Nutrient Use Efficiency and Effectiveness in North America:

Indices of Agronomic and Environmental Benefit

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MINERAL FERTILIZERS have made it possible to sustain the world's growing population, sparing millions of acres of natural and ecologically-sensitive systems that otherwise would have been converted to agriculture[1]. Today, economic and environmental challenges are driving increased interest in nutrient use efficiency. Higher prices for both crops and fertilizers have heightened interest in efficiency-improving technologies and practices that also improve productivity. In addition, nutrient losses that harm air and water quality can be reduced by improving use efficiencies of nutrients, particularly for nitrogen (N) and phosphorus (P).

The world's population, growing in both numbers and purchasing power, is projected to consume more food, feed, fiber, and fuel—increasing global demand for fertilizer nutrients[2]. Since fertilizers are made from non-renewable resources, pressure to increase their use efficiencies will continue. At the same time, efforts should increase to enhance fertilizer use effectiveness for improved productivity and profitability of cropping systems.

System Efficiency

Efficiencies are generally calculated as ratios of outputs to inputs in a system. The "system" can be defined in many ways, depending on the interest of the observer.

Agricultural cropping systems contain complex combinations of components, including: soils, soil microbes, roots, plants, and crop rotations. Improvements in the efficiency of one component may or may not be effective in improving the efficiency of the cropping system. Efficiency gains in the short term may sometimes be at the expense of those in the long-term. Short-term reductions in application rates increase nutrient use efficiencies, even when yields decline. However, in the long-term, lower yields reduce production of crop residues, leading to increased erosion risks, decreased soil organic matter, and diminished soil productivity. Sustainable system efficiency demands attention to the long-term impacts.

Best management practices (BMPs) focus on the effectiveness of fertilizers and keeping them in the field for use by the intended crop in adapting cropping systems to the economic and environmental challenges noted above. Effectiveness is maximized when the most appropriate nutrient sources are applied at the right rate, time, and place in combination with conservation practices such as buffer strips, continuous no-till, cover crops, and riparian buffers within intensively managed cropping systems that achieve both increasing yields and diminishing nutrient losses[3]. This approach ensures that improvements to the nutrient use efficiency of the components contribute toward improving the efficiency of the entire system.

Many components contribute to the efficiency of a cropping system.

Because a cropping system includes multiple inputs and outputs, its overall efficiency depends on the science of economics. To maximize profit is to obtain the maximum value of outputs per unit value of all inputs. At the rate where the net return to the use of one input peaks, the input is making its maximum contribution to increasing the efficiency of all other inputs involved. Rates of nutrient application optimal for economic yields often minimize nutrient losses[4].

Component Efficiencies

A recent review identified no fewer than 18 different definitions and calculations of nutrient use efficiency[5]. Even the most useful component efficiencies require careful interpretation if they are to contribute to effective nutrient use in cropping systems. In **Table 1**, we

Table 1. Four selected definitions of nutrient use efficiency (NUE)[6].

NUE Term	Calculation	Reported examples
PFP Partial factor productivity of applied nutrient	Y/F	40 to 80 units of cereal grain per unit of N[6]
AE Agronomic efficiency of applied nutrient	$(Y-Y_0)/F$	10 to 30 units of cereal grain per unit of N[6]
PNB Partial nutrient balance (removal to use ratio)	U_H/F	0 to greater than 1.0- depends on native soil fertility and fertility maintenance objectives[3] <1 in nutrient deficient systems (fertility improvement) >1 in nutrient surplus systems (under-replacement) Slightly less than 1 to 1 (system sustainability)
RE Apparent crop recovery efficiency of applied nutrient	$(U-U_0)/F$	0.1 to 0.3 – proportion of P input recovered first year[13] 0.5 to 0.9 – proportion of P input recovered by crops in long-term cropping systems[13] 0.3 to 0.5 – N recovery in cereals – typical[6] 0.5 to 0.8 – N recovery in cereals – best management[6]

F – amount of nutrient applied (as fertilizers, manures, etc.)
Y – yield of harvested portion of crop with applied nutrient
Y_0 – yield in control with no applied nutrient
U_H – nutrient content of harvested portion of crop
U – total nutrient uptake in aboveground crop biomass with nutrient applied
U_0 – total nutrient uptake in aboveground crop biomass with no nutrient applied

list and describe four commonly used component efficiencies related directly to fertilizer nutrient use.

Two of these deal with production efficiency, where the output is the harvested crop product. The remaining two deal with recovery efficiency, or the nutrient recovered by the crop.

Production Efficiencies

The simplest form of crop output efficiency is termed partial factor productivity (PFP). It is calculated in units of crop **yield** per unit of nutrient applied. Another term, agronomic efficiency (AE), is calculated in units of **yield increase** per unit of nutrient applied. It more closely reflects the impact of the applied fertilizer. The former is easily calculated for any farm that keeps records of inputs and outputs. The latter requires a plot without nutrient input, so is only known when research plots have been implemented on the farm.

The PFP answers the question, "How productive is this cropping system in comparison to its nutrient input?" The AE answers a more direct question: "How much productivity improvement was gained by the use of this nutrient input?"

Recovery Efficiencies

Nutrient recovery efficiency also has at least two forms. The simple form, nutrient output per unit of nutrient input, is sometimes termed a partial nutrient budget (PNB)[6]. It is calculated as nutrient in the harvested portion of the crop per unit of nutrient applied. Reported as a ratio of "removal to use", it is fairly easily measured by and useful to crop producers. It can be reported for any number of growing seasons.

The more complex form—preferred by scientists studying the crop—is termed recovery efficiency (RE), defined as the **increase** in crop uptake of the nutrient in above-ground parts of the plant (for most crops) in response to application of the nutrient. Like AE, its measurement requires the implementation of research plots without nutrient input. Operationally, it is limited to the description of the result of either a single nutrient application, or of a single cropping season.

The PNB answers the question, "How much nutrient is being taken out of the system in relation to how much is applied?" The RE, on the other hand, answers the question, "How much of the nutrient applied did the plant take up?" For nutrients that are retained well in the soil, PNB may be considerably higher than RE (e.g. as in **Table 2**).

Table 2. Efficiency values calculated from N responses reported for an irrigated corn field in Nebraska (mean of 3 years).[14]

N rate, lb/A	Yield, bu/A	Total N uptake, lb/A	Grain N uptake, lb/A	Production Efficiencies		Recovery Efficiencies		Net return to applied N, $/A
				PFP	AE	PNB	RE	
0	120	108	73	–	–	–	–	–
60	137	132	85	128	16	1.42	0.39	37
90	143	141	90	89	14	1.00	0.36	45
120	**147**	**148**	**94**	**69**	**13**	**0.78**	**0.33**	**47**
150	149	153	97	56	11	0.64	0.30	43
180	149	157	98	47	9	0.55	0.27	32

PFP = partial factor productivity, lb yield
AE = agronomic efficiency, lb yield increase
PNB = partial nutrient balance, lb grain N uptake
RE = recovery efficiency, lb increase in total N uptake
} per lb of N applied
Net return calculated assuming prices of $3.50/bu for corn and $0.40/lb for N

Choice of Efficiency Term

Each of the major crop nutrients is also important in the nutrition of animals and humans. Where the nutrient in question has output value, greater emphasis should be placed on recovery relative to production efficiency. If the crop's end use is feed or food, efficiencies gained at the expense of the concentration of the nutrient in the product may diminish the value of the product. For instance, a corn hybrid high in AE may contain less N and therefore less protein, requiring other protein sources to be included in the diet[7]. This concern is valid even for some biofuel and fiber end uses, since co-products may be used for animal nutrition.

On the other hand, where nutrients in the crop output are in excess of end-use needs, the emphasis should be placed on production efficiencies. Examples may include P in feeds grown for ruminants, particularly in areas where soils have been enriched with P over time.

Interpretation

There are limitations to the interpretation of all measures of component efficiencies within cropping systems. The nutrient source(s) should be clearly stated in the interpretation of calculated efficiencies. The AE and RE terms are most informative about single sources. The PFP and PNB terms can overestimate efficiency when applied only to a single source, if other sources are also significant.

In the short term, all four component efficiencies increase as rates of fertilizer application are decreased below economic optimum, as indicated in **Table 2.** This might cause one to falsely conclude that the lowest fertilizer rate would result in the most efficient cropping system. This is untrue, as production depends on many non-nutrient inputs, including seed, fuel, crop protection products, machinery, labor, land, and capital. Also, in the long term, limiting nutrient rates in a deficient situation reduces production of crop residues, leading to increased erosion risks, decreased soil organic matter, and diminished soil productivity.

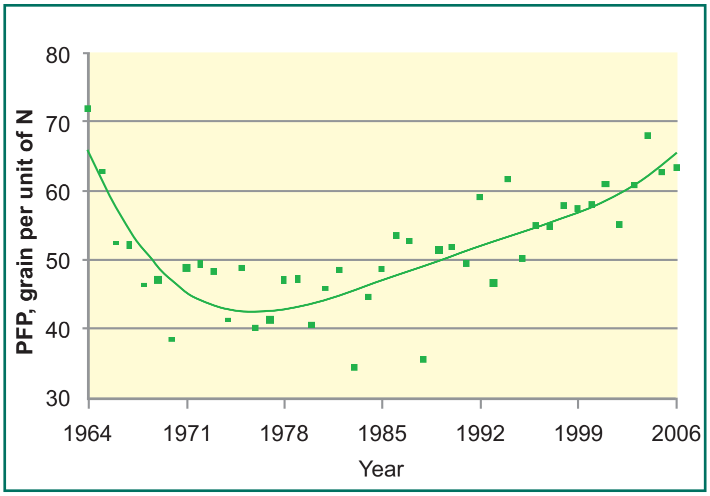

Figure 1. Corn grain produced in the U.S. per unit of N applied (PFP), 1964 to 2006[8].

The more valuable increases in efficiency come from yield improvement. For example, the PFP for N applied to U.S. corn increased by 50% between 1975 and 2006 (**Figure 1**)[8]. This increase did not result from a decrease in N application rates. In fact, rates applied rose by 24%, but better genetics and improved management boosted yields by no less than 86%. The high PFPs observed before 1975 were a result of reliance on net mineralization of soil organic matter as a source of N. Since then, conservation practices that stabilize soil organic matter have reduced its net input of N to the crop.

A PNB (ratio of removal to use) close to 1 over a number of consecutive growing seasons reflects an ideal situation with minimal opportunity for losses, but only if the rest of the system is in a steady state. If, for example, soil organic matter is declining and releasing nutrients, the PNB may lead to a false sense of security. In this situation, or if PNB is less than 1, it becomes important to understand the fate of the unaccounted for nutrients, and to find out whether they are benign or harming the environment.

The RE reflects the portion of the applied nutrient taken up by the plant. Not all of the nutrient taken up is harvested, but the portion that remains in crop residue is often beneficial to the cropping system. The conversion of crop residues to stable soil organic matter depends largely on the nutrients they contain. The nutrients absorbed and retained by plant roots and the soil organisms that flourish in response to root exudates are not reflected in RE.

Values for RE well below 1 can be compatible with an efficient cropping system, provided that the nutrient is retained in the soil from season to season in an available form. A good example is potassium (K) in a soil with reasonable cation exchange capacity. A fertile soil will be capable of supplying a good portion of the K needs of any crop (and thus RE of applied K will be low), but the application of an amount equal to removal will be needed to prevent depletion of available soil K in the long term. The same applies to P in many soils where a supply of slowly available forms of P is maintained over time. However, in soils that fix nutrients irreversibly into unavailable forms, or in soils that do not retain nutrients, improvement of cropping system efficiency depends on improvement of RE.

Studies that have looked at RE under farm conditions have found wide variability.[9] Where soil N supply is high, RE is usually low. While a low RE indicates a risk of loss for a mobile nutrient like N (i.e. nitrate), there are two additional factors that can limit the loss. First, if the residual N is absorbed during the decomposition of crop residue or the growth of cover crops, it may be protected from losses, and available to the following crop. Second, if the soil characteristics and water status are not conducive to leaching or denitrification, even nitrate stays available for the next crop.

Toward Improvement

Despite the existence of many comprehensive reviews of the literature on nutrient use efficiency, information on nutrient use efficiencies under practical farming conditions is insufficient.[6] On-farm research utilizing nutrient budgets (extensively) and response trials (intensively) are essential to identify the cropping systems and their component parts that are most in need of efficiency improvement. Industry, universities, and other research institutes should seek opportunities to work together in ramping-up the level of such research.

A PNB for North American agriculture recently reported that nutrient removal as a proportion of applied fertilizer and manure was 0.64 for N in non-legume crops, and 0.95 and 1.43 for P and K, respectively, in all crops[10]. The average for N indicates significant opportunity for improvement. The averages for P and K indicate that despite known areas of excess application, areas with deficient levels of application also exist.

Opportunities abound for improving nutrient use efficiency through implementation of fundamental BMPs and the following:

- Selection of genetics and management practices assuring maximum economic yields.
- Enhanced-efficiency fertilizer products using controlled-release technologies and inhibitors of N transformation.
- Precision agriculture technologies to map fields and sense crop needs[11].
- Precision application equipment improving timing and placement of nutrient applications.
- Increased use of on-farm (field and sub-field specific) cropping system nutrient budgets.

To improve nutrient use efficiency, more research under practical farming conditions is needed.

- More frequent soil testing and improved interpretation.
- Decision support tools that facilitate science-based nutrient management decisions at the farm level.
- Design of cropping systems that use more of the nutrients released through the growing season.

While improved efficiency is expected to reduce the risk of nutient loss from cropping systems, other management practices like conservation tillage, vegetative buffers, and cover crops can also be used to further minimize nutrient losses to water and air resources.

Conclusion

In his book titled *Feeding the World*, Vaclav Smil[12] concluded that the "effect of improved fertilizer use...should be impressive....with careful agronomic practices it should be possible to raise the average N use efficiency by at least 25 to 30% during the next two generations." This efficiency gain will benefit society by "moderation of environmental stresses from reduced nutrient loss, and lower demand for energy needed to synthesize and apply fertilizers."

Partial factor productivity (PFP) and partial nutrient balances (PNB) should be part of practical record-keeping for crop producers, since they can identify inefficiencies deserving management attention. Where nutrients are suspected to be "leaking" from agricultural systems, on-farm research evaluating enhanced efficiency technologies and management practices should be accompanied by assessment of agronomic production and nutrient recovery efficiencies.

Nutrient use efficiency improvements must always be evaluated in the context of maintaining the effectiveness of nutrient inputs in supporting the efficiency of the cropping system. Optimizing efficiencies of multiple inputs requires economic analysis, appropriately including external costs relating to environmental impacts. ■

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