem, F., Prystupa, P., Salvagiotti, F., Couretot, L., and Dignani, D..2005. Fertilización azufrada en maíz. Actas VIII Congreso Argentino de Maíz. Rosario, Sante fe , Argentina

Fontanetto H. 2004. Nutrición de los cultivos y manejo de la fertilidad del suelo en la región central de Santa Fe. *In* Actas Fertilidad de Suelos para una Agricultura Sustentable. INPOFOS Cono Sur. Pag. 19-25.

Fontanetto H., O. Keller, C. Negro and L. Belotti. 2006. Perdidas por volatilización de amoníaco de diferentes fuentes nitrogenadas en trigo bajo siembra directa. Actas CD XX Congreso Argentino de la Ciencia del Suelo. Salta-Jujuy. AACS.

García F.O. 2007. Requerimientos nutricionales del cultivo: Respuestas a la fertilización. *In* E. Satorre (ed.). Producción de trigo. 1a. edición. AACREA. Buenos Aires, Argentina. pp. 37-42. ISBN 978-987-22576-8-2.

García F., M. Boxler, J. Minteguiaga, R. Pozzi, L. Firpo, G. Deza Marin and A. Berardo. 2006. La Red de Nutrición de la Región CREA Sur de Santa Fe: Resultados y conclusiones de los primeros seis años 2000-2005. AACREA. 32 pp. Buenos Aires, Argentina.

García F., K. Fabrizzi, L. Picone and F. Justel. 1999. Volatilización de amoniaco a partir de fertilizantes nitrogenados aplicados superficialmente bajo siembra directa y labranza convencional. 14º. Latinamerican Congress of Soil Science. Pucón, Chile. 8-12 November 1999.

García F., K. Fabrizzi, M. Ruffo and P. Scarabicchi. 1997. Fertilización nitrogenada y fosfatada de maíz en el sudeste de Buenos Aires. Actas VI Congreso Nacional de Maíz.

AIANBA. Pergamino, Buenos Aires, Argentina.

González Montaner, J., G. Maddonni, N. Mailland and M. Porsborg. 1991. Optimización de la respuesta a la fertilización nitrogenada en el cultivo de trigo a partir de un modelo de decisión para la Subregión IV (Sudeste de la Provincia de Buenos Aires). Ciencia del Suelo 9:41-51.

González Montaner, J., M. Di Nápoli, P. Calviño, N. Mailland, M. Posborg, F. Dodorico and J. Andenoche. 2003. Nitrógeno en trigo. CREA Magazine. 272:56-59.

Gutiérrez Boem F.H., J.S. Scheiner, J. Moyano and R.S. Lavado. 2002. Cambio en la disponibilidad de fósforo del suelo por el agregado de fertilizante. Actas XVIII Congreso Argentino de la Ciencia del Suelo. Puerto Madryn. Versión CD.

INE. 2007. Available at http://www.ine.gov.bo/.

Martínez F. and G. Cordone. 2005. Avances en el manejo de la fertilización de cultivos y fertilidad de suelos en el sur de Santa Fe. Simposio "Fertilidad 2005: Nutrición, Producción y Ambiente". Rosario, 27-28 Abril. INPOFOS Cono Sur-Fertilizar A.C. pp. 3-11.

Melchiori R. 2002. Fertilización de trigo, soja y maíz en Entre Ríos. Proceedings "Fertility 2002". PPI-PPIC Southern Cone. Acassuso, Buenos Aires, Argentina. pp. 24-30.

Melchiori R. and O. Paparotti. 1996. Fertilización nitrogenada en trigo, evaluación de dosis y momento de aplicación. Jornada de Actualización Técnica en el cultivo de Trigo. Serie Extensión Nº9. EEA INTA Paraná.

Melchiori R. 2007. Estado actual del manejo sitio específico de nitrógeno en Argentina. Proceedings "Fertility 2007". IPNI Cono Sur-Fertilizar A.C. pp. 74-78.

Melgar R. 2005. El mercado de fertilizantes en la Argentina y su relación con el sector agropecuario. *In* H. Echeverría and F. García (ed.). Fertilidad de suelos y fertilización de cultivos. Ed. INTA. Buenos Aires, Argentina. pp. 489-502.

ODEPA. 2007. Available at http://www.odepa.gob.cl/odepaweb/jsp/odepad.jsp.

Reussi Calvo N.I., and H.E. Echeverría. 2009. Azufre: Marco conceptual para definir las mejores prácticas de manejo en los cultivos. *In* F. Garcia e I. Ciampitti (ed.). Simposio Fertilidad 2009: Mejores prácticas de manejo para una mayor eficiencia en la nutrición de cultivos. IPNI Cono Sur. Acassuso, Buenos Aires, Argentina. ISBN 978-987-24977-1-2.

Rubio G., M.J. Cabello, and F. Gutierrez Boem. 2007. ¿Cuanto fósforo hay que aplicar para alcanzar el umbral crítico de fósforo disponible en el suelo? II. Cálculos para las zonas Sur y Norte de la Región Pampeana. Informaciones Agronómicas 35: 6-10. IPNI Cono Sur. Acassuso, Buenos Aires, Argentina.

Ruiz R., E. Satorre, G. Maddoni, J. Carcova and M. Otegui. 2001. Umbrales de decisión para la fertilización nitrogenada en maíz. VII Congreso Nacional de Maíz. AIANBA. Pergamino, Buenos Aires, Argentina.

SAGPyA. 2007. Available at http://www.sagpya.mecon.gov.ar/.

Sainz Rozas H. and H. Echeverría. 1998. Relación entre las lecturas del medidor de clorofila (Minolta SPAD 502) en distintos estadios del ciclo del cultivo de maíz y el rendimiento en grano. Rev. Fac. Agron. La Plata 103 (1):37-44.

Sainz Rozas H., H. Echeverría, G. Studdert and F. Andrade. 1999. No-till maize nitrogen uptake and yield: Effect of urease inhibitor and application time. Agron. J. 91:950-955.

Sainz Rozas H., H. Echeverría, G. Studdert and G. Dominguez. 2000. Evaluation of the presidedress soil nitrogen test for no-tillage maize fertilized at planting. Agron. J. 92:1176-1183.

Salvagiotti, F., 2004a. Estrategias en el manejo de nutrientes en el sur de Santa Fe. Actas Simposio Fertilidad 2004. Rosario, Argentina

Salvagiotti, F. 2004b. Análisis de la respuesta a la fertilización con azufre en soja de primera. Para mejorar la produccion - INTA Oliveros 27[SOJA], 80-83.

Salvagiotti, F., Cordone G., Castellarín, J.M., Bacigaluppo S., Capurro, J., Pedrol, H.M., Gerster G., Martínez F., Méndez J., Trentino, N. 2004a. Diagnóstico de la fertilización nitrogenada en trigo utilizando un umbral de disponibilidad de nitrógeno a la siembra. Para mejorar la produccion - INTA Oliveros 25[TRIGO], 50-52.

Salvagiotti, F., Pedrol, H.M., Castellarín, J.M., Cordone G., Capurro, J., Felizia, J.C., Gargicevich, A., Gentile, O., Martínez F., Méndez J., Prieto G., Trentino, N. 2004b. Umbrales de nitrógeno a la siembra para el diagnóstico de la fertilización nitrogenada en maíz según el potencial de rendimiento. Para mejorar la producción - INTA Oliveros 26[MAIZ], 84-88.

Salvagiotti, F., Vernizzi, A. 2006. Pérdidas de nitrógeno por volatilización y su efecto en el rendimiento del cultivo de maíz. Para mejorar la produccion - INTA Oliveros 32[MAIZ], 96-102.

Salvagiotti, F., G. Gerster, S. Bacigaluppo, J. Castellarín, C. Galarza, N. González, V. Gudelj, O. Novello, H. Pedrol, and P. Vallone. 2004c. Efectos residuales y directos de fósforo y  azufre en el rendimiento de soja de segunda. Ciencia del Suelo 22(2):92-101.

Salvagiotti, F., Castellarin, J.M., Miralles, D.J., Pedrol, H.M., 2009. Sulfur fertilization improves nitrogen use efficiency in wheat by increasing nitrogen uptake. Field Crops Research 113, 170-177.

Satorre E., F. Menéndez and G. Tinghitella. 2005. El modelo Triguero: Recomendaciones de fertilización nitrogenada en trigo. Proceedings "Fertility 2005". Rosario, 27-28 April. INPOFOS Cono Sur-Fertilizar A.C. pp. 3-11.

Satorre, E., R. Ruiz, D. Miralles, D. Calderini and G. Maddoni. 2001. Bases de decisión para la fertilización nitrogenada en las zonas Norte de Buenos Aires, Sur de Santa Fe y Centro de AACREA. Pp. 30-38. *In* Wheat Tech. Bull. AACREA. Buenos Aires, Argentina.

Snyder C.S. and T.W. Bruulsema. 2007. Nutrient use efficiency and effectiveness in North America: Indices of Agronomic and Environmental Benefit. IPNI. Junio 2007. Ref. # 07076. Available at www.ipni.net/ipniweb/portal.nsf/0/d58a3c2deca9d7378525731e006066d5/$FILE/NUE.pdf

Urricarriet S. and R. Lavado. 1999. Indicadores de deterioro en suelos de la pampa ondulada. Ciencia del suelo 17 (1): 37-44.

# TOOLS TO IMPROVE NUTRIENT USE EFFICIENCY IN CORN IN TROPICAL LATIN AMERICA

**José Espinosa M.[1] and Juan Pablo García M.[2]**

## Introduction

Millions of hectares are cultivated annually to corn in Latin America, but only Brazil and Argentina produce enough to export grain consistently. In the countries located in the tropical areas of Latin America, corn grain is used mainly for human consumption, but its use for animal feed is growing steadily. Corn cultivation is strategic for these countries from the standpoint of food security and as a source of rural employment.

Until not too long ago, little attention was paid to corn production from different sectors of the economy of several countries of tropical Latin America, mainly due to the possibility to import grain at a lower price than it could be produced locally. Local production costs are relatively high due to low yields as a consequence of poor production technology. The aggressive promotion of ethanol production in 2008 in the United States drastically reduced grain availability, increased prices in the international market, and made the import of corn difficult. On the other hand, this situation represented an excellent opportunity for local production and farmers thought they finally could approach corn production as a profitable activity. However, international prices decreased again due to the economic crisis that affected the world in 2009. It is the general consensus that international corn prices will not reach those of 2008, but they will not decrease to the levels seen at the beginning of this decade. The effect of all this economical commotion on grain availability and prices has left several preoccupations among governments of the region. Perhaps the biggest concern is the real possibility of suffering shortages of corn supply which can threaten food security in several countries of the region. This fact has stimulated the development of agronomic programs in government and private agencies to increase corn yields. The only way that farmers of the region can transform corn production as a profitable and sustainable activity is by increasing yields to competitive levels.

Corn production in the countries of tropical Latin America has confronted productivity problems attributed to soil fertility loss, use of low yielding varieties, and inappropriate use of the new high yielding hybrids. However, research conducted in the region has demonstrated that yield can be improved substantially with the use of appropriate crop management technologies, particularly the right plant population and nutrition (Espinosa and Garcia, 2008).

Field research work conducted during the past few years has demonstrated that fertilizer recommendations used in corn production in the region do not adequately satisfy the nutritional needs of the crop to realize high and profitable yields. Often, these recommendations consist of a predetermined set of nutrient application rates to be used across a vast production area. These recommendations assume that nutrient needs are the same for extensive production areas without taking into account the effect of climate on yield potential.

Vegetative growth and the potential to accumulate yield, consequently the total need for nutrients, vary with the conditions of the different locations where corn is cultivated in the region. This is particularly true in the corn producing areas of tropical Latin America where the diverse climate conditions result in different yield potentials. In tropical areas, latitude and altitude have a profound effect on yield accumulation. It is also a known fact that very few corn growers in the region use soil testing as a diagnostic tool, and even if fertilizer recommendations are soil test-based, this tool cannot detect the variable effect that climate has on the magnitude of attainable yield and its total need for nutrients. For these reasons, it is necessary to determine yield potential and attainable yield with the best known management practices. It is also necessary to quantify the effect of such management in nutrient use efficiency, particularly for nitrogen (N).

## Site-Specific Nutrient Management for Corn in Tropical Latin America

Nutrient management in tropical Latin America can benefit from new methods to develop fertilizer recommendations that adjust nutrient rates to fit the specific needs of the corn crop at each climatic region. One of these methods is called site-specific nutrient management (SSNM), and this is a

[1]International Plant Nutrition Institute, IPNI, jespinosa@ipni.net
[2]Federación Nacional de Cultivadores de Cereales de Colombia, FENALCE, juanpagar@yahoo.com

procedure which helps to provide nutrients to the plant in the right amount to realize the attainable yield for the local climate conditions. This concept allows for dynamic adjustment of nutrient use to effectively fill the gap between the total crop nutrient need to obtain high yields and the soil nutrient supply. This deficit is satisfied with fertilizer application. This nutrient management scheme seeks to apply nutrients at the right rate and time to maximize nutrient use efficiency. The three steps needed to implement a SSNM program are discussed below.

***Yield Potential and Attainable Yield Determination***

The determination of yield potential is achieved using models that simulate growth, assuming ideal conditions for the crop. Yield potential is defined as the yield of a crop growing in an environment to which it is adapted, without water or nutrient limitations, and with effective pest and disease control (Evans, 1993). For this reason, yield potential of a hybrid or variety in a specific growth environment is determined by the amount of solar radiation, temperature, and plant density. One of the more versatile corn simulation models, called *Hybrid Maize*, was developed by the University of Nebraska (Haishun et al., 2006).

Management decisions like the selection of plant material, date of planting, and plant population can affect yield potential at a specific site by affecting the use of available light and soil moisture reserves during the production cycle. Yield potential also fluctuates year-to-year due to the normal variation in solar radiation and temperature (Evans, 1993).

As mentioned before, to achieve yield potential, the crop should have optimum water and nutrient supply, and it has to be completely protected from pest, disease, and weed attacks, as well as the occurrence of other factors which can affect crop growth. It is obvious that these conditions are rarely seen in the field; however, yield potential determination for a site is an excellent reference point that helps to identify yield gaps.

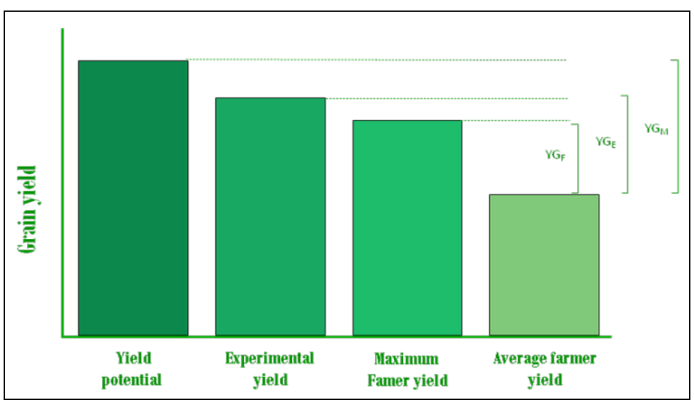



**Figure 1**. Conceptual framework of yield gaps as discussed by Lobell et al., 2009.

The attainable yield is achieved by using all available technology for the crop at a particular site to eliminate limiting factors, identified through either field research or compilation of yield data from farmers' fields with very good management. The difference between yield potential and attainable yield measures the magnitude of the first yield gap. This yield gap will be as wide as the effect of crop management on attainable yield. The attainable yield achieved at one site establishes the yield goal for a homogeneous area (recommendation domain) for the next production cycle. Crop and nutrient management is fine-tuned with the information obtained in the first cycle as a way to increase attainable yield and reduce the first yield gap. This approach not only allows for better yields, but also increases nutrient use efficiency. The process continues in following crop growth cycles until an accurate recommendation for the domain is developed.

It's important to determine attainable yield for each recommendation domain because the amount of nutrients taken up by the crop is directly related with yield. Attainable yield determines the total amount of nutrients that the crop needs to achieve that yield level and clearly establishes real nutrient demand. This information is essential to develop fertilizer recommendations. Soil testing does not allow this type of analysis.

The second yield gap, or exploitable yield gap (Witt et al., 2009) arises between the actual yield obtained by the average farmer and the attainable yield. The final goal of a SSNM project is to guide farmers to reduce this yield gap and to approach their attainable yield as often as possible. The conceptual scheme of these yield gaps is presented in **Figure 1** (Lobell et al., 2009), and **Table 1** presents yield potential, attainable yield, and actual yield of several sites

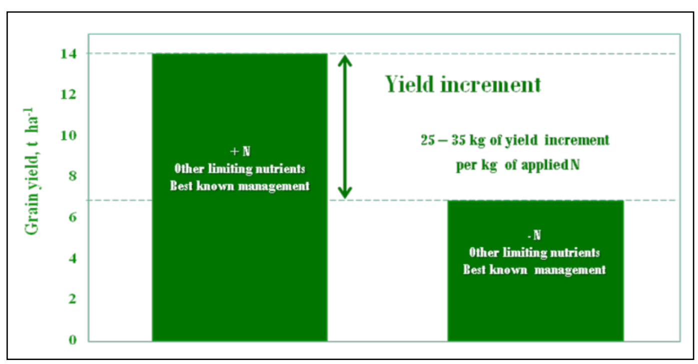



**Figure 2.** Schematic representation of the procedure to determine nutrient rate using the omission plot technique (Witt et al., 2006).

**Table 1**. Yield potential determined using the Hybrid Maize simulation model (Haishug et al., 2006) and attainable yield data obtained by field research at several sites in Latin America.

| Site | Yield Potencial[4] | Simulated population[5] | Attainable yield[6] | Field population[7] | Altit. | Soil order | Text. | Hybrid | Planting date[8] | Physio-logical maturity |
|---|---|---|---|---|---|---|---|---|---|---|
| | t ha$^{-1}$ | Plants ha$^{-1}$ | t ha$^{-1}$ | Plants ha$^{-1}$ | meters | | | | | days |
| Granada[1] | 8.10 | 75000 | 4.41 | 60000 | 322 | Inceptisol | Loam | FNC3056 | 04-april | 87 |
| Campoalegre[1] | 8.50 | 75000 | 6.84 | 75000 | 526 | Inceptisol | S L | FNC3056 | 04-april | 92 |
| Obando[1] | 8.90 | 75000 | 7.74 | 75000 | 940 | Mollisol | C L | P 30F80 | 18-septem | 91 |
| Cañaveral[1] | 9.30 | 75000 | 5.56 | 55000 | 222 | Inceptisol | C L | FNC514 | 25-august | 85 |
| Sopetran[1] | 9.50 | 75000 | 5.06 | 70000 | 588 | Vertisol | C L | FNC3056 | 26-march | 88 |
| Espinal[1] | 9.60 | 75000 | 6.17 | 60000 | 367 | Inceptisol | S L | FNC3056 | 26-march | 90 |
| Aguachica[1] | 10.50 | 75000 | 6.84 | 70000 | 211 | Inceptisol | S C | FNC3056 | 16-march | 79 |
| Bolívar[1] | 10.52 | 75000 | 9.61 | 70000 | 1052 | Entisol | ClayAr | FNC3056 | 24-april | 94 |
| Pichilingue[2] | 11.90 | 75000 | 8.95 | 70000 | 86 | Andisol | Loam | AG-003 | 26-dicem | 105 |
| Gualipe[2] | 12.10 | 75000 | 10.86 | 70000 | 131 | Andisol | Loam | AG-003 | 12-january | 110 |
| Come Gallo[2] | 11.80 | 75000 | 10.92 | 70000 | 92 | Andisol | LoamF | AG-003 | 09-january | 110 |
| Cereté[1] | 11.20 | 75000 | 5.33 | 60000 | 30 | Inceptisol | Clay | FNC3056 | 15-april | 89 |
| Buga[1] | 11.50 | 75000 | 6.20 | 75000 | 946 | Mollisol | Clay | FNC514 | 30-septem | 92 |
| Villanueva[1] | 11.50 | 75000 | 5.00 | 55000 | 221 | Inceptisol | C L | FNC514 | 23-august | 86 |
| Toluca[3] | 13.74 | 75000 | 10.00 | 75000 | 2372 | Inceptisol | C L | H-47 | 26-may | 140 |
| Bugalagran[1] | 13.86 | 75000 | 9.90 | 75000 | 940 | Mollisol | Clay | FNC3056 | 16-april | 95 |
| Palestina[1] | 14.10 | 75000 | 13.51 | 60000 | 1690 | Vertisol | Loam | FNC3056 | 08-septem | 120 |
| Montenegro[1] | 15.50 | 75000 | 8.11 | 65000 | 1224 | Inceptisol | Loam | FNC514 | 20-septem | 105 |
| Celaya[3] | 24.00 | 120000 | 17.00 | 120000 | 1800 | Vertisol | C L | DK-2027 | 30-april | 150 |

1. Colombia
2. Ecuador
3. Mexico
4. Yield potential calculated using the Hybrid Maize simulation model and NASA climatic data, 10 years average
5. Population utilized in the simulation
6. Attainable yield in the field with the best available technology
7. Population in the field experiments
8. All sites are rainfed with the exception of Celaya which is totally irrigated

in important corn producing areas of tropical and subtropical Latin America.

***Soil Nutrient Supply Determination***

A SSNM program makes effective use of soil nutrient supply. Soil native nutrient supply is characterized by those nutrients coming from other sources excluding fertilizers (organic matter, crop residues, irrigation water, manure, etc.). The omission plot technique is used to evaluate soil native supply through its measurement of nutrient accumulation in the crop that is not fertilized with the nutrient of interest, but fertilized with all other needed nutrients in ample amounts.

***Determination of the Fertilizer Needed to Fill the Gap between Crop Nutrient Need and Soil Native Nutrient Supply***

Fertilizer is applied to satisfy the portion of crop nutrient requirement that is not satisfied totally by native soil nutrient supply. Total fertilizer rate depends on the deficit between the total need of nutrients to attain the yield goal and the nutrients supplied by the native soil sources as determined by the respective nutrient omission plot. The steps needed to determine the rate of the nutrients of interest are presented summarized in **Figure 2** (Witt et al., 2006).

## Discussion of the SSNM concept with case examples

As is indicated above, SSNM is a plant-based approach


**Figure 3**. Nitrogen omission plot (front) and complete treatment (back) as part of a set of omission plots at two sites located in different recommendation domains.

that uses the omission plot technique to determine the yield that can be obtained with indigenous soil reserves and the attainable yield obtained when nutrients are not limiting. **Figure 3** show two sets of omission plots at two different recommendation domains. The attainable yield becomes the yield goal for the next growing season. The fertilizer requirement is then calculated from the yield difference between the complete plot and the respective omission plot divided by a preset agronomic efficiency (AE) for the nutrient. In this case, the preset agronomic efficiency for N ($AE_N$) for corn is 30 kg of grain increase per kg of applied nutrient, while the preset agronomic efficiency for P ($AE_P$) is 45 kg/kg and the corresponding agronomic efficiency for K ($AE_K$) is 15 kg/kg. The recommended rate of fertilizer is tested and refined the following year along with other management practices that can improve fertilizer use efficiency. However, the rate can be used by farmers in the surrounding fields as their first approach to evaluating a recommendation that is based on an attainable yield goal for the site. This is a sound approach in areas where soil testing is not used regularly. An example of testing the approach in Colombia is presented for discussion.

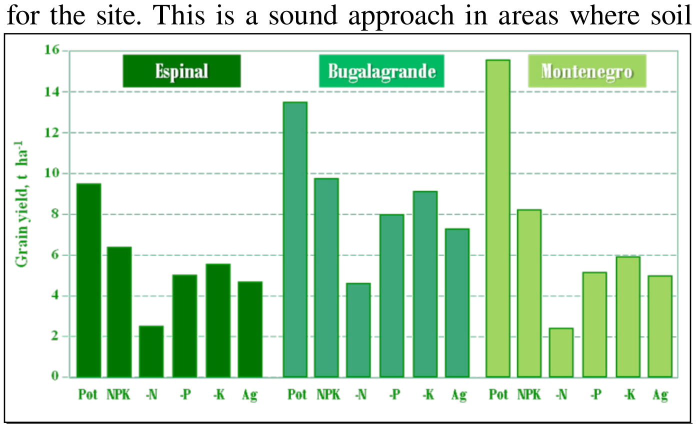



**Figure 4.** Yield potential (Pot), attainable yield (NPK), N, P, K omission plot yields, and farmer yields (Ag) at three sites with different climatic conditions in Colombia.

**Figure 4** shows yield potential calculated with NASA climatic data, as well as yields for the complete treatment (attainable yield), -N, -P and -K omission plots, and the common farmer treatment at three different sites in Colombia with different yield potential. This situation is common in the tropics where microclimates can markedly influence yield potential. The Espinal site is located at the bottom of the Magdalena River Valley and it is characterized for having high day and night temperatures that restrict yield accumulation. The other two sites (Bugalagrande and Montenegro) are at higher altitude and have cooler nights, conditions which allow for greater yield potential. The 2007 yields of the complete NPK plots define attainable yield which is then set as the yield goal for the next cropping season. This is a reasonable yield target because it reflects the effect of climate on yield accumulation. This yield goal also defines the magnitude of the nutrient requirement. **Table 2** shows the calculated nutrient requirement to reach attainable yields at the different sites.

## Nutrient Use Efficiency Improvement

One of the objectives of a SSNM program is to increase nutrient use efficiency. This is accomplished only by increasing AE. In corn, the number of rows per cob and the number of grains per row, which determine the total number of grains per cob, are defined during the vegetative stages between V6 and V12 (Ritchie et al., 2002). The plant nutritional status during this period, particularly N, is an important regulator of the number of grains, and consequently, yield accumulation. To achieve greater use efficiency, the total N rate should be split during the period of greater uptake. The corn plant needs a small amount of N to support

**Table 2**. Omission plots and complete treatment yields, and calculated nitrogen requirement for three sites with different climatic conditions in Colombia.

| Treatments | Yield, t $ha^{-1}$ | Yield increment, t $ha^{-1}$ $R_X - R_0$ |
|---|---|---|
| | Espinal | |
| -N | 1.5 | 4.7 |
| -P | 5.0 | 1.2 |
| -K | 5.5 | 0.7 |
| NPK | 6.2 | |
| Farmer | 4.4 | |
| Yield goal = 6.2 t $ha^{-1}$ | | |
| Fertilizer recommendation to reach yield goal = 157 N – 27 $P_2O_5$ – 47 $K_2O$ | | |
| | Bugalagrande | |
| -N | 4.5 | 5.4 |
| -P | 7.9 | 2.0 |
| -K | 9.3 | 0.6 |
| NPK | 9.9 | |
| farmer | 7.6 | |
| Yield goal = 9.9 t $ha^{-1}$ | | |
| Fertilizer recommendation to reach yield goal = 180 N – 44 $P_2O_5$ – 40 $K_2O$ | | |
| | Montenegro | |
| -N | 2.5 | 5.6 |
| -P | 5.2 | 2.9 |
| -K | 5.4 | 2.7 |
| NPK | 8.1 | |
| Farmer | 4.0 | |
| Yield goal = 8.1 t $ha^{-1}$ | | |
| Fertilizer recommendation to reach yield goal = 187 N – 64 $P_2O_5$ – 180 $K_2O$ | | |

$AE_N$ = 30; $AE_P$ = 45; $AE_K$ = 15

$R_X$ = yield of the complete treatment; $R_0$ = yield of the omission plot.

initial growth, but its demand increases during the period between V6 and V12 and N splitting during this period can be an effective way of managing this nutrient. Generally, N applications after this period are not economic. Once the total N rate is defined, it is important to determine the number of split applications and the time of application.

Research conducted in Colombia at 16 sites demonstrated the positive effect of split N application on grain yield and

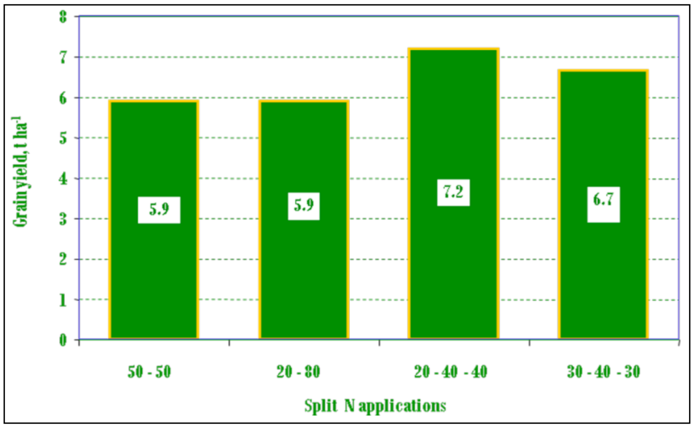



**Figure 5.** Effect of four options of split N application on grain yield of the FNC 3056 corn hybrid across 16 sites in Colombia.

$AE_N$, $AE_P$, and $AE_K$. The following schemes were tested:

- Application of 50% of the total N rate at planting time and 50% side dressed at V6
- Application of 20% of the total N rate at planting time and 80% side dressed at V6
- Application of 20% of the total N rate at planting time and 40% side dressed at V6 and V10.
- Application of 30% of the total N rate at planting time and 40 and 30 % side dressed at V6 and V10, respectively.

Results of the combined analysis of split N application across sites are presented in **Figure 5**. Data demonstrated that the triple split was superior to the double split application. These results suggest that the higher yield response to the three step application is a consequence of applying N at the physiological stages of maximum N demand. At V6, the stalk initiates a period of elongation and the tassel tissue is above ground. At around V10, the number of rows per cob and number of grains per row are defined and the plant has a steady increase in dry matter accumulation and nutrient demand (Ritchie et al., 2002).

Early applications of N fertilizer are not effective due to the dynamics of the nutrient in soil and do not guarantee N availability during the period of greater demand, particularly before and after V10. This potential deficit of N can significantly reduce grain yields. However, fertilizer N application at V10 presents challenges for mechanized application in certain large corn operations, which have to evaluate the effect on profit of the extra cost of a manual application.  An alternative mechanized application at stages V8 o V9 could represent yield advantages in these

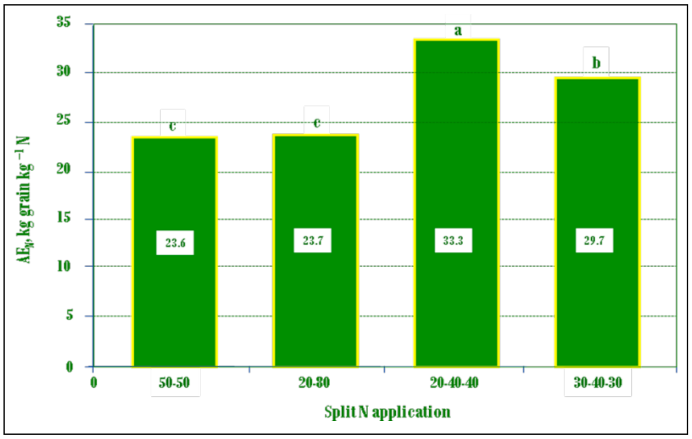



**Figure 6.** Effect of four options of split N application on AEN of corn across 16 sites in Colombia.

situations. For medium and small producers in the region this is not a problem and fits well in the normal operation.

The triple split applications not only benefit total grain yield, but also increase $AE_N$. **Figure 6** presents the effect of four options for split N applications on $AE_N$ across the 16 sites studied in Colombia. The positive effect of the 20-40-40 split application on $AE_N$ is evident, reaching values of 33 kg of grain increase per kg of applied N, which is an acceptable level of N recuperation.

Phosphorus agronomic efficiency ($AE_P$) and K agronomic efficiency ($AE_K$) were also affected positively by N split application. The better AE for both nutrients was attained again with the 20-40-40 N split application (**Figure 7**) for the ample P and K rates used in the omission plot experiments to make sure that these nutrients were not limiting. Even in these conditions, N split application promoted higher nutrient use efficiency.

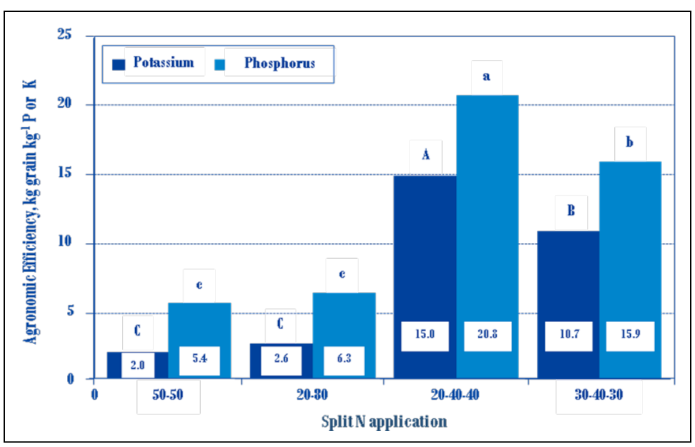



**Figure 7.** Effect of four options of split N application on $AE_P$ and $AE_K$ of corn across 16 sites in Colombia.

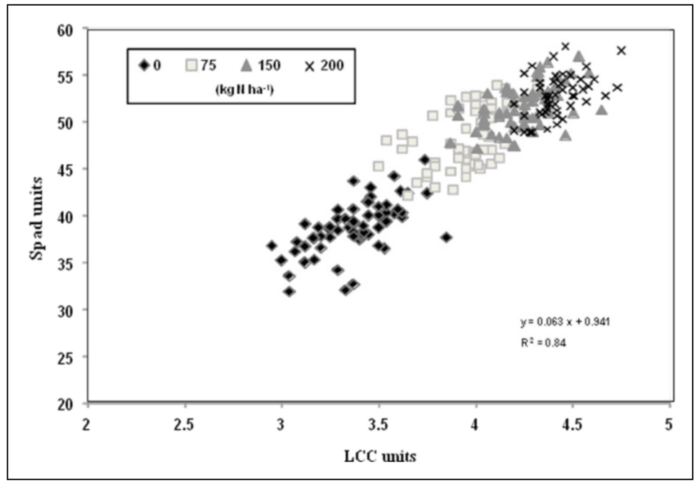



**Figure 8.** LCC and SPAD readings correlation in Buga, Colombia, for all hybrids tested from V6 to R2.

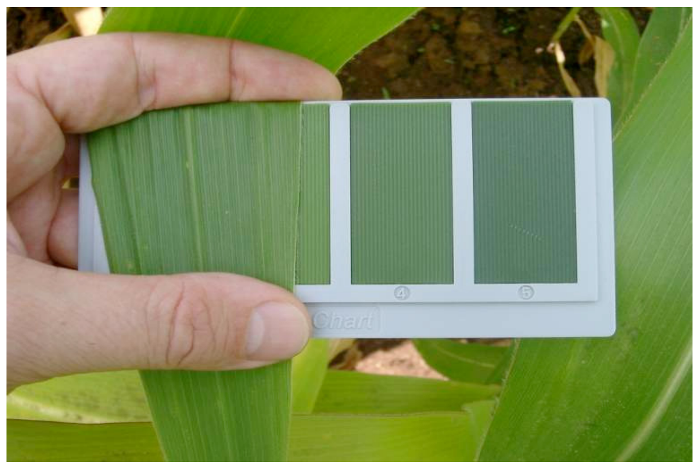


**Figure 9.** Leaf color chart can be used to fine-tune N applications during the period of greater N demand.

A fundamental component of a program aimed to increase N use efficiency is the determination of the plant N status from V6 to V12, due to the profound effect that N nutrition has on yield accumulation during this growth period. It is well known that there is a direct positive relationship among chlorophyll content (greenness) and N status of the plant, which in turn depends on the combination of genetic characteristics and the level of plant N uptake. In consequence, a measure of the greenness index in plant tissue can be a good tool to manage N nutrition. For most of the corn growing conditions of tropical Latin America, the greenness index can be measured using a portable GreenSeeker®, a SPAD chlorophyll meter, or leaf color chart (LCC) developed by IRRI (Witt et al., 2005), which are all supporting tools to improve N use efficiency. The LCC is a very simple tool that can be used by most farmers in the region.

**Table 3**. Critical levels of greeness readings with LCC for tropical corn hybrids in Colombia.

| Hybrid | Stage | Concordia | Sabana Torres | Bolívar | Buga | B/grande | M/negro | Obando | Cereté 1 | Cereté 2 | C/alegre | Espinal |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Critical levels of LCC readings | | | | | | | | | | |
| FNC3056 | V6 | 3.25 | 3.5 | 3.5 | 4 | 4 | 3.5 | | | 3.75 | 3.75 | 4 |
| | V10-V12 | 4 | 4.25 | 4.25 | 4.25 | 4.5 | 4.5 | | | 4.5 | 4.35 | 4.5 |
| FNC514 | V6 | 3.25 | | | 4 | 4 | 3.75 | | | | 3.5 | 3.75 |
| | V10-V12 | 4.25 | | | 4.5 | 4.25 | 4.25 | | | | 4.5 | 4.25 |
| FNC114 | V6 | | | | | | | 3.75 | 3.75 | | | |
| | V10-V12 | | | | | | | 4.5 | 4.75 | | | |
| DK777 | V6 | 3.25 | 4.25 | | 4.25 | 4.25 | 4 | | | 4 | 4.25 | 4 |
| | V10-V12 | 4.25 | 4.75 | | 4.75 | 4.5 | 4.5 | | | 4.75 | 4.75 | 4.5 |
| DK234 | V6 | 3.25 | 4 | | 4.25 | 4 | 3.75 | | | 3.5 | 4 | 3.75 |
| | V10-V12 | 4 | 4.5 | | 4.5 | 4.25 | 4.25 | | | 4.5 | 4.5 | 4.25 |
| DK1040 | V6 | 3 | 4 | 3.75 | 4.25 | | | 3.75 | 3.75 | | 3.75 | 3.75 |
| | V10-V12 | 4 | 4.25 | 4.25 | 4.25 | | | 4.25 | 4.75 | | 4.5 | 4.5 |
| DK003 | V6 | 3.50 | 4 | 4 | 4.25 | | | 3.5 | 3.75 | | 4.25 | 4 |
| | V10-V12 | 4.25 | 4.5 | 4.5 | 4.5 | | | 4.5 | 4.75 | | 4.75 | 4.5 |
| P30F80 | V6 | | 3.75 | 4 | 4.25 | | | 3.75 | 3.5 | | 4 | 3.75 |
| | V10-V12 | | 4.25 | 4.5 | 4.5 | | | 4.25 | 4.5 | | 4.5 | 4.25 |
| P30F83 | V6 | 3 | | | 4.25 | 4.25 | 3.75 | | | 3.5 | | 3.75 |
| | V10-V12 | 3.75 | | | 4.5 | 4.75 | 4.25 | | | 4.75 | | 4.25 |
| SV1127 | V6 | 3.25 | 4 | | | 4.25 | 3.5 | | | | | |
| | V10-V12 | 4 | 4.5 | | | 4.5 | 4.25 | | | | | |

Data from a study conducted in Colombia at 11 sites with several hybrids demonstrated a good correlation among greenness index measured by SPAD chlorophyll meter and the N content of the corn leaf tissue, and a good relationship among greenness reading by SPAD chlorophyll meter and the LCC (**Figure 8**), indicating that the determination of greenness index with the LCC is a viable option for N management in corn (**Figure 9**).

Collected data show that greenness index is affected by the physiological stage of the crop, N rate, and hybrid. In general, the higher greenness indexes were detected at the period between V12 and V16, and the lower indexes at V6 and R2. Greenness index increased significantly with an increase in N rate, and the magnitude of this increment was greater from 75 to 150 kg N $ha^{-1}$ than from 150 to 200 kg N $ha^{-1}$. The greenness indexes obtained with the LCC varied from 2.25 to 3.25 for the zero N treatments, from 3.5 to 4.25 for the 75 kg N $ha^{-1}$ treatments, and 4.0 to 4.75 for the 200 kg N $ha^{-1}$ treatments. This way it was possible determine the critical greenness index for each hybrid at stages V6 and V10 using the LCC (**Table 3**).

The LCC readings of the greenness indexes at the stages more susceptible to N stress (V6 to V10) permit the fine-tuning of the N rate needed at each predefined split, which increases AEN. If the LCC reading is low at the time of the predetermined N split, more N could be needed to satisfy plant need, but if the reading is high a lower rate might be needed. In general, LCC readings higher than 4 indicate N sufficiency and similar or higher readings guarantee high yields if the climatic conditions at the reproductive stage from R1 to R3, the period when the final weight of the grain is set (Ritchie et al., 2002), are adequate.

## References

Espinosa, J., and J.P. García. 2008. High fertilizer prices: what can be done. Better Crops with Plant Food 92(3):8-10.

Evans, L.T. 1993. Crop evolution, adaptation, and yield. Cambridge University Press, Cambridge, UK.

García, J.P. 2009. Manejo eficiente de nutrientes en el cultivo de maíz en Colombia. FENALCE, Bogotá.

Haishun, Y., A. Dobermann, K. Cassman, and D. Walters.

2006. Hybrid-Maize (ver 2006). A Simulation Model for Corn Growth and Yield. Nebraska Cooperative Extension CS 9. University of Nebraska-Lincoln, Lincoln, NE.

Ritchie, S., H. John, and B. Garren. 2002. Como se desarrolla una planta de maíz. Spanish edition. Iowa State University.

Lobell, D.B., K.G. Cassman, and C.B. Field. 2009. Crop yield gaps: their importance, magnitudes, and causes. Annu. Rev. Environ. Resour. 34:4.1-4.26.

Witt, C., J.M. Pasuquin, and A. Dobermann. 2006. Towards a site specific nutrient management approach for maize in Asia. Better Crops with Plant Food. 90 (2): 28-31.

Witt, C., J.M.C.A. Pasuquin, R. Mutters, and R.J. Buresh. 2005. New leaf color chart for effective nitrogen management in rice. Better Crops with Plant Food 89(1):36-39

IPNI
INTERNATIONAL
PLANT NUTRITION
INSTITUTE


**Headquarters**

3500 Parkway Lane, Suite 550
Norcross, Georgia 30092
USA
Tel. 001-770-447-0335
E-mail: info@ipni.net

**Northern Latin America Program**

Gaspar de Villarroel E14 – 171 and
Av. Eloy Alfaro
Casilla Postal 17-17-980
Quito – Ecuador
Tel. 593-2-246-3175
E-mail: jespinosa@ipni.net

**Brazil Program**

Rua Alfredo Gueded, 1949
Edificio Racz Center, Sala 701
Caixa Postal 400
13400-970 Piracicaba-SP
Brasil
Tel. 55-19-3433-3254
E-mail: lprochnow@ipni.net

**Latin America—Southern Cone Program**

Av. Santa Fe 910
B 1641 ABO Acassuso
Argentina
Tel. 54-011-4798-9939
E-mail: fgarcia@ipni.net


**www.ipni.net**