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Nutrient Use Efficiency and Effectiveness in Australia: *Assessing Agronomic and Environmental Benefit*

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***MINERAL FERTILIZERS** have made it possible to sustain the world's growing population, sparing millions of hectares of natural and ecologically-sensitive systems that otherwise would have been converted to agriculture[1]. Now, economic and environmental challenges are driving increased interest in nutrient use efficiency. Fluctuating prices for both agricultural produce 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 the 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, there is continued importance in ensuring they are used efficiently. At the same time, research is showing how 4R Nutrient Stewardship is increasing fertilizer use effectiveness for improved productivity and profitability of farming systems.

System Efficiency

Efficiencies of any system are generally calculated as ratios of outputs to inputs. 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 a range of crops and pastures grown in rotations. Improvements in the efficiency of one component may or may not be effective in improving the efficiency of the whole cropping system. Efficiency gains in the short term may sometimes be at the expense of those in the long-term. For example, short-term reductions in nutrient application rates can increase nutrient use efficiency, and yields may not be greatly affected. In the longer term, the lower inputs mean that yields are using soil reserves which are not being replaced, adversely affecting yields and soil productivity over time. Sustainable system efficiency demands particular attention to the long-term impacts of the changes made.

Nutrient best management practices focus on the effectiveness of fertilizers and keeping them within the field so they can be used by the intended crop, at the same time addressing economic and environmental challenges. Effectiveness is maximized with 4R Nutrient Stewardship by choosing the **Right Nutrient Source** to apply at the **Right Rate** in the **Right Place** at the **Right Time**[3]. When this is done in combination with conservation practices such as buffer strips, continuous no-till, cover crops, and riparian buffers within intensively managed cropping systems, increased yields, enhanced soil fertility and diminished nutrient losses can be achieved[4]. 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 many different inputs and can produce a range of outputs, the overall efficiency is really assessed economically. Maximum profit will occur when the maximum value of outputs is reached for each 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[5,6]. Even so, where climatic or other risks are important, the optimum value for profit may be less than the maximum value[7].

Component Efficiencies

There are at least 18 different definitions and calculations of nutrient use efficiency[8]. Even the most useful component efficiencies require careful interpretation if they are to contribute to effective nutrient use in cropping systems. Indicators developed need to be systematic in their estimation, scalable from field to farm to region to national, be estimated as repeated measures over time, and most importantly, inform management. **Table 1** lists and describes 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 amount of nutrient recovered by the crop.

Critical aspects of developing these metrics is to ensure that the data being used are transparent, auditable, referenced, consider all nutrient sources, are regionally relevant and appropriate to the intention as to how the metrics are to be interpreted[11]. When taken alone, the numerical value of these indicators is of limited value, as they need to be considered over time and in concert with other measures. They are not environmental or economic indicator in their own right and interpreting them as such is inappropriate. The indicator values calculated need to be linked to other indicators such as yield and soil test values to gain an appreciation of their significance.

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.

In crop-livestock farming systems, production efficiencies are difficult to calculate as there are diverse

Table 1. Four selected definitions of nutrient use efficiency[8].

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[9]
AE Agronomic efficiency of applied nutrient	(Y-Y0)/F	10 to 30 units of cereal grain per unit of N[9]
PNB Partial nutrient balance (removal to use ratio)	UH/F	0 to greater than 1.0 depends on native soil fertility and fertility maintenance objectives[9] <1 in nutrient deficient systems (fertility improvement) >1 in nutrient surplus systems (under-replacement) Values around 1 (system sustainability)
RE Apparent crop recovery efficiency of applied nutrient	(U-U0)/F	0.1 to 0.3 – proportion of P input recovered first year[10] 0.5 to 0.9 – proportion of P input recovered by crops in long-term cropping systems[10] 0.3 to 0.5 – N recovery in cereals – typical[8] 0.5 to 0.8 – N recovery in cereals – best management[8]

F – amount of nutrient applied (as fertilizers, manures, etc.); **Y** – yield of harvested portion of crop with applied nutrient; **Y0** – yield in control with no applied nutrient; **UH** – nutrient content of harvested portion of crop; **U** – total nutrient uptake in aboveground crop biomass with nutrient applied; **U0** – total nutrient uptake in aboveground crop biomass with no nutrient applied.


Image: R. Norton/IPNI

Canola crops from Mount Arapiles. *The Wimmera in Victoria is a sea of yellow with canola in the spring.*

outputs. For example, a dairy farm produces milk, but also calves and cull cows, while sheep for wool and/or meat are a common enterprise on cropping farms.

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

Similar to production 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)[8]. It is calculated as the amount of nutrient in the harvested portion of the crop per unit of nutrient applied. This is most often reported as a ratio of removal to use, and is fairly easily measured by growers, as well as at regional or national levels. Over time, it can be used to assess trends of nutrient removal or buildup. Because a range of crops are usually grown in a rotation, it should be taken over a number of growing seasons.

The more complex form - preferred by scientists studying how the crop access nutrients from the soil and fertilizer - 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. Its use is limited to the description of the effect of a single nutrient application and for a single cropping season. The most accurate way to make estimates of RE is using isotopes of plant nutrients.

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

Choice of an Efficiency Term

Each of the major crop nutrients is also important in the nutrition of animals and humans. Where a particular nutrient has a high value the food produced, such as nitrogen (protein), zinc or iron, greater emphasis should be placed on recovery relative to production efficiency. If the end use for the crop is feed or food,

Table 2. Efficiency values calculated from N responses reported from a long term (19 years) fertilizer experiment on rainfed mixed cropping system in the Wimmera district, Victoria, Australia. Crops differed each year in basically a canola, wheat, barley and pulse rotation and the yield and production efficiencies are derived from the mixture of crops grown. The values calculated include an estimate of fixed N during the pulse phases[12].

N rate, kg N/ha/yr	Mean yield, t/ha/yr	Mean annual N balance, kg N/ha/yr	Production efficiencies		Recovery efficiencies		Net return on N, A$/ha
			PFP	AE	PNB	RE	
0	1.90	-16	-	-	1.36	0.54	
20	2.29	-12	141	22	1.04	0.47	97
40	2.22	-2	71	11	0.74	0.37	56
80	2.31	+19	38	8	0.42	0.19	53
160	2.32	+77	18	3		3	-34
LSD ($p<0.05$)	0.09						

PFP = partial factor productivity, kg yield/kg nutrient; **AE** = agronomic efficiency, kg yield increase/kg nutrient; **PNB** = partial nutrient balance, kg grain/kg nutrient; N removed/kg nutrient; **RE** = recovery efficiency, kg increase in removed/kg nutrient, Net return is calculated assuming a price of $300 AUD/t averaged over all the grain produced, and cost of $1.00 AUD/kg N

yield improvements gained at the expense of the concentration of the nutrient in the product may diminish the value of the product. For instance, depending on variety, the grain of wheat grown in a high yielding environment may contain a lower concentration of N and therefore less protein, producing flour with a lower baking quality. This concern is also valid where crop co-products such as meals from some oilseed, biofuel and fiber crops may be used for animal nutrition.

On the other hand, where nutrients present in the crop output are in excess of end-use needs, the emphasis should be placed on production efficiencies. For example, the yield response to added P by feed grains, forages or fodders grown for use by ruminants is probably more important that the P concentration, even when the soil may have been enriched with P over time.

Interpretation

There are limitations to the interpretation of any single measure of component efficiencies within farming systems. Because of differences is nutrient release rates from different products, the source used should be clearly stated in the interpretation of calculated efficiencies. The AE and RE terms are most informative for products that supply a single nutrient, but many fertilizers contain multiple nutrients. For example, mono- and di-ammonium phosphate contains both N and P and some S, while single superphosphate supplies P, S and Ca. The PFP and PNB terms can overestimate efficiency when applied only to a single source if other important nutrients in short supply are also supplied.

In the short term, all four component efficiencies decline as rates of fertilizer application are increased above an economic optimum, as indicated in **Table 2**. Based on these trends, it may be concluded that the lowest fertilizer rate would result in the most efficient use of nutrients. This is untrue, as with low application rates and high production, the nutrients removed come from soil reserves. Most importantly, where nutrients are removed from organic or mineral pools in the soil, the decline in soil reserves over time ultimately means lower soil productivity as well as diminished soil health and system resilience.

In general, the more significant increases in efficiency come from increasing yields. For example, the PFP for N applied to corn production in the United States of America increased by about 43% between 1975 and 2016. This increase did not result from a decrease in N application rates[13]. In fact, rates applied rose by about 27%, but better genetics and improved management boosted yields by 82%. 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 contribution from mineralized N to the crop.

A PNB (ratio of removal to use) close to 1.0 over a number of consecutive growing seasons reflects an ideal situation indicating minimal 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 1.0, it becomes important to understand the fate of the unaccounted nutrients, and to find out whether they are benign or harmful 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 or can access from the soil. 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 PNB and RE well below 1.0 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 in the long term, if removal is more than supply the soil reserves of available K will be depleted. The same applies to P in many soils where annual values for RE can be low, because the crop accesses soil and fertilizer P sources, and fertilizer P not taken up is converted to slowly or less available forms of P that, over time, return to the available P pools and are accessed by the crop. 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, which can be achieved by address the particular loss processes occurring.

Studies that have estimated PNB and RE under farm conditions have found wide variability[14]. Where soil N supply is high, PNB and RE are usually low. While low values indicate a risk of loss for a mobile nutrient like N in its nitrate form, 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. Because of the second factor, taking long term trends in PNB and RE are more important than data from a single crop or year.

Toward Improvement

Despite the existence of many comprehensive reviews of the literature on nutrient use efficiency, there is little information on nutrient use efficiencies under practical farming conditions[8]. 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. IPNI-ANZ, supported by the Australian Grains Research and Development Corporation, undertook a survey of over 500 cropping fields in southeastern Australia to investigate nutrient removal and use over a five-year period for each field, including assessments of N fixation[15]. At a field scale, there was huge variation in the PNB values for both N and P, and the values were not normally distributed with a strong skew to the right in both data sets. In essence, these data indicate that 30% of fields had PNB-N greater than 1.5 and PNB-P less than 0.6. On those fields, there was 50% more N removed than applied while 80% of fields had more P applied than removed over the audit period. When assessed against soil test changes over the same periods, these removal-to-use values can assist growers refine their nutrient management practices.

At a state or national scale, IPNI has collated data on nutrient balances for all of Australian agriculture from farm production figures, nutrient concentration values and state level fertilizer consumption. The data for the period 2002-2010 PNB for Australian agriculture indicates 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[11]. 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 by ensuring the selection of appropriate genetics and management practices, complemented by the

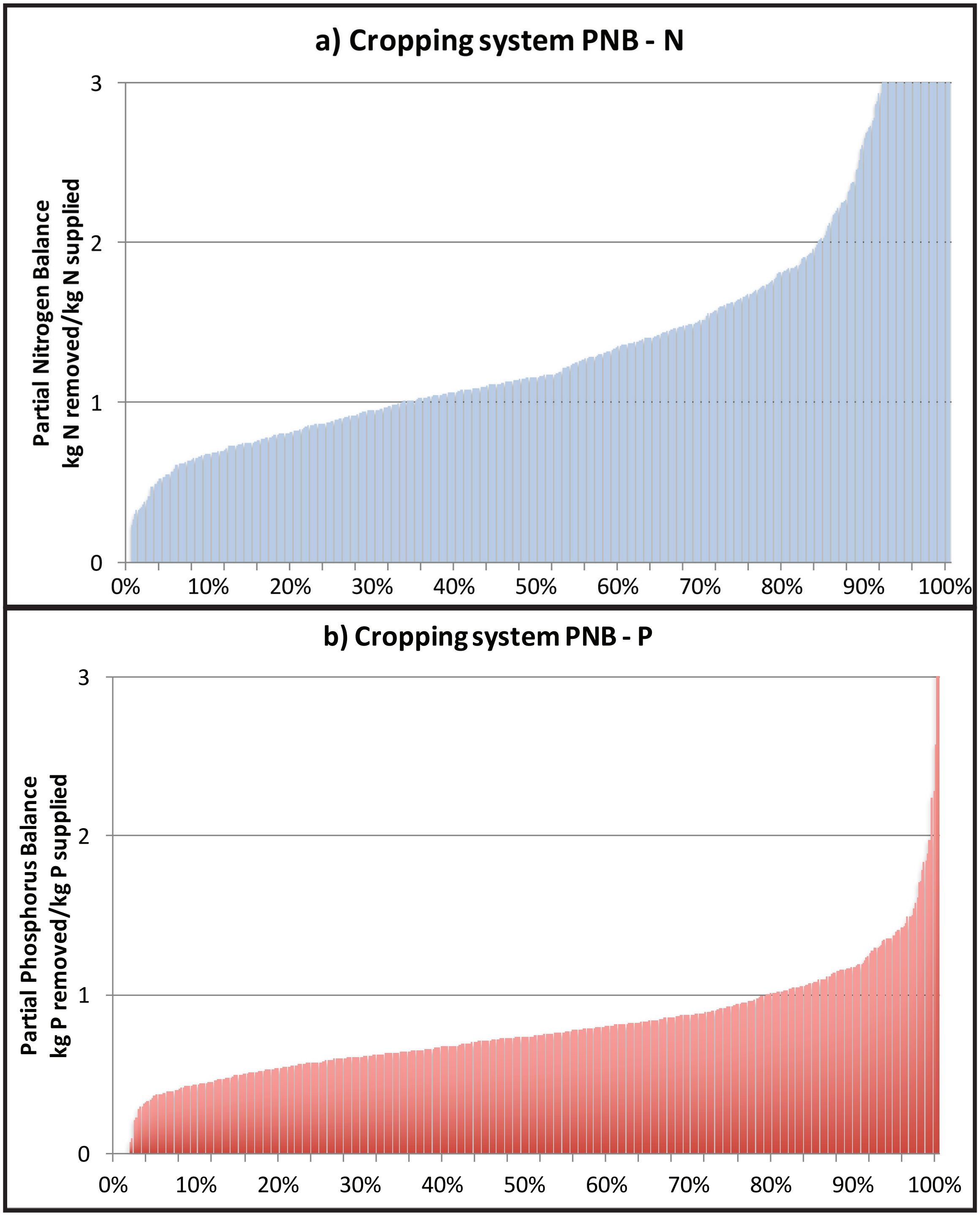

Figure 1. Cropping system partial nutrient balances for a) N and b) P from a survey of 500 fields over 5 years in southeastern Australia. The mean for N is 1.62 and the median 1.17 (Q1 0.9; Q3 1.66) and the mean for P is 0.80, and the median 0.74 (Q1 0.57; Q3 0.93)[15].

implementation of 4R Nutrient Stewardship considering:

- **The Right Source** – such as using enhanced efficiency fertilizers such as slow or controlled release formulations or the use of inhibitors can reduce potential losses where the enhancer addresses the loss process operating.
- **The Right Rate** – such as matching supply and demand by using nutrient budgets or soil tests help to identify the most appropriate amount of nutrient to supply.
- **The Right Place** – such as using precision agriculture technologies to map fields and sense crop needs[17].

- **The Right Time** – such as matching the timing of nutrient supply to the period of crop nutrient demand to ensure as much nutrient gets into the crop as possible.

When assessed with practical farming conditions, the adoption of 4R Nutrient Stewardship strategies should improve nutrient use efficiency. The combination of systems monitoring such as frequent soil testing with improved interpretation will assist in the development of decision support tools that apply evidence-based nutrient management decisions at a field level. While improved efficiency is expected to reduce the risk of nutrient loss from cropping systems, other management practices like timely planting, conservation tillage, vegetation buffers, and cover crops can also be used to further minimize nutrient losses to water and air.

National and Global Assessments

There is a growing literature on indexing nutrient performance at national and regional level as part of the assessment of N (in particular) management effectiveness. It is not possible here to review all the literature, but two papers in particular have assessed the national trends over time in PNB-N for a large number of countries[18, 19]. These assessments considered crop yield, and N inputs to land including manure, synthetic fertilizer, biological N fixation and atmospheric deposition. The derived nutrient balances showed large spatial and temporal variation, and these differences could indicate that countries are at different stages of an environmental "Kuznets" curve[20]. Taken from economics, this curve (**Figure 2**) indicates that as an agricultural system develops, it initially exploits soil fertility as yields improve and nutrients are exported, so PNB declines. Increasing yields with declining N fertilization and values clearly indicating agricultural mining of soil N (i.e., organic matter). As improved agronomic practices are adopted, PNB improves back to a steady state where fertilizers become the main sources of nutrients to sustain productivity.

At present, Australia shows a general downward trend in PNB-N over time, with an N surplus (fertilizer plus fixed N less yield) of a little less than 20 kg N/ha in 2009[18]. Other countries have N-PNB trends that show a decline then increase in PNB-N with improved agronomic practices. So, the current differences in PNB among countries can be partly explained by the degree of development of the production system, but it also indicates the different types of systems that are nationally significant. Land management activities such as fruit and vegetable production have an inherently lower PNB than field crops like cereals and oilseeds[19]. Consequently, the national levels and trends noted can be rooted in the types of agricultural systems that dominate rather than a reflection on overall nutrient management.

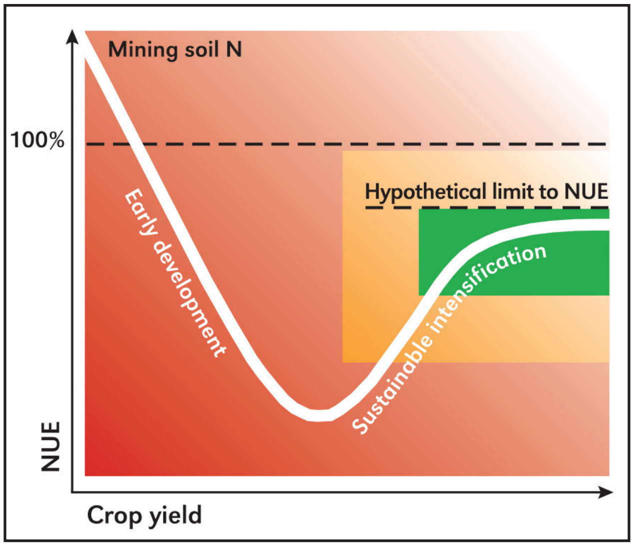

Figure 2. Typical N use efficiency (NUE) trend relative to crop yield over time. Farming systems progressively move from the red zone to the orange zone and, ultimately, the green zone, which reflects high yield and optimum N use efficiency[20].

The assumptions underlying the data can all be challenged, and while these indicators are presented as national values, access to better quality data will enable disaggregation farming system and/or region.

Conclusion

In his book titled *Feeding the World,* Vaclav Smil[21] 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."*

While national assessments are important, farm or field level values of PFP and PNB will help inform producers of opportunities to improve nutrient management. Incorporating PFP and PNB can be easily extracted from field records. On-farm research evaluating options

developed using 4R Nutrient Stewardship can be used to develop improved practices where nutrients are suspected to be inefficiently used.

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 and reference to the guidelines developed using 4R Nutrient Stewardship.

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