Assessing strategies for efficient and effective nutrient management

Robert Norton

International Plant Nutrition Institute, 54 Florence St, Horsham, Victoria, 3400, Australia. rnorton@ipni.net

Abstract: Monitoring nutrient performance through a range of metrics or indicators is essential to assess changes over time. These metrics need to be described in terms of the system boundary, the time scale used and the sources of the raw data used. For broad scale nutrient use efficiency and effectiveness estimates, only PNB or PFP are easily derived and provide some useful information, but neither are complete productivity or environmental indicators. The most appropriate performance indicator terms depend on the context in which they are to be applied. For regional nutrient risk assessments, a PNB will be of use, whereas to assess the effectiveness of nutrient use for food production PFP will be useful. Neither metric assesses environmental fate, as loss pathways may – or may not – be environmentally benign and a better assessment is made when these are linked to measures of soil fertility. Similarly monitoring and reporting of the use of 4R practices can complement the reporting of nutrient performance, but additional practices and additional indicators are necessary to reflect the full range of social, economic and environmental impacts.

Improved nutrient-use efficiency, especially for N and P, will be a cornerstone of future farming systems and will require a range of approaches and techniques as no single method will provide increases in all situations and across all crops. There is merit in the judicious use of enhanced-efficiency fertilizers using the 4R principles to ensure nutrient supply matches plant demand, so minimizing losses. Tools for meeting the source-rate-time-place optimum include better soil tests and crop monitoring to match nutrient demand and supply on a site-specific basis. As well, the development of nutrient-use-efficient crops using conventional and novel plant breeding methods will deliver improvements in the short to medium term.

Key Words: nutrient performance indicators, nutrient balance, enhanced efficiency fertilizers, nutrient stewardship site specific nutrient management, 4R nutrient stewardship.

Introduction

Increasing productivity in agriculture is the key strategy to meet food security, and the impact of science has been to improve grain yields, without recourse to expanding production areas. The increase in production during the Green Revolution—into the Evergreen Revolution—is a case study in ecological intensification, which has delivered increased food supply as well as preserved land for wildlife and non-agricultural pursuits. These changes have come about by improvements in efficiency of the use of resources such as water, nutrients, and radiation, achieved through agronomic and genetic adjustments to production systems. As a result, farmers have adapted to changes in climate, markets, social and environmental challenges and have improved productivity.

The use of fertilizers is fundamental to intensification to feed the global population, with around half of current food production made possible by balanced crop nutrient input. At the same time, there are parts of the world where fertilizers are under-used so that food security is threatened, or where they are overused to the point of contributing to environmental pollution. In order to bring balance to these two situations, it is useful to distinguish between effectiveness and efficiency of nutrient use. Efficient (e.g., increasing output per unit of fertilizer applied) and effective (e.g., increasing farmer productivity) nutrient use will balance environmental, economic and social issues, as the improvements in all three are not mutually exclusive (Norton

Nutrient Performance Indicators

Before a discussion on strategies to improve nutrient use efficiency (NUE), it is important to provide a definition of this metric, as it is one of suite of nutrient performance indicators (NPI) that can assist in assessing changes in system function (Norton et al. 2015). There are several types of metrics that could be developed to understand nutrient performance. While *outcome* metrics like NUE are most commonly discussed, these are only achieved through new processes being adopted. *Enabler* metrics describe the elements need to facilitate improved nutrient management, such as the number of extension professionals engaged or a quantum of the research effort towards improved efficiency. These enablers need to be transformed into *actions* through measures of such as the participation by farmers in education or the area under 4R nutrient stewardship.

There has been considerable interest in developing ways to express the trends in efficiency, and a range of NPI's have been developed (Dobermann 2007). Selecting the most appropriate NPI requires a detailed understanding of the processes involved in acquisition, residence time, allocation, remobilization and losses within plants. Acquisition or uptake efficiency and remobilization or utilization efficiencies are important to plant breeders selecting more efficient genotypes. Alternatively, responses can be expressed as agronomic efficiencies or apparent recovery efficiencies, but both require a nil fertilizer application treatment to estimate the extra yield in response to added nutrient. Of the range of output NPIs, partial nutrient balance (PNB; nutrient removal to use ratio) and partial factor productivity (PFP; crop yield per unit of nutrient applied) offer the benefits of being readily assessed for fields, farms, regions or nations, and together they link productivity and nutrient cycling at these scales.

PNB is widely reported as a metric, but the use of plant nutrients does not have a single dimension. Sound nutrient management is based on balancing economic, social and environmental goals. PNB can be readily estimated using existing data and Figure 1 shows an example of PNB values for selected countries calculated for cereals using data from FAO (production data, FAOStat 2014), IFA (nutrient use by crop, Heffer 2009, 2013) and IPNI (nutrient concentrations in grain, IPNI 2012). Rather than giving PNB values, Figure 1 presents it as a surplus of (in this case) N over the output of N from the system. All these data have errors inherent in their derivation, and so due diligence should be given to deriving N contributions from manures and N fixation, the nutrient concentrations of the materials removed and the regional use patterns for fertilizers. However, any single indicator such as PNB may be prone to misinterpretation and may fail to bring attention to unintended compromises in overlooked dimensions (Fixen et al. 2015).

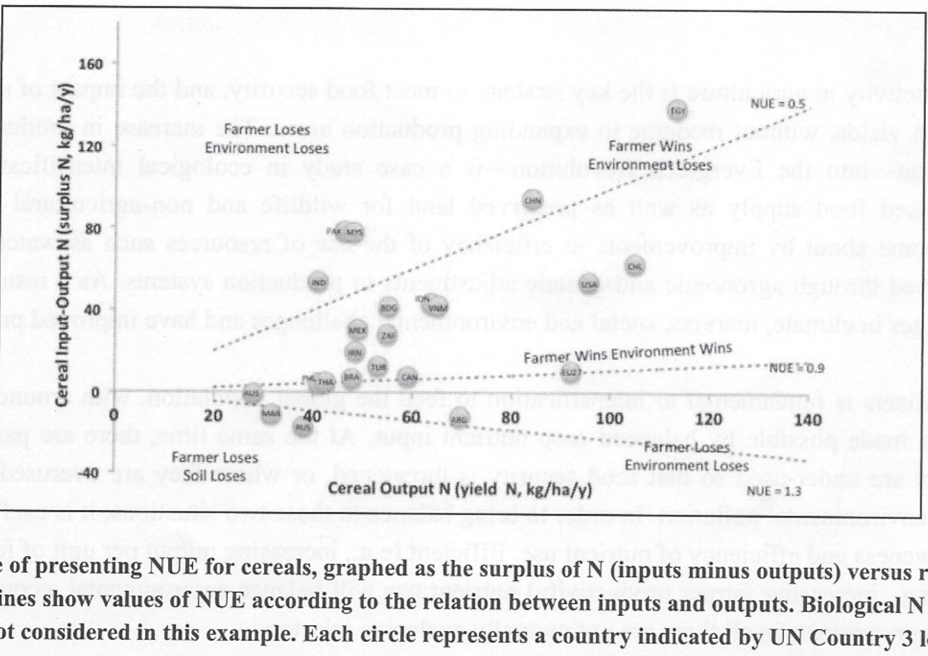

Fig. 1 An example of presenting NUE for cereals, graphed as the surplus of N (inputs minus outputs) versus removal (output) of N. The dotted lines show values of NUE according to the relation between inputs and outputs. Biological N fixation and manure use are not considered in this example. Each circle represents a country indicated by UN Country 3 letter code

A low removal-to-use ratio may be appropriate if the soil requires building up of N, P or K status. In that case, the extra nutrient enters soil pools (including soil organic matter N and P fractions) that will reduce the external input demand for those nutrients in the future, and in this situation they are not lost to the environment. However, if soil loss processes such as leaching, denitrification and erosion are high, and the extra nutrient can be transferred from one place to another—possible adverse environmental effects may result. Alternatively a high nutrient removal-to-use ratio (PNB) may occur if the crop has access to large pools of avail- able nutrients in the soil, so that residual fertility is being drawn upon. If soil fertility is low, then a high value will result in soil degradation and reduce fertility down to and below critical concentrations necessary to maintain soil fertility, soil health, and productivity.

It should also be noted that NUE, expressed as – for example – PNB varies among crops, cropping systems, environments and production practices, so benchmarking NUE needs to be undertaken locally, at the farm and/or paddock level over time. Livestock systems tend to be inherently less efficient than crop based systems, and within cropping systems some crops have inherently higher PNB and PFP than others. So part of the variation in PNB among regions in Figure 1 is likely a consequence of the differences rather than issues where direct management interventions could be used. It is also important to follow trends over time as discussed by Lasseletta et al. (2014).

A final point is that NUE can improve without a change in the aggregated value. Within a region, there is likely to be a distribution from high to low in NUE values for fields or farms. Raising the lower NUE cohort and decreasing the higher NUE would not change the mean but give improvements because of the narrower distribution of values.

The interpretation of these indicators is not as simple as "more (or less) is better" as the ratios expressed need to be interpreted in a similar way to the data from Figure 2. A very high PNB value indicates that more nutrient is being removed than added, and this may be of value where soil residual nutrient levels are high. On the other hand, a high PNB could indicate unacceptable depletion of soil nutrients, such as through the breakdown of soil organic matter. Alternatively, if the PNB is very low, where more nutrient is being applied than being removed, then this may be because the soil has a high binding capacity or that additional nutrient is required to build up soil nutrient levels. A very low PNB does not necessarily indicate that nutrients are being lost, as they may be used in subsequent phases of the farming system. In both cases, the impact of high or low PNB requires an understanding of the fate of the nutrients applied and unless indexed against soil fertility trends and climatic conditions, the number is of little value.

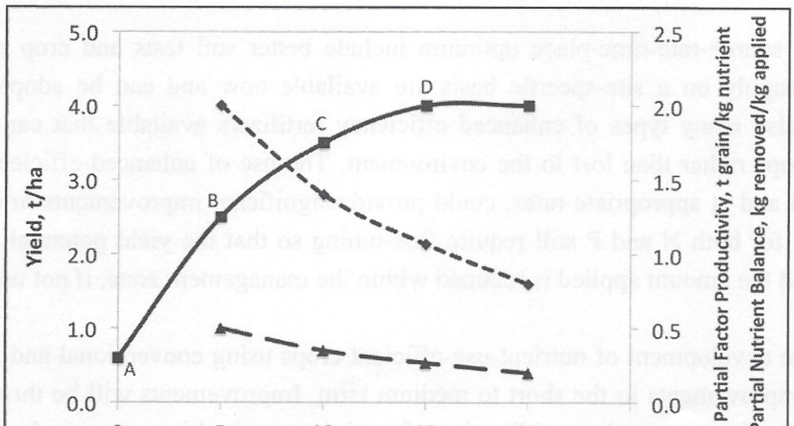

Fig.2 Example of crop yield, and the performance indicators of Partial Nutrient Balance (kg nutrient removed/ kg nutrient applied) and Partial Factor Productivity (t yield/kg nutrient applied). This nutrient balance illustration is based on a nutrient concentration of 4 kg nutrient per tonne of product

Overview of strategies to improve nutrient performance

Improved NUE, especially for N and P, will be a cornerstone of future farming systems and will require a range of interventions, including the judicious use of enhanced-efficiency fertilizers using the 4R principles, improved genetics and site-specific nutrient management. Efficient and effective nutrient performance is underpinned by good farming practice, with best practice pest and weed control, reduced soil erosion, enhancing soil health (e.g. structure, pH), matching water supply to yield potential and good planting and harvesting techniques. If the underlying agronomic practices are not optimum then NUE will be compromised from the start. Good agronomy is the first step in improving nutrient performance.

Even though both N and P have strong environmental imperatives behind efficiency improvements, there are more diverse potential loss pathways for N (leaching, denitrification, volatilization, fixation) compared with P, as fertilizer P that is not removed by the crop essentially remains in the soil, although there are situations where there are losses through deep drainage or lateral flow of soluble P (Burkitt et al. 2004) as well as by soil erosion. Improving efficiency relies on intervening in those loss processes so that more nutrient is taken up by the crop.

Developing and implementing strategies to increase nutrient-use efficiency will be logical and improve productivity only if the nutrient in question is the limiting or co-limiting factor. Water availability (Norton and Wachsmann 2006), soil salinity (Soliman et al. 1994) and various other biotic and abiotic factors can restrict the capacity of a crop to respond to added nutrients so that nutrient-use efficiency will be compromised. Selection of crop cultivars with high yield potential will also raise the response to applied nutrients even without specific selection for improved nutrient-use efficiency. For example, higher yielding modern wheats produced around 20% higher yields at the same P rate as lower yielding older types (Batten et al. 1984)

It is also important to remember that strategies to increase nutrient use efficiency, such as new products, microbial supplements, best practice agronomy or improved germplasm, or even the system-wide adoption of fertigation (Kafkafi and Tarchitzky 2011), will provide benefits. However, the law of conservation of matter still applies and if nutrients are removed in produce, then that mass must have come from the soil, been applied as fertilizer or come from some other source, such as from water or by atmospheric deposition. Except for input of biologically fixed N, improved nutrient-use efficiency cannot create any more nutrients than what is presented. If more nutrients are removed than added, then soil reserves decline. This, in turn, can reduce the PNB of applied nutrients as the soil fertility and nutrient status or the soil test level declines. Conversely, if more nutrients are applied than removed, then they either move to another place by various loss processes or remain in the soil, albeit in forms that may not be biologically active or useful to the plant

Tools for meeting the source-rate-time-place optimum include better soil tests and crop monitoring to match nutrient demand and supply on a site-specific basis are available now and can be adopted along with good agronomy. There are also many types of enhanced efficiency fertilizers available that can assist in preserving nutrients for use by crops rather than lost to the environment. The use of enhanced-efficiency N sources, when appropriately deployed and at appropriate rates, could provide significant improvements in efficiency. Tools for selecting the right rate for both N and P still require fine-tuning so that the yield potential is limited by factors other than nutrients, and the amount applied is retained within the management zone, if not used.

In the medium term the development of nutrient-use-efficient crops using conventional and novel plant breeding methods will deliver improvements in the short to medium term. Improvements will be through traits associated with better acquisition and/or improved remobilization of nutrients acquired into crop products. Irrespective of the strategy, there is no escaping the law of conservation of mass—at full RE, crops will still require the replacement of nutrients removed in the harvested products.

However, in the longer term, improved efficiency alone is not likely to ensure future food security. Whole system changes may be needed to develop new products or to relocate land-use activities to different areas as new agroecological zones develop in response to climate change and altering resource availability. Furthermore, there are limits to improving NUE, as the balance of input and output should aim to approach unity although full recovery would seem aspirational rather than achievable. Figure 3 gives a pictorial suggestion about the timing and magnitude of different elements to improving NUE.

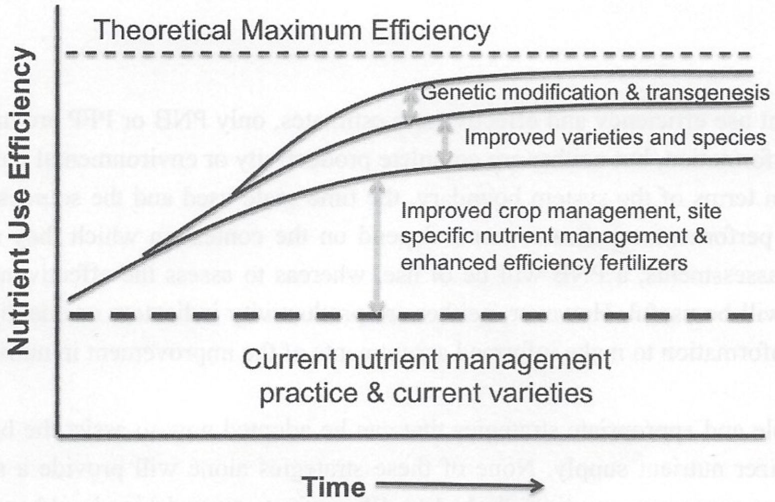

Fig. 3A view of the elements that would progress NUE over time – adapted from A. Mosier, et al. (eds.), Agriculture and the nitrogen cycle: Assessing the impacts of fertilizer use on food production and the environment. Scientific Committee on Problems in the Environment (SCOPE), Island Press, Washington, DC, 2004

The challenge set by Smil (2000a) of increasing N-use efficiency by 25%–30% during the next 50 years would seem achievable through the application of nutrient best management practices coupled with good agronomy and improved germplasm. As climate change impacts take effect across time, gains in efficiency by agronomic and genetic adaptations may be made, but production systems may need to relocate to regions where higher efficiency is conferred by more favorable soils or climates. This continual adaptation to develop a secure food supply will initially be based on integrating risk management strategies with improved agronomic practices and then the adoption ofbetter adapted germplasm, which can then lead on to systems transformations in land use (Howden et al. 2007).

Farm-level nutrient performance

For farmers, the amount of fertilizer to use is fundamentally an economic decision moderated by their attitude to risk, and is largely based on the relative price paid for the nutrient and the price received for the produce. If the cost of nutrients is very low then the rates used would be higher than if the cost were higher. Alternatively, if the value of the produce is very low, there would be little incentive to use nutrients as there would be little return on even a small investment. However, if the value of the produce is high — either in commercial terms or in terms of food security — extra fertilizer will be added to move the yield potential towards its maximum. How closely that maximum yield is approached depends on the risk attitude and financial resources of the producer.

Better nutrient performance will rely on engagement with farmers. This is clearly because the inter-ventions appropriate will be made by farmers within the constraints of their production system. While rate is often mentioned as part of the decision, choice of the right nutrient source, applied at the right time and in the right place are also key parts of effective delivery of nutrients to meet the demand pattern of crops and pastures. Using 4R Nutrient Stewardship guidance will enable growers to better match nutrient supply through adjusting source, rate, time and place to match the soil characteristics, climatic constraints, and the spatial and temporal demand of the cropping system; while also considering social and environmental goals (IPNI, 2012).

There is a need to collect farm level nutrient efficiency data. Despite its importance, there are few measures of the farm level PNB or PFP, nor is the distribution of these values publicly available for regions or industries. Farm level surveys could assist in developing key management practices for improving both indicators, when linked to other aspects of nutrient performance. IPNI is currently engaged in collecting this farm level data in the US, Canada, India and Brazil, and a new GRDC project has been started in Australia to collect this information for the grains industry.

Conclusions

For broad scale nutrient use efficiency and effectiveness estimates, only PNB or PFP are most easily derived and provide some useful information, but neither are complete productivity or environmental indicators. These metrics need to be described in terms of the system boundary, the time scale used and the sources of the raw data used. The most appropriate performance indicator terms depend on the context in which they are to be applied. For regional nutrient risk assessments, a PNB will be of use, whereas to assess the effectiveness of nutrient use for food production PFP will be useful. However, neither are productivity indicators or quantify environmental risk, so require additional information to make informed assessments of the improvement in nutrient performance.

There are various viable and appropriate strategies that can be adopted now to assist the better matching of crop demand and soil/fertilizer nutrient supply. None of these strategies alone will provide a solution alone, but the adoption of current best agronomy practices, linked to 4R nutrient stewardship should enable efficiencies to be raised but this will require engagement with growers to facilitate their adoption of these practices.

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