Grains Research and Development Corporation
More Profit from Crop Nutrition II –

Nutrient performance indicators
IPN00003

A scoping study to investigate the development of grains industry benchmarks partial factor productivity, partial nutrient balance and agronomic efficiency of nitrogen, phosphorus, potassium and sulphur.

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PLAIN ENGLISH SUMMARY:

Selecting an appropriate nutrient performance indicator

Because of the importance of fertiliser use economically and environmentally, there is increasing interest is developing ways to evaluate the efficiency and effectiveness of their use on farms. While there are many metrics that can be used as nutrient performance indicators (NPI), three in particular have become widely quoted. They are:

- Partial Nutrient Balance (PNB), which is the quotient of nutrient removed in product and nutrient supplied to the crop. Because it is a ratio, it is dimensionless.
- Partial Factor Productivity (PFP), which is that quotient of grain and nutrient supplied to the crop. This has the unit of kg grain/kg nutrient supplied.
- Nutrient Balance Intensity (NPI), which is the amount of nutrient in deficit or surplus per hectare. It has the unit kg nutrient/ha.

The development and promulgation of nutrient performance indicators needs to be considered in the light of the purpose of the undertaking. The reason may be as an indicator of management for growers at field scale or as a statement of accountability at a regional and/or industry scale. The two reasons – while not mutually exclusive – do require clarity of purpose.

The nutrient performance indicators partial nutrient balance (PNB), partial factor productivity (PFP) and nutrient balance intensity (NBI) are useful in assessing system performance. They are not indicators of environmental fate.

Nutrient performance indicators need to be:

- Systematic in their estimation
- Scalable from field to farm to region to national
- Be informative to management
- Able to be estimated as repeated measures over time

PNB, PFP and NBI can be estimated at a range of scales but the assumptions that underpin the calculations needs to be explicit. The following data sources in particular need to be addressed

- product nutrient concentrations
- sources of production data and land area used
- time over which the assessments were made
- boundary to which the assessment applies

These metrics can be applied at a range of scales from fields, to farms to regions to countries. 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. 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 its 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.

The international literature is particularly focused on N performance indicators and there have been several studies in assessing nutrient performance indicators for Australia, at different times and over different datasets. For example, Lassaletta et al. (2012) estimated the N-NPI as 20 kg N/ha/y for Australia and trending higher, our national N footprint was estimated the second highest in the report by Oita et al. (2016) and Zhang et al. (2015) reported the N-PNB for Australia as 0.68 for the period 2002-2011. Norton et al. (2014) estimated the N-PNB, P-PNB and K-PNB as 1.02, 0.44 and 1.8 respectively for grain production in Australia. The N-PFP, P-PFP and K-PFP values were 52 kg grain/kg N, 128 kg grain/kg N and 724 kg grain/kg K. The N-NBI, P-NBI and K-NBI values were +4.6 kg N/ha, +7.2 kg P/ha and -5.7 kg K/ha. Overall, Australia in general has modest N imbalances using the assumptions implicit in the current literature, compared to other countries. P balances are generally positive (removal<use) while K balances as generally negative (removal>use).

In comparison to other countries, the P-PNB for P for Australia are relatively small (~0.5) with more P is supplied in fertiliser than is removed in products in Australia. The K balances indicate that more K is removed than is supplied which is similar to the global mean, while the N imbalance is modest by global standards.

The national accounts for nutrients require very good quality data presented in a consistent format with clear assumptions presented if they are to be reported to groups such as the UNEP or the OECD.

Synthesis, summary and evaluation of Australian Information on nutrient performance indicators

Using currently available data on production and nutrient use, nutrient performance indicators can be estimated at national level (Table S1), although these data – and many other estimates – either ignore or over simplify the input of biological nitrogen fixation – either by selecting a national value derived from crop data only and/or ignoring inter-annual variations. High quality production data is available down to natural resource management zone (as defined by the ABS), but there are few sources of good quality fertiliser use by crop data at regional scale. Different data sources on regional fertiliser use by crop were compared, and while there is some concordance, but each source has its own problems. The ABS data is not disaggregated by crop and the International Fertilizer Industry Association (IFA) data is only presented by region. The ABS does have some inconsistencies over time in the wording of particular questions concerning land management practices. The quality of the data used and a definition of the industry cohort assessed are important in developing reliable and consistent estimates of these nutrient performance indicators. It is appropriate and encouraged that GRDC consider on-going assessments of field surveys such as the paddock survey.

The assessments undertaken show reasonable consistency in the size and distribution of partial nutrient balances for Australia. In general, Australian agriculture has a near neutral or slightly positive N balance, a positive P balance and a negative K balances. As a consequence, soil P levels are likely to be increasing, while soil N and K levels are being depleted. These values show large inter-annual variation, with nutrient removals (i.e. production) showing larger variation than nutrient inputs.

Using the data from the regional nutrient budgets, maps were created for three audit periods (2007-08, 2009-10 and 2011-12 and these are posted on the Centre for eResearch and Digital Innovation at Federation University (http://www.ozdsm.com.au/ozdsm_map2.php). The maps have very limited functionality, and there are tentative plans to develop the functionality further, similar to the information provided through the IPNI NuGIS on-line tool.

Similar to the whole of Australian agriculture, the Australian grains industry on the whole shows a negative N and K balance and a positive P balance, and these values are consistent with the data reported earlier from the international survey by Norton et al. (2014) and the Australian Agricultural Assessment (2001).

Table S1. The mean nutrient balance intensity for particular industry sectors as derived from the ABS farm survey information for the period 2007-2008, 2009-2010 and 2011-12. The denominator is land area fertilized for each industry. The N values do not include biological nitrogen fixation.

Industry	N-NBI (kg ha/y)	P-NBI (kg ha/y)	K-NBI (kg ha/y)	S-NBI (kg ha/y)
Grain & Livestock	-9.4	5.8	-3.7	2.0
Other Grain Growing	-10.1	3.3	-4.1	0.2
Rice Growing	0.4	5.3	-7.7	0.2
Cotton Growing	36.2	1.9	9.1	1.6
Sugar Cane Growing*	2.8	-5.8	-78.2	-11.5
Vegetable Growing (outdoors)	14.1	11.4	-4.1	6.6
Tree Fruits & Vines	10.5	1.8	10.5	0.8
Sheep Farming Specialised	-4.1	8.1	-3.6	7.0
Beef Cattle Farming (specialised)	-23.5	1.2	-3.3	6.4
Sheep-Beef Cattle Farming	-0.4	7.4	-3.6	8.5
Dairy Cattle Farming	5.7	4.4	-5.2	4.5

* Balances for Sugar Cane Growing do not included recycled processing by-products.

Mean values are useful for industry reporting but care should be taken as products and farming systems obviously differ among industries and direct comparisons among industries can be misleading about the comparative efficiency and effectiveness of nutrient use. To be of value to growers as guides for improving nutrient management, the distribution of these values at a regional or farming system level will assist with benchmarking.

Nutrient performance indicators from southern Australian grain farms.

Field records of fertiliser use and crop type and yield were collected from 514 fields from 125 growers covering over 35,000 ha over 4 or 5 years in south-eastern Australia. The data came from either consultants or directly from farmers and the cohorts from the Mallee, High Rainfall Zone, the Wimmera and southern New South Wales were considered adequate to interrogate for nutrient performance indicators.

The frequency distribution of PNB and PFP were skewed to the right, with the mean larger than the median, so that comparing mean regional values is not statistically valid. Because of this, data may be best presented as distributions (Figure S1).

The data from the 500 fields reported showed N-PNB was generally higher than 1.0, while P-PNB is generally lower than 1.0. The N-PNB is higher than 1.0 for over half the fields assessed in all regions except the Mallee where 39% were above 1.0. The P-PNB value reported in this study is lower than data from other countries and this is likely a consequence of the P-sorbing soils fixing some of the applied P.

The P-PFP values collected from the farms surveyed are generally around 200 kg grain/kg P. The N-PFP values show wide variations due to rotation and soil N status and the around half the values from the farmers' fields are less than 50 kg grain/kg N suggesting that those low values may be limited by some biotic or abiotic constraints other than nutrients. It is debatable if the high values indicate that N supply is limiting production but rather that extra N is being drawn from soil reserves, either from new or old organic N sources.

Despite the limitations of PNB, PFP and NBI, if growers can develop these nutrient performance indicators for their fields or farms, it will allow them to index the performance against others. The PNB will advise whether nutrients are being added or removed from the field, the NBI indicates the magnitude of that change and the PFP indicates the sort of return achieved for the nutrients supplied. These metrics are indicators and are not efficiency measures or environmental loss assessments and so should be the start of the process of investigating opportunities for improving nutrient performance. They need to be aligned with other indicators such as soil nutrient levels or other soil health measurements.

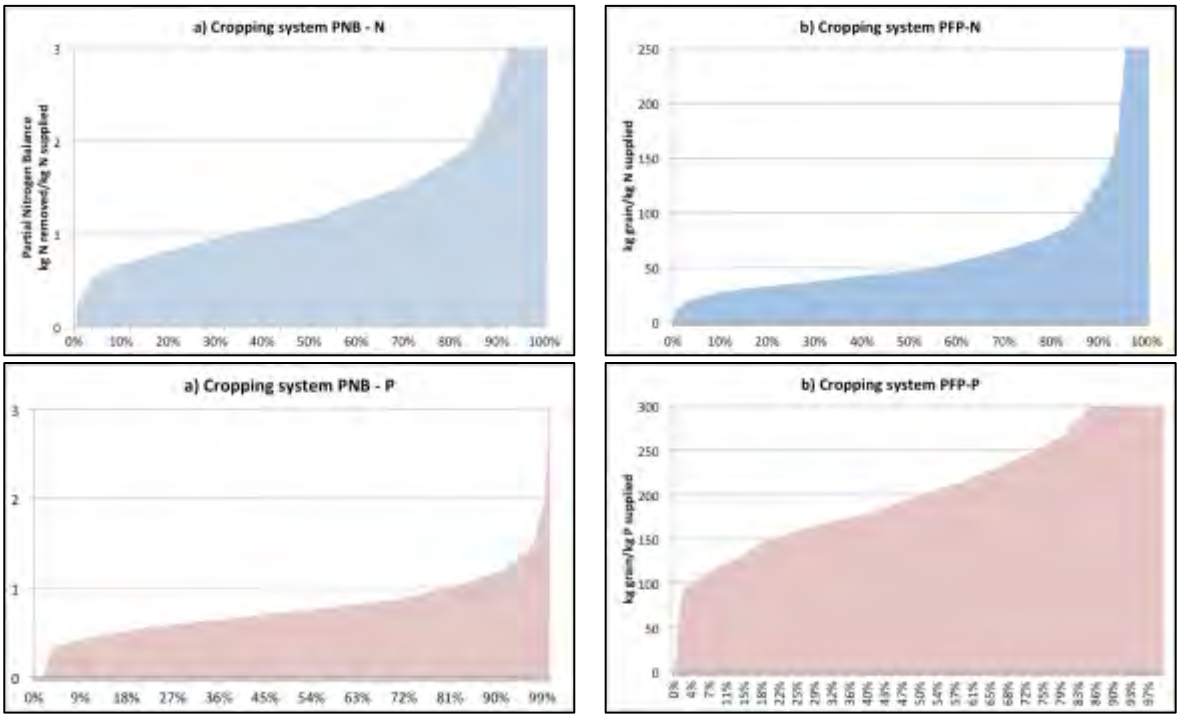

Figure S1. Cumulative distributions of nitrogen and phosphorus nutrient performance indicators for south-eastern Australian cropping systems, a) Partial factor productivity and b) Partial nutrient balance.

Nutrient performance indicators from field experiments

Nutrient performance indicators Agronomic Efficiency (AE) and Recovery Efficiency (RE) are marginal production or nutrient recovery and these along with PNB and PFP for wheat crops were calculated for N, P and K using N data from 47 Incitec Pivot Ltd field experiments between 2001 and 2011, and the 1224 P and 172 K experiments drawn from the Better Fertiliser Decisions for Crops database. 67% of N-PNB measures were > 1, meaning for the year of the experiment soil N is being mined. This is the same proportion as was estimated from the field survey. The P experimental data estimated that P-PNB was >1 in 14% of examples, while the field survey estimated that 19% were >1.

In general, the rate of nutrient input and the corresponding nutrient performance indicators were inversely proportional and the response of AE, RE, PNB and PFP are shown in the appendices. The pattern of an inverse proportion was more obvious for PFP and PNB than for AE and RE and this is largely because the numerator in the latter pair is a marginal value rather than an absolute value.

In addition, a meta-analysis of the N dataset was undertaken to compare the information conveyed by the different indicators. The marginal indicators AE and RE are more responsive and therefore informative about the effects of different interventions compared to PFP and PNB. AE and RE are effective as research tools in assessing a range of options to refine management, but in reality they are not suited to field scale assessments. PNB and PFP both reflect changes in application rates, with lower responses at higher rates.

Further development of nutrient performance indicators

For growers

If growers are to be encouraged to investigate the performance indicators, the reference methods reported should all follow the same protocols. This will ensure the nutrient performance indicators are comparable. There are important aspects of developing the methods to estimate indicators which includes:

- Validation of the BNF calculations, particularly for green/brown manure crops or pastures.
- Verification of the nutrient concentrations in products removed, including crop residues.
- Nutrient inputs from manures considered where appropriate.
- Nutrient losses from residue removal or burning are considered.

IPNI Brazil developed an on-line nutrient balance calculator (http://brasil.ipni.net/article/BRS-3293) that is at present being adapted to other regions. This tool will be able to be used with regional grain nutrient concentrations and adopting BNF estimates using the methods outlined in Appendix 13. The data will be reported back to growers as PNB, NBI or PFP and there will be the option for single year or multi-year entries. The reporting will be with the number, but the graphic interface will seek to place growers fields in the cohort that is most appropriate to them – such as region or crop type. With the permission of those entering data, a database will be build up from these entries that will then enrich to entire data set.

GRDC also supported the Lime and Nutrient Balance calculator that has not been widely used by the industry. It was released as a CD but cannot operate on MS systems other than XP, so currently it is largely unusable. It does require quite a lot of user-entered data but this program could be adapted to become a web-tool and automatically access data of importance such as weather information and possible soil types.

Any proposal to further develop these indicators as tools for growers to assess nutrient performance requires a way to communicate the information and an explanation of what the information means. The concept could be to present PNB and PFP values in the distribution graphs (Figure S1) with the position the growers data occupies highlighted. Expanded discussions on values, including the effect of different rotations and soil characteristics (e.g. Phosphorus Buffering Index) on interpreting the meaning of the metric.

For researchers and MPCNII targets

Research is in a good position to measure the various nutrient performance indicators as the field work invariably contains nil or check plots. Measuring and understanding efficiency improvements is important, but it is highly rate, site and season dependant as shown by our analysis of the data from the Better Fertilizer Decisions for Crops (BFDC) database. A very good AE and RE can be gained if the site selected has a very low nutrient status, and is a low rate of fertiliser is supplied to crops growing under good conditions. However, the vagaries of field research make site selecti on, even with comprehensive soil testing difficult. It should also be clear that the highest nutrient efficiency is not related to profitability, and indeed the highest efficiency if often at the start of the response curve rather than the point at which marginal returns meet marginal costs.

Defining the success if a nutrient management research project solely on the basis of the efficiency measured due to the intervention is not likely to lead to positive outcomes overall. Certainly getting improved comparative efficiency such as among different nutrient sources, or with different timings or through alternative placement strategies are all valid ways to make comparisons, particularly when done at the same rate. There is no absolute number that can be used to define an acceptable efficiency, as the different loss processes have different impacts. For example, where a RE or PNB are less than 1, the nutrient that is unaccounted for may be entering lower available nutrient pools and/or contributing to increased soil test levels. Alternatively, where soil nutrient status is high, a high RE or PNB (ie >1) may be desirable to target, while if nutrient status is low, a high PNB would be mining the soil resource.

Metrics like PNB and AE do not provide any intelligence about the fate of the nutrients not taken up and removed by the crop. These metrics are not environmental indicators and a low or high PNB or AE is not necessarily good or bad. Losses may or may not be detrimental environmentally, and residual nutrient values may be significant. The recovery and productivity of nutrient inputs is better suited to long term studies of 3 to 5 years rather than single year responses.

For the Australian Grains Industry

If there is desire to maintain an ongoing review of the performance of nutrients for the Australian grains industry, good quality production data are available at national, state and NRM level through the ABS data collection services. Nutrient concentrations for Australia produce are known although this requires on-going verification and monitoring particularly of regional values. In combination, the removal of nutrients can be reasonably estimated at national and state level but the precision is diminished when downscaled to regional (e.g. NRM) level.

Good quality data on nutrient supply from fertilisers to all agricultural industries is available from Fertiliser Australia down to state level. Scaling of the Farm Survey data does not reflect the industry data, so consideration of addressing processes to monitor nutrient use patterns for the grains industry. The "Paddock Survey" presents an excellent opportunity to capture some of these data, but the grains industry does not exist in isolation from other agricultural industries and nutrient input for pastures used for grazing livestock are likely to have residual value in to the grain production activities – and *vice versa.*

When considering nutrient monitoring for the grains industry, the purpose will determine the scale and time frame, and the processes adopted need to be clearly articulated and systematically and consistently applied.

OVERVIEW OF THE SCOPING STUDY

In response to the 2015 GRDC call for projects, the International Plant Nutrition Institute proposed to undertake a project that would develop and test a process to develop nutrient use benchmarks Partial Nutrient Balance (PNB) and Partial Factor Productivity (PFP) at farm and regional scale for the Australian grains industry for N, P and K. These performance metrics are part of a suite of measures that can be developed to assess the efficiency and effectiveness of nutrient use. Because of the nature of these metrics, they are not environmental or economic indicators and should be not be considered in isolation but viewed in the light of other measures such as soil health.

The aim of this project was to collect and collate nutrient performance data relevant to the Australian grains industry and then to use that information to develop performance indicators in a configuration that may assist growers identify strategies to improve nutrient performance. The approach is similar to the approach of developing water use efficiency (WUE) benchmark, which has gained strong acceptance with growers even though WUE is not a rigorous assessment of water limitation to crop performance. There are some particular and important differences between a WUE and indicators like PNB and PFP and the following is a discussion of the various indicators and their calculations.

The term nutrient "performance indicators" is preferred compared to nutrient use efficiency as the latter term is variously and imprecisely defined in the general literature. Improving efficiency is often an objective of management, but that may be only one aspect of better nutrient performance. Higher efficiency is not fundamental to systems improvement, as social and economic outcomes may also need to be considered. Furthermore, as the discussion in the first section will demonstrate, a higher efficiency is not always better than a lower efficiency because high efficiency often occurs at low productivity. The term performance indicator necessarily covers the various aspects of assessing the effectiveness of nutrient management, which includes social and economic as well as environmental goals and the other terms (as below) are more specific aspects of nutrient performance.

The project description in the GRDC prospectus requested that all grain regions at farm, agroecological zone and national level be used to estimate the benchmarks

- Partial factor productivity (PFP) of N, P, K and S (kg of grain harvested per kg of nutrient supplied
- Partial nutrient balances (PNB) of N, P, K and S (kg of nutrient in the grain per kg of nutrient supplied)
- Agronomic efficiency (AE) of N, P, K and S (kg of yield increase per kg of nutrient supplied)

The study reported here focused on wheat, canola and pulses, and the field survey drew data from the southern region only. The approach reported here is applicable to the other regions. The approach adopted here is to recognise that fertilisers are used within farming systems, so that improvement in nutrient performance will rely on engagement with farmers, as they are the ones who will facilitate the improvement. It is also recognised that fertiliser use is an agronomic and economic issue and often the decisions made are based on a response curve, which has embedded in it the law of diminishing returns.

SELECTING AN APPROPRIATE NUTRIENT PERFORMANCE INDICATOR

The use of fertilisers is fundamental to feeding 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 fertilisers are under-used so that food security is threatened, or where they are overused to the point of contributing to environmental pollution. In Australian grain production systems, over use also represents an uneconomic use of resources, while underuse can restrict yields and therefore profitability, as well as impacting negatively on soil health. Selecting the most appropriate way to express system nutrient use efficiency can be a helpful tool in prioritizing areas for improvement for some, but not all, environmental impacts associated with nutrient management. Approaches to improving nutrient use efficiency often emphasize selecting the right rate, but 4R Nutrient Stewardship includes considerations of source of nutrients, timing and place of application as well, since these can be crucial to managing several high impact nutrient loss processes.

Selecting the most appropriate performance measure requires a detailed understanding of the processes involved in acquisition, residence time, allocation, remobilization and losses within plants. The acquisition or uptake efficiency and then remobilization or utilization efficiencies are important to plant breeders as they look for traits that can be used in selecting more efficient genotypes. As well as the biological and biophysical aspects, the measures should also be specific, measureable, attainable, realistic and timely (SMART). Table 1 provides a summary of the most common metrics. Responses can be expressed as agronomic efficiencies or apparent recovery efficiencies, but both require a nil fertiliser application treatment to estimate the extra yield in response to added nutrient. Of a wide range of potential methods to assess nutrient use efficiency, PNB (nutrient removal to use ratio) and PFP (crop yield per unit of nutrient applied or supplied) offer the benefits of being readily assessed for fields, farms, regions or nations, and together they link productivity and nutrient cycling at these scales. To fully represent the contribution of crop nutrition to sustainable production, however, any metric of nutrient use efficiency requires complementary me trics to reflect crop productivity and soil fertility. Nutrient use efficiency is a useful, complex, and incomplete metric of crop nutrition performance.

Different nutrient performance indicators address different questions, and so the purpose to which the indicator is to be put should be clear. For example, PNB advises the amount of nutrient being removed from the system relative to the amount applied, while RE indicates the proportion of applied nutrient being take up and then removed. At a more general level, the purpose of these indicators should be to measure and improve systems. The indicators may be used as:

- Indicators of management – so that farming systems can be monitored and improved by farmers.
- Statements of accountability – which may be for reporting at regional, industry and/or national levels.

PNB is only one of a range of nutrient performance indicators (Table 1) indicating that the use of plant nutrients does not have a single dimension, but sound nutrient management is based on balancing economic, social and environmental goals. Any single indicator may be prone to misinterpretation and may fail to bring attention to unintended compromises in overlooked dimensions (Fixen et al., 2014).

For example, 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 available 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.

Table 1. Some Dimensions of nutrient use efficiency in cereals using N as an example (after Dobermann, 2007).

Term	**Calculation**	**Range for N in cereal cops harvested for grain.**
Cumulative Expressions		
Partial Nutrient Balance (Nutrient Removal Ratio)	PNB = kg nutrient removed/kg applied = UgF/F (kg/kg)	0.1 to 0.9 kg/kg; >0.5 where background supply is high and/ or where nutrient losses are low; >1 implies soil fertility mining or potential productivity degradation.
Partial Factor Productivity	PFP = kg yield/kg nutrient applied = YF/F (kg/kg)	40-80 kg/kg: >60 in well managed systems, at low N use or at low soil N supply.
Nutrient Balance Intensity	NBI = kg nutrient removed/ha less kg nutrient applied/ha. = (UgF-F) (kg/ha) *OR* = kg nutrient removed/unit of yield = (UgF-F)/Y	The closer the difference is to zero, the smaller the amount of nutrient accumulated in the system. Positive values could reflect a decline in the soil fertility.
Relative Expressions		
Agronomic Efficiency	AE = kg yield increase/kg nutrient applied = (YF-YN)/F	10 to 30 kg/kg; >25 in well man- aged systems, at low N use or at low soil N supply.
Recovery Efficiency	RE = kg nutrient removed/kg applied (UgF – UgN)/F	0.2 to 0.4 kg/kg on an annual basis, higher recoveries reported in multi-year experiments.
YF=crop yield with applied nutrients; YN =crop yield with no applied nutrients; F=fertiliser applied; Ug= crop nutrient uptake into harvested portion. UgF = crop nutrient uptake into harvested portion of fertilized crop. UgN = crop nutrient uptake into harvested portion of unfertilized crop.		

In addition to the indicators in Table 1, others may be selected with different numerators and denominators in the ratios used. The numerator could be an output (grain, biomass, nutrient contained) and the denominator could be an input (nutrient supplied, biological N fixed, manures, total from all sources) and they could be taken within seasons or over single or multiple seasons. The indicator should be clear about the source of the data used. For example, there are large regional and temporal differences in N and P content of outputs such as grain, so values used should be regional rather than national or international (Jensen and Norton, 2012). Other nutrient performance indicators can be developed, based on the apparent nutrient balance rescaled to an area (e.g., per hectare) or a productivity (e.g. per tonne of grain) basis. These types of indices helps in comparing systems with large productivity differences, but does not give context for the impact of the nutrient surplus or deficit. Small surpluses over large production systems may have quite different impacts to large surpluses in small or isolated systems.

The selection of an indicator requires definition of the boundaries of the systems of interest, the time scale for production cycles, selection of an appropriate numerator as system output (e.g. grain or nutrient) and the selection of an appropriate denominator (nutrient input). This report provides collated data on selected indicators at international, national, state and natural resource management region for a selection of cropping system and for different regions. It is also important to understand that the metrics of PNB and PFP are outcome metrics, which rely on science as an enabler of the technology to be developed and actions that support the adoption of best management practices. So, while attention can be paid to the outcome, equal attention should be paid to the processes that support achieving the outcome.

A final point is to appreciate that indices such as PNB, PFP or NBI do not identify the scale of a nutrient imbalance nor do they identify the nature of the losses or gains within the systems. A low PNB over a small area may be less important than a higher PNB over a large area. Interpreting the value – either high or low – is critical to understanding the approaches to be made in improving nutrient performance over time.

Summary

- The development and promulgation of nutrient performance indicators needs to be considered in the light of the purpose of the undertaking. The reason may be as an indicator of management for growers at field scale or as a statement of accountability at a regional and/or industry scale. The two reasons – while not mutually exclusive – do require clarity of purpose.

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