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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IPNI

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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.

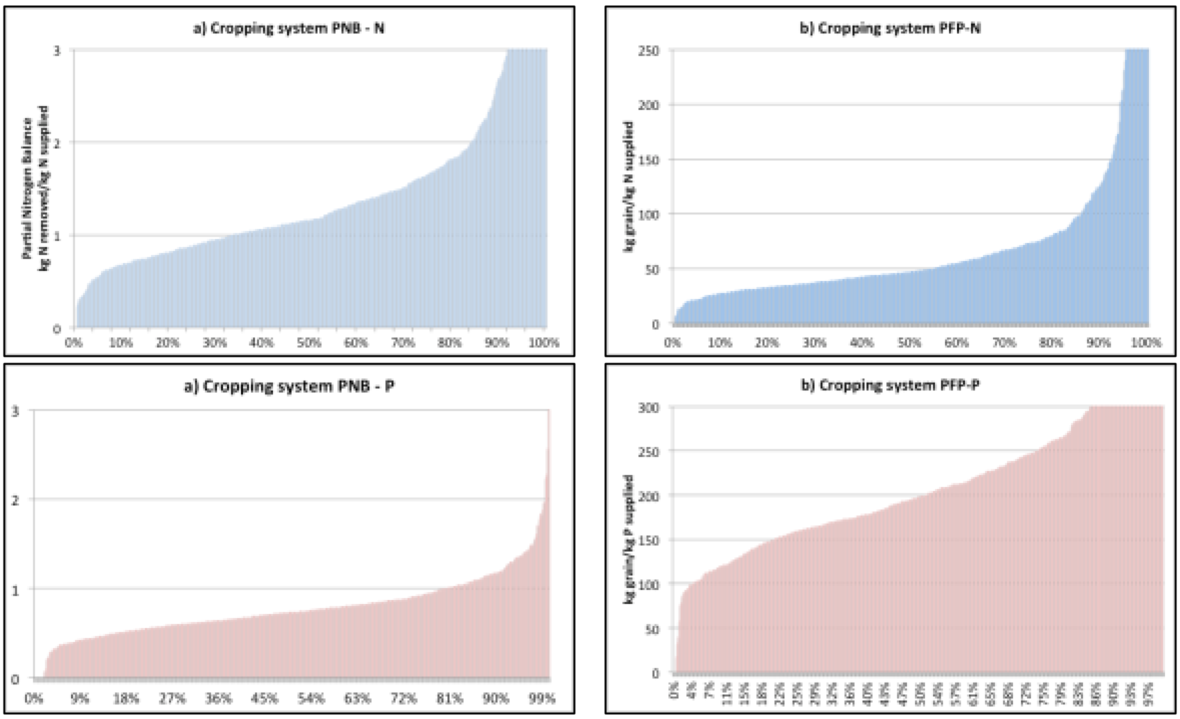

Figure S1. Cumulative distributions of nitrogen and phosphorus nutrient performance indicators for south-eastern Australian cropping systems, a) Partial factor productivity and b) Partial nutrient balance.

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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- 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.

INTERNATIONAL NUTRIENT PERFORMANCE INDICATORS.

There is a growing literature on indexing nutrient performance at national level as part of the assessment of N (in particular) management effectiveness. Two papers in particular are having a significant effect on the global conversation concerning N efficiency. Lassaletta et al. (2014) reported 50-year trends in NUE at a national scale for 124 countries. The assessment considered crop yield, and N inputs to land (manure, synthetic fertiliser, biological N fixation and atmospheric deposition). The procedure is described in the appendices to the report and the summary page for Australia is presented below for information and shows the general downward trend in N-PNB (they call NUE) over time. In other countries, the trend here is following a typical pattern of decline with regularly increasing fertilization and a gradual reduction in crop yield response. The data suggests an N surplus (fertiliser+BNF less yield) of a little less than 20 kg N/ha in 2009. Other countries have N-PNB trends that show a decline then increase in N-PNB with improved agronomic practices (termed an environmental Kuznets curve). Increasing yields with declining N fertilization and values clearly indicating agricultural mining of soil N (i.e. organic matter). The assumptions underlying the data can all be challenged, and while these indicators are presented as national values there is little attempt to disaggregate the data to farming system and/or region.

Zhang et al. (2015) analysed historical patterns from 113 countries between 1961 and 2013 and also noted that the pattern of NUE changes along an environmental Kuznets curve, with N excess firstly increases and the decreases with economic growth. These authors proposed patterns of NUE to 2050 based on where different countries and crops were along this curve. They also indicate that crop mix is critical in the discussion, with land management activities such as fruit and vegetable production having an inherently lower NUE than field crops like cereals and oilseeds. Consequently the national levels and trends noted are rooted in the types of agricultural systems that dominate.

There is also a significant literature on N foot-printing, which is an estimate of the potential for nitrogen pollution due to the use of food and energy resources by a given user. Recent estimates by Oita et al. (2016) place Australia as second overall with a “footprint” of around 90 kg N cap^{-1} y^{-1}, second only to Hong Kong (~240 kg N cap^{-1} y^{-1}), with the US and Brazil third (~65 and 60 kg N cap^{-1} y^{-1} respectively). How these types of metrics will be used and abused nationally and globally is as yet unclear. It seems to me unreasonable to use a per-capita denominator for a large country with a small population and an export economy.

Norton et al. (2015) has collated and published PNB and PFP indicators for cereal production systems at national level. Appendix 1 contains the full data set for the selection of countries reported. These data were collected and presented as an example of how data could be collated from existing information, not as a definitive assessment of the nutrient balances for each country. The yield data were obtained from the FAOSTAT database and the nutrient use by crop data were obtained from surveys undertaken by the International Fertilizer Industry Association (Heffer 2009, 2013). Crop nutrient concentrations were derived from the IPNI nutrient content database. While such information is illustrative, there are several important limitations.

- Assumptions must be made regarding the fraction of N within the plants that is from biological nitrogen fixation (BNF) and the fraction of total plant N that is removed. An estimate of total plant N times the fraction from BNF must be included in the input term to calculate NUE. Such estimates are available in the agronomic literature (e.g. Salvagotti et al., 2008; Peoples et al., 2009) and can be provided in simple look-up tables for use by farmers or by national agronomic policy analysts, similar to look-up terms now in use for calculating greenhouse gas emissions for IPCC accounting requirements.

- There are seasonal, regional and farm level differences in crop product nutrient concentration that should be considered in developing balance figures.
- Atmospheric deposition (wet and dry) can be regionally significant.
- Single year data on crop NUE ignores the rotational systems in which crops are grown.
- More complex calculations are required when animals are involved in the production system, as estimates of manure nutrient recycling and pasture N cycling may be important in these systems.
- Changes in NUE need to be considered over time, rather than a single snapshot years estimate for a farm or a nation. If repeated over time, then the trajectory of the NUE trend can be informative.
- Nutrient use is an economic consideration, and the economic optimum is set on the basis of diminishing marginal cost and return. As such, because of diminishing returns, efficiency declines with added nutrient. So both PNB and PFP inevitably decline as more nutrient is added.
- Nutrient balance intensity (NBI) requires nutrient balance to be divided by area. The denominator in this could be agricultural area (ie the area of the farm), the farmed area (ie where the land is actively managed for production), the cropped area (ie where crops are sown), or the fertilized area (ie where fertiliser was applied). Clarity is needed in citing this metric.

Figure 1 is a summary of that information graphed as the N excess (application less removal) and the N removal, which is a reflection of the yields achieved. The cereal figures for Australia of around 27 kg N/ha applied and a cereal yield of around 1.39 t/ha (Appendix 1), which is in approximate N balance (not considering BNF or manures). This is a modest position compared to other countries although the importance of BNF in our farming systems should not be ignored, as virtually every farmer knows. Angus (2001) estimated in 1998-1999 that nationally BNF from crops and pastures was 1,555 kt, which was approximately twice the N supplied by fertilisers at that that time. The N-PNB nationally was around 0.65.

The data from Australia can be disaggregated by crop based on the Heffer (2009, 2013) reports and these data are shown in Table 2. The N balances are relatively small in Australia compared to other places, but the P balances are quite high and the P-PNB is very low. The K values all indicate substantial net K removals in the cereal production systems assessed. The full data set developed is shown in Appendix 2.

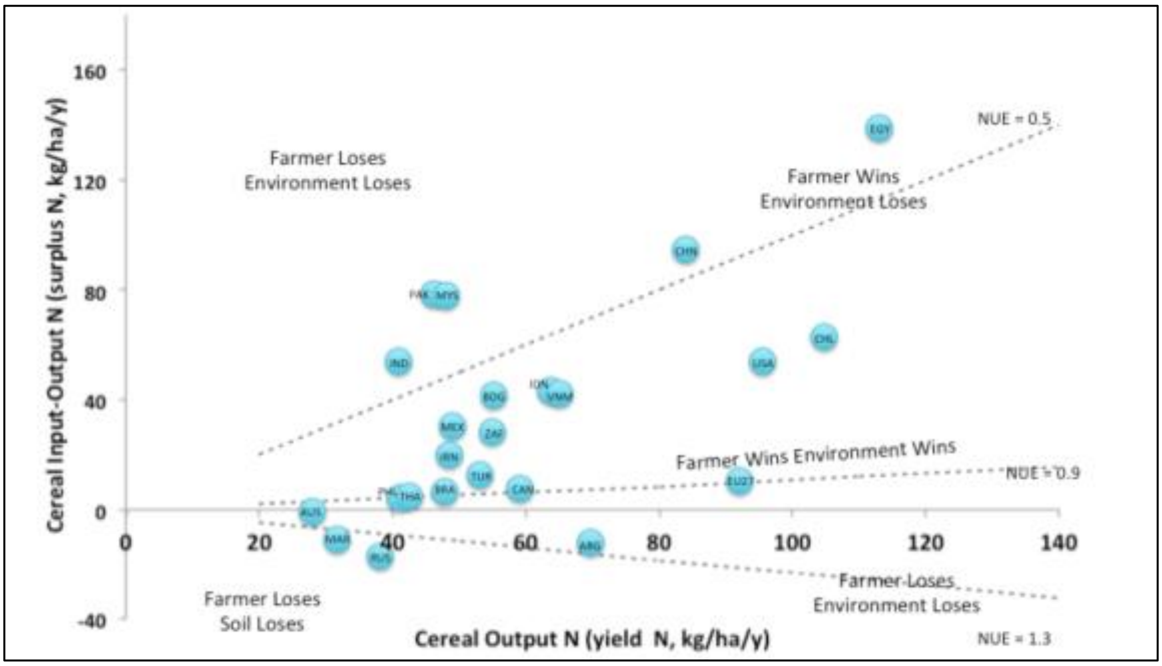

Figure 1. NUE for cereals, graphed as the surplus of N (inputs minus outputs) versus removal (output) of N. The dotted lines show values of NUE according to the relation between inputs and outputs. Biological N fixation and manure use are not considered in this example. Each circle represents a country indicated by UN Country 3 letter code (Norton et al. 2015).

Table 2. Nutrient performance indicators for cereal production in Australia, Canada, the EU27, USA and Globally, for the period 2007-08 and 2010-11.

	N-PNB kg N grain/kg N fert	N-PFP kg grain/kg N fert	N-NBI kg/ha	P-PFP kg grain/kg P fert	P-PNB kg P grain/kg P fert	P-NBI kg/ha	K-PFP kg grain K/kg K fert	K-PNB kg K in/kg K fert	K-NBI kg/ha
Australia	0.82	52	5	128	0.44	7.16	724	3.91	-5.7
Canada	0.71	45	22	335	1.14	-8.41	386	2.08	-10.8
EU27	0.74	47	27	454	1.54	-14.06	256	1.38	-6.8
USA	0.74	47	38	262	0.89	-19.23	178	0.96	4.8
World	0.67	43	26	281	0.96	-8.15	278	1.50	-6.3

Part of the reason that values change from country to country relates to the different crops grown in each region. In the US, the predominant cereal is maize with a relatively low N-PNB, (Table 3) while countries that grow other cereals such as sorghum in Africa may have relatively higher PNB.s Similarly the balance between legumes/pulses and cereal can mean the N-PNB may seem lower as the pulses contribute N to the farming system.

Table 3. N-PNB (removal to use ratio) for particular commodities comparing Australia to the rest of the world. Neither biological N fixation nor manure applications are considered in this example and crop removal is estimated using mean values rather than regionally relevant data.

Country	Australia	World
Wheat	1.10	0.77
Maize	1.06	0.55
Rice	2.60	0.56
Other Cereals	0.86	1.14
All Cereals	*1.02*	*0.67*
Soybean	-	1.15
Palm	-	0.81
Other Oilseeds	0.63	0.73
Sugar	0.93	0.89

Summary

- Partial nutrient balance (nutrient removal to use ratio) and partial factor productivity (grain produced by nutrient use) be used as measures of nutrient performance. Nutrient removal intensity (kg nutrient balance per hectare) can also be used.
- There are several significant limitations that mean PNB and PFP values require contextual interpretation when applied in management situations or as system performance indicators.
- In comparison to other countries, the partial balances for P for Australia are relatively low, 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

The objective in this section is to collate and present information on nutrient balances from Australian data. The assessment reported by McLaughlin et al. (1991) drew data from 1987-1988 was at a continental scale. They reported that while continental exports of P, S and N have increased since 1800, in most areas inputs match or exceed exports in agricultural commodities, by six-fold for P and S and possibly five-fold for N. This assessment estimated total removals and additions of nutrients and indicated that the national P budget indicated that there was ~360 kt P/y addition in excess of removal. The national sulfur budget was estimated as almost 600 kt S/y more additions than removals, while the nitrogen budget was around 1000 kt in surplus. For the N budget, atmospheric deposition was estimated as ~1100 kt/y and BNF from crops and pastures as ~1900 kt/y.

The data from McLaughlin et al. (1992) can be used to re-estimate PNB data for food production systems and based on their figures the P-PNB was 0.15, S-PNB was 0.16 and the N-PNB was 0.22. As mentioned earlier, Angus (2001) estimated the national N-PNB for agriculture as 0.65.

Weaver and Wong (2011) reported P balances for cropping and pasture systems in south-eastern Australia. Their farm-gate assessments indicated that P-PNB varied regionally and also among industries. Sheep and beef grazing showed lower median P-PNB values (0.11 and 0.19 respectively) than cropping industries (0.48) reflecting the inherent difference in systems identified internationally. P inputs for these systems were similar, and removals were lowest in the grazing industries. Gourley et al. (2012) surveyed 41 contrasting dairy farms to investigated nutrient input and removal in the dairy industry. They reported great variation in partial nutrient balances among farms, with median values of 0.26 for N-PNB, 0.35 for P-PNB, 0.20 for PNB-K and 0.21 for PNB-S. Higher PNB values for all nutrients were positively correlated with stocking rate and milk production.

Australian Agricultural Assessment 2001

As part of the Australian Agricultural Assessment 2001, an audit of land and water resources was undertaken. The data included in this audit were a series of farm-gate nutrient balances. The audit noted the pattern of N, P, K and S PNB across Australia and the data presented was from the 1990's which was a period of major change in nutrient use, especially N. Farm-gate nutrient balances differ across Australia's regions. Balances for nitrogen, phosphorus, sulfur, and calcium are mainly neutral (inputs = exports) or moderately positive (inputs > exports) across much of the southern agricultural zone. At the gross regional farming scale, this suggests that levels of these nutrients are generally being maintained in soils. Potassium and magnesium balances are usually negative (inputs < exports) indicating that soil reserves are being progressively depleted.

In intensive industries with high nutrient use, such as sugar cane, dairying and horticulture, nitrogen and phosphorus balances were assessed as positive (inputs > exports). Highly positive (inputs > exports) nutrient balance indicates the likelihood that nutrients are moving off-farm to streams and groundwater.

Mainly negative nutrient balances were derived for the subtropical regions, suggesting nutrient depletion is occurring on these soils, many of which are naturally fertile. This implies that close attention to nutrient status needs to be maintained from a productivity perspective, so that soils retain their nutrient status.

The data in these audits was mapped against statistical local area and a set of graphics were published showing the spatial distribution of the balances. We do have an electronic copy of the database developed but the mapping units used have been superseded by other area based units, and despite several request to the ABS, we could not find a key to match the codes in the data tables to the older regions, nor could we match the older regions to the current statistical local areas or natural resource management zones.

Table 4 is taken directly from the audit and shows the farm gate nutrient balances from the audit period (1994-1996) for grazing and cropping industries by nutrient and state. The N assessment included BNF. For the cropping industries, the balances for N were generally negative, while P balances were more variable. Potassium balances were invariably negative across all regions.

Table 4. Generalized state assessments of farm gate nutrient balance for two broad land uses within Australian agricultural zones from the AAA audit of 1994-1996.

Nutrient	Western Australia	South Australia	Victoria	Tasmania	New South Wales	Queensland*
Grazing						
Nitrogen	positive	positive	variable	neutral/positive	positive/neutral	negative
Phosphorus	positive/neutral	neutral/negative	neutral/positive	positive	positive/neutral	negative
Potassium	negative/positive	negative	positive/negative	neutral/positive	neutral/negative	negative
Sulfur	positive	positive/neutral	positive/neutral	positive	positive/neutral	negative
Calcium	positive	positive	positive	positive	positive	negative
Magnesium	neutral	negative	neutral/negative	neutral	neutral	negative
Cropping						
Nitrogen	positive/neutral	neutral/negative	negative	positive	neutral/positive	negative/neutral
Phosphorus	neutral/positive	neutral	negative/neutral	positive	neutral/negative	negative
Potassium	negative	negative	negative	neutral	negative	negative
Sulfur	positive/neutral	neutral/positive	neutral/positive	positive	neutral/positive	negative/neutral
Calcium	positive	neutral/positive	positive/neutral	positive	positive/neutral	negative/neutral
Magnesium	negative/neutral	negative	negative	neutral	negative/neutral	negative/neutral

* Atherton Tableland in Queensland had positive nitrogen, phosphorus, potassium and calcium balances.

Temporal and spatial patterns of partial nutrient balances for Australia (IPNI)

Assessing the balance between nutrients applied and those removed in products assists the early detection of emerging nutrient deficiencies or excesses. Regional-level assessment identifies areas in which on-going imbalance is occurring and is useful to inform requirements for more detailed investigation by researchers and advisors, responses by policy makers, or emerging commercial opportunities and risks for nutrient suppliers. In Australia, N and P are the major limiting nutrients in many agricultural systems, leading to substantial use of those fertilisers. These data were prepared by IPNI for its internal use but the summary is presented here.

Methodology

Nutrient balance over time

IPNI ANZ commissioned and undertook a study of the pattern of nutrient use and removal over the 7 year period 2002-03 to 2011-12. The purpose was to validate the methodology and assess how variable the nutrient balance data were over the audit period. The study estimated nutrient use using fertiliser data from the Fertilizer Australia (then Fertilizer Industry Association of Australia) on state and national use (sales) of N, P and K. Those data are only reported back to 2002 so that is why the assessments do not go earlier. Sulfur was not included in this study as there were no data from Fertilizer Australia on gypsum use, which is a major S source for agriculture.

Agricultural production data by state over the audit period were derived from the Australian Bureau of Statistics “Agricultural Commodities” data series (7121.0) was used for crops, fruit and vegetables; for meat and wool, ABS 2013 7218.0.55.001 Livestock and Meat, Australia; for milk, Dairy Australia data http://www.dairyaustralia.com.au/Statistics-and-markets/Production-and-sales/Milk.aspx.

Nutrient concentration figures in the products were derived from the same data tables used in the Australian Agricultural Assessment (2001) and these are reproduced in Appendix 11. There is also a compendium of nutrient concentrations at the IPNI site as taken from the United States National Research Council and IPNI literature sources (see http://www.ipni.net/NURD). Nutrient removals were calculated for each commodity and then aggregated to provide total nutrient removals by state. These data were then used to calculate PNB (removal to use) and NBI for N, P and K. There was no attempt in this study to assess the amount of BNF nor were transfers (such as hay and grain) between states assessed. The removal intensity calculation was based on the area of agricultural land for each year, rather than the area fertilized or the crop area.

Because the output from farms varies from a range of crops, to various livestock products, it is not possible to calculate PFP for agriculture as a whole. Values for grain production can be estimated, but the mix of crops grown has an effect due to carryover of nutrients from one crop to the next, as well as different energy and nutrient densities of different species.

Nutrient balances over industries and regions

While the production level data from ABS (ABARES) can be downscaled to region or natural resource management zone, the fertiliser use data from Fertilizer Australia cannot be segregated by either industry or zone. Estimating nutrient removal was undertaken using the same method as for Part 1, for three audit periods (2007-08, 2009-10 and 2011-12) and removal data can be assessed by region or industry from the Australian Bureau of Statistics “Agricultural Commodities” data series (7121.0) was used for crops, fruit and vegetables; for meat and wool, ABS 2013 7218.0.55.001 Livestock and Meat, Australia; for milk, Dairy Australia data http://www.dairyaustralia.com.au/Statistics-and-markets/Production-and-sales/Milk.aspx. Meat and milk production at the NRM level is not presented in the ABS tables so the following approach was undertaken based on related surrogates. These were:

a) Meat statistics at state and national level from ABS 2013 7218.0.55.001 Livestock and Meat, Australia. Meat production at NRM region level is not available. To estimate the following factors were calculated and applied:

- Beef: National meat production/national beef cows and heifers older than 1 year; (0.15t/ count cows and heifers)
- Sheep meat: National meat production/lambs marked (0.0015 t/lamb marked)
- Pig meat: National meat production/number of pigs (0.16 t/pig)
- Wool: National wool clip/merino ewes (0.022 t/merino ewe)

b) Milk statistics; Dairy statistics at national and state level from Dairy Australia, http://www.dairyaustralia.com.au/Statistics-and-markets/Production-and-sales/Milk.aspx. Production at NRM region level is not available. To estimate national milk production, the total number of cows in milk and dry were assessed as producing 5.5 kl/cow/y. All feed materials were treated as an export from fields. This is an important factor for some regions, particularly considering hay.

At the scale of Natural Resource Management (NRM) regions, ABS data for fertiliser use is available for the years 2007-08, 2009-10 and 2011-12. Since these data were analysed addition data has become available but these are yet to be collated and analysed. These were surveys completed by farmers, with 32-35 thousand farm businesses surveyed (out of about 135-141 thousand farm businesses in total in Australia over the period), over 53 NRM regions, and these data were used for fertiliser use patterns. However, they are aggregated figures (i.e. by farm, allocated to industry) and do not disaggregate to crop or specific land uses. Industry-based statistics were extracted from the 2007-8 and 2009-10 for selected business types, as identified by ANZIC codes assigned by the Australian Bureau of Statistics. Business types for which data was extracted were: Grape Growing, Apple and Pear Growing, Stone Fruit Growing, Citrus Fruit Growing, Sheep Farming, Specialised Beef Cattle Farming (specialised), Sheep-Beef Cattle Farming, Grain-Sheep or Grain-Beef Cattle Farming, Rice Growing, Other Grain Growing, Sugar Cane Growing, Cotton Growing and Dairy Cattle Farming. Data for all the fertiliser used and the commodities produced by each business type were included, not just the primary commodity. Data was extracted at national, state and NRM region scales. The process applied to ensure confidentiality meant that the number of types of business was small at the NRM region scale, with only data for those types with several businesses in the region being provided.

The same nutrient concentrations were used to estimate removal, and similar to Part 1, there was no estimate of BNF or atmospheric deposition or supply in irrigation waters. Manures were not included in the estimates of nutrient inputs, even though around 1 Mt are reported to be used annually. There is difficulty assigning an appropriate nutrient concentration, and even at a nominal 1% N concentration, the total amount of N (for example) would be less than 10,000 t/year. Recycled materials such as sugar cane mill wastes are also not considered even though they have a strong regional impact.

In estimating the NBI, the difference between the removal and use of nutrients is divided by the area of land mainly used for agricultural production, rather than the total area of holdings, although the former is on average 98% of the latter. Alternatively, the area of land mainly used for crops could have been used as the denominator, and around 8% of the areas of holdings was cropped. The agricultural land was used because fertiliser is applied to grazing as well as cropping lands.

Results

Nutrient balances over time

Table 5 shows the partial nutrient balances and nutrient balance intensities for N, P and K for all agriculture the states of Australia and nationally. The fertiliser use in these calculations was derived from the Fertilizer Australia database rather than the data collected by the ABS. All states have N-PNB more than 1 indicating that more N is removed than is applied as fertilisers, so that there is a net negative N balance of around 16 kg N/ha of agricultural land. As mentioned, this figure does not include any allowance for N derived from the atmosphere. At a continental scale, there is 76% more N removed than applied. On the other hand, except for Queensland, P-PNB are all less than one and at a national scale there is about 36% of the P applied that is recovered and then exported in produce. All P balances are positive, but these metrics are not able to identify if the extra P is retained in the soil or lost to the environment. Potassium balances over the audit period as also above unity and overall 78% more K is removed than applied, with the largest removals in Queensland and New South Wales, and only Tasmania shows a net positive K balance.

Table 5. The partial nutrient balance (PNB) and the nutrient balance intensity (kg/ha) for N, P and K for each state of Australia and nationally for the period 2002 to 2010. Data are for all agriculture industries, fertiliser use is derived Fertilizer Australia and the area base is for the area fertilized.

		NSW	Vic	Qld	WA	SA	Tas	NT	AUS
N	PNB	2.05	2.49	1.08	1.48	2.28	1.25	4.20	1.76
	N /ha	-22.2	-26.6	-5.8	-21.2	-7.7	-9.9	-66.0	-15.7
P	PNB	0.36	0.29	1.20	0.33	0.31	0.15	0.87	0.36
	P /ha	7.4	9.1	-1.7	11.9	2.6	20.4	10.3	6.2
K	PNB	8.05	1.68	1.83	1.11	6.00	0.40	1.44	1.78
	K /ha	-6.9	-3.2	-14.9	-0.4	-1.9	18.3	-4.6	-3.4

The balance and surplus figures in Table 1 are for all agricultural industries and the fertiliser use data is derived from the Fertilizer Australia industry figures. Within these means there are quite large differences from year to year, as well as between industries.

Over the decade 2002-2010 nitrogen fertiliser use was quite flat while nitrogen exports in commodities varied widely (Figure 2) in response to different seasonal conditions. Consequently, the partial nutrient balance for N (N-PNB) also varied strongly. This means that there was more N removed than applied as fertiliser. Nitrogen removed in commodities also includes N fixed biologically. The imbalance intensity was between -3.2 (2003) to -34.7 kg N/ha (2006).

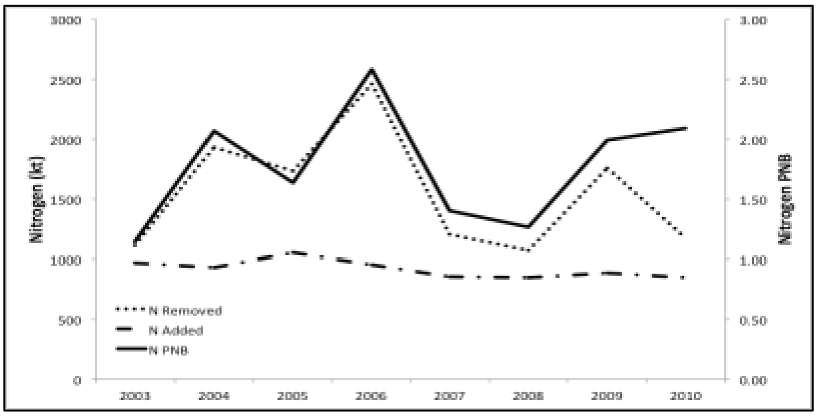

Figure 2. Estimates of nitrogen removed in agricultural commodities, nitrogen added as fertiliser and the partial nutrient balance for N 2002-2010.

Over the decade 2002-2010 phosphorus fertiliser use has trended down, to a minimum amounts through the drought years of 2008- 2009 (Figure 3). This was not matched by reductions in P exported in commodities, although the amount of applied P always exceeded the amount removed, consequently, the P-PNB has risen to around 0.6 although the mean value over the audit period was 0.36. The excess of applied P to removed P reduced, from around 300 kt P/y early in the decade to less than 200 kt P/y at the end of the decade.

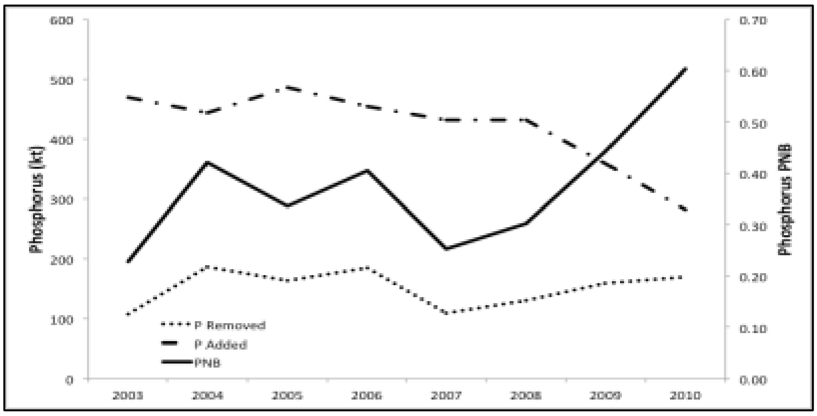

Figure 3. Estimates of phosphorus removed in agricultural commodities, phosphorus added as fertiliser and the partial nutrient balance for P 2002-10.

Over the period assessed, K fertiliser use declined, while production (and so K removal) varied quite widely over the period (Figure 4). As a consequence, the K-PNB values varied quite widely but there was always more K removed than added. Eastern Australian soils such as Vertosols have quite high levels of soil K, so that depletion may not be a major issue, but on other soils the continued depletion of K suggests that at some time in the future growers may need to pay more attention to K nutrition.

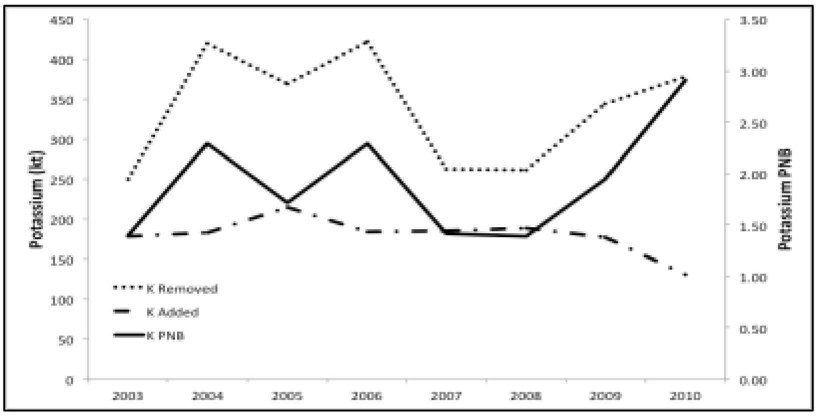

Figure 4. Estimates of potassium removed in agricultural commodities, potassium added as fertiliser and the partial nutrient balance for K 2002-10

The nature of the data collected mean that fertiliser input cannot be determined by industry, but in terms of nutrient removals, the products from the grains industry accounts for 53%, 63% and 43% of the N, P and K removed respectively (see Appendix 3).

The use of N, P and K fertiliser over the audit period was reasonably consistent, but production, and therefore nutrient removal, was much more variable. As a consequence, partial nutrient balances also showed large temporal variations. Even so, the P-PNB was always less than one, indicating more P is applied than is removed, while the K-PNB and N-PNB were approaching two indicating that twice the amount of K and N were removed as were applied. Since that audit was undertaken, fertiliser use – especially N – has increased significantly. This increase is likely a consequence of the relieving of the Millennium drought and changing terms of trade for fertiliser. Figure 5 shows the large increase in N use since 2010, and the recovery on P and K use back to the levels approaching the start of the 2000's.

Because of the large changes in nutrient balance from year to year, a reliable estimate should be done over a three or more years rather than a single measure. It is also clear that mean values for agriculture, while interesting, are not informative to the industry and the growers unless they are disaggregated. The mean does not show the values that make it up, where both low PNB (adding extra nutrients) and high PNB (removing nutrients from soil reserves) can both occur in the population.

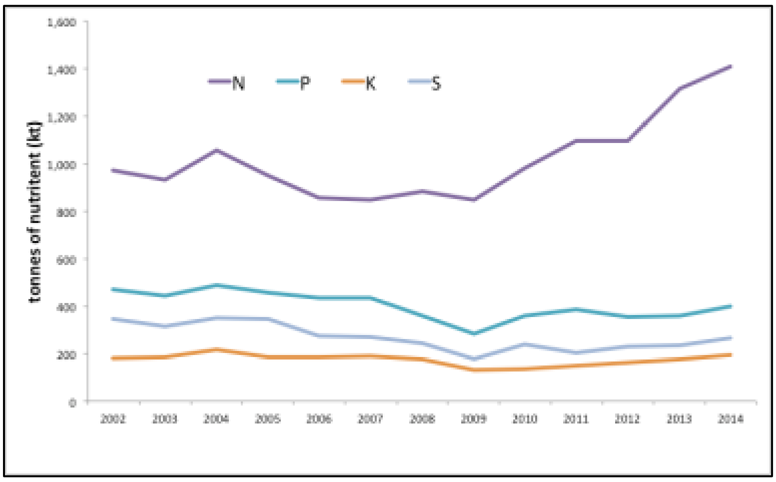

Figure 5, Nutrient use in Australia, 2002-2014. Data are from Fertilizer Australia.

Nutrient balances over industries

Removal to use ratios are recognised to vary among industries. For example, the study by Weaver and Wong (2011) reported on the farm-gate P balances in Australia. They estimated median livestock P balances as for sheep, beef, and dairy of 0.11, 0.19 and 0.29 respectively, and these were lower than cropping enterprises, which had a median value of 0.48. As a consequence, enterprise mix will play a large role in the farm gate nutrient balances, and any trends seen would need to be considered in the light of changing mixes on-farm.

The data collected from the ABS Farm Surveys is disaggregated by NRM zone as well as by industry code or business types (Table 6). The data collected do include farm level fertiliser use, although some terms are not very precise or not included. For example, MAP and DAP are aggregated as ammonium phosphates and in the surveys post-2013, muriate of potash (MOP) is not included, although potassium nitrate is reported. This seems a little odd as 300,000 t of MOP are used in Australia, and Fertilizer Australia does not report potassium nitrate because it is considered a minor fertiliser.

The aggregation of farm businesses by ANZIC business type combines businesses across scales and specific enterprises. More detail on the effect of farm size on nutrient balances is provided in Appendix 4 and this section will present farm gate balances for N, P, K and S by industry (firstly) and then by NRM zone. Table 6 shows the balance figures in kg of nutrient per fertiliser hectare for each industry sector. The data presented for sugar, particularly for K, may be misleading, as there is no account of recycled mill wastes in the values derived. Similarly the data for cotton is based on a relatively small sample size so may also be misleading.

Without the consideration of BNF, the grains industries are in net negative nitrogen balance, while the other cropping industries indicate that more nutrients are supplied than removed. The phosphorus balance is most often positive with more P applied than removed, and the K balance is usually negative. Sulfur balance values show a small surplus of application over removal. These values are consistent with the national figures for cereals reported earlier, and also with the AAA 2001 report.

Table 6. 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.

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.

Partial nutrient balances are given in the Appendices 3-6 for different industries. These data do not provide either farm or field level nutrient inputs or output and are aggregated by industry rather than by crop. They do, however, provide broad benchmarks for PNB within these industries.

Nutrient balances in Natural Resource Management regions.

The data collected was mapped over the Natural Resource Management regions of Australia to show any regional patterns of nutrient balance. It was considered that there was not sufficient data in the farm survey database to disaggregate each region by industry, although regions often support particular industries. The maps presented in Figure 6 were developed from the 2009-2010 audit and are posted on the Centre for eResearch and Digital Innovation at Federation University, (http://www.ozdsm.com.au/ozdsm_map2.php). Maps for 2007-08 and 2011-12 are shown in the Appendix 8 and Appendix 9. The data presented in the maps has the same issues with quality as the nutrient balance by industry, as they are derived from the same source data but configured differently. Those limitations are that the N balances do not include BNF, and the S balances do not include the application of gypsum.

a) Nitrogen b) Phosphorus c) Potassium d) Sulfur

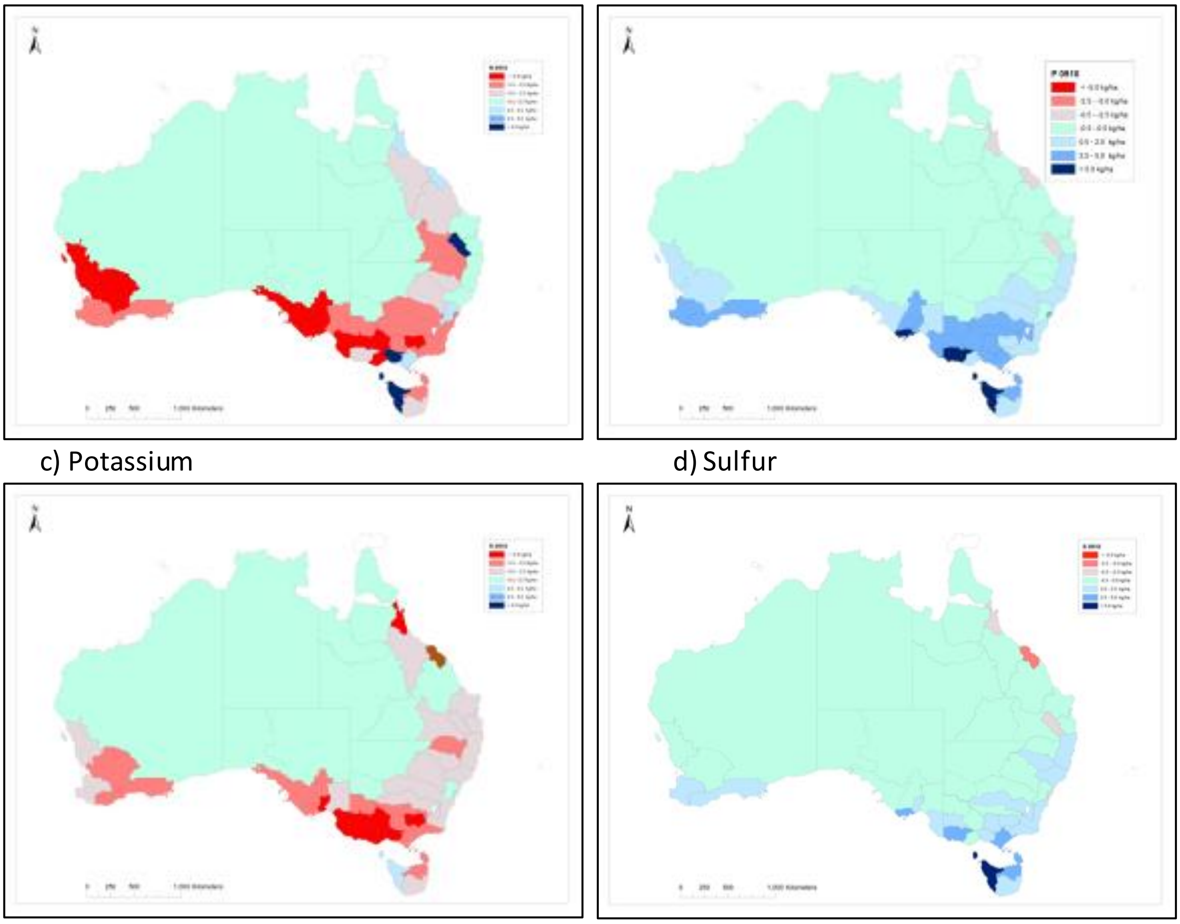

Figure 6. 2009-2010 nutrient balance intensity for N (a), P (b). K (c) and S (d) across different natural resource management regions across Australia. In general, the red regions indicate where nutrient removal is more than nutrient supply, and the scales are provided on the individual graphics.

The data presented in Figure 6 and in the Appendix 8 identifies that much of the cropping region is in modest N and K deficits and modest S surplus. Most regions are also consistently in P surplus. The Australian Agricultural Assessment (2001) did include BNF and gypsum and essentially drew the same conclusions about nutrient balances for cropping and grazing within each state (see Table 4).

Data quality in these studies.

There are at least three areas where data quality is questionable when undertaking these sorts of estimates from survey data. The small-scale fertiliser use data is questionable, and there is no downscaled fertiliser use by crop data available, so that actual nutrient input is requires careful assessments. Heffer (2009, 2013) has provided data on fertiliser use by crop but these reports present national estimates only, with no disaggregation to state or region.

Table 7. State level partial nutrient balances (PNB) and nutrient balance intensity (NBI) for N, P, K and S as derived from two difference sources of fertiliser input data, either from Fertilizer Australia (FA) or from the Australian Bureau of Statistics (ABS) farm survey data sets. The area fertilized was used to derive the NBI.

		FA t	**ABS t**	**% DIFFERENCE**	**PNB-FA**	**PNB-ABS**	**NBI FA**	**NBI ABS**
N	NSW	161,099	177,041	9	1.49	1.36	-1.4	-1.1
	NT	682	456	-49	14.79	22.10	-0.2	-0.2
	QLD	174,307	107,194	-63	0.95	1.54	0.1	-0.4
	SA	104,962	78,881	-33	1.69	2.25	-1.6	-2.2
	TAS	22,701	8,632	-163	0.53	1.41	7.0	-2.3
	VIC	144,828	115,188	-26	1.45	1.82	-5.3	-7.7
	WA	282,386	139,524	-102	0.73	1.48	0.9	-0.8
	Total	**890,965**	**626,917**	**-42**	**1.15**	**1.63**	**-0.3**	**-1.0**
P	NSW	78,868	91,399	14	0.41	0.35	0.8	1.0
	NT	365	145	-152	7.48	18.81	-0.0	-0.0
	QLD	19,395	14,086	-38	1.51	2.08	-0.1	-0.1
	SA	55,628	57,077	3	0.37	0.36	0.8	0.8
	TAS	12,163	7,185	-69	0.18	0.30	6.6	3.3
	VIC	83,056	82,414	-1	0.35	0.35	4.4	4.4
	WA	108,982	53,396	-104	0.23	0.47	1.0	0.3
	Total	**358,457**	**305,702**	**-17**	**0.39**	**0.46**	**0.6**	**0.4**
K	NSW	6,842	14,215	52	9.56	4.60	-1.0	-0.9
	NT	503	260	-93	2.90	5.60	-0.0	-0.0
	QLD	43,167	30,027	-44	1.84	2.64	-0.3	-0.4
	SA	10,103	6,796	-49	4.48	6.67	-0.8	-0.9
	TAS	17,693	5,052	-250	0.44	1.56	6.5	-1.9
	VIC	34,249	23,674	-45	2.32	3.36	-3.7	-4.5
	WA	45,997	32,187	-43	1.01	1.44	-0.0	-0.2
	Total	**158,554**	**112,209**	**-41**	**2.05**	**2.90**	**-0.4**	**-0.5**
S	NSW	-	39,104	-	-	0.50	-	0.3
	NT	-	90	-	-	6.77	-	-0.0
	QLD	-	8,799	-	-	2.22	-	-0.1
	SA	-	18,607	-	-	0.65	-	0.1
	TAS	-	7,252	-	-	0.18	-	3.9
	VIC	-	42,180	-	-	0.42	-	2.0
	WA	-	29,887	-	-	0.52	-	0.2
	Total	**219,929**	**145,919**	**-51**	**0.39**	**0.59**	**0.15**	**0.2**

In this report, the data used to prepare these balances by industry and region were derived from ABS farm survey data using the upscale survey data by NRM region, In calculating the state level PNB (Table 5) fertiliser use was derived from Fertilizer Australia. Table 7 shows the difference between these two fertiliser use estimates and the effect this has on PNB and NBI. The Fertilizer Australia data was nearly always more than the ABS Farm survey data, although differences at state level were smallest for P, but the ABS up-scaled data shows large discrepancies especially in Western Australia. The Fertilizer Australia data is collected from the industry and is likely a more reliable measure of the true fertiliser use at a regional level than the ABS data. If is unlikely the that Fertilizer Australia data could be downscaled to NRM zone, and even if the ABS data were rescaled against the Fertilizer Australia data, there are large differences in the proportions among states. For example, the Fertilizer Australia data suggests that 32% of N is used in WA, but the ABS data suggests 22%, so that the disagreement means almost 100% difference between the two estimates. The consequences of these differences are that the PNB and NBI values derived also show large differences depending on the data source used (Table 7).

Secondly, the area used to estimate the NBI metric can be from the total area of agricultural holdings, the total area of agricultural land, the area that is fertilized or some other area base that may pertain to particular enterprises such as the cropped area. ABS collects and presents these data, but there seems to be some internal inconsistencies that may be a consequence of the up-scaling. Table 8 summarises the data from the 2007-08 and 2009-10 ABS survey, and shows that there was 6 Mha more area fertilized in WA than was used for cropping. On the other hand, in NSW, these data suggest that at least 3.5 Mha of cropping land was sown but not fertilized. While these values do not affect the PNB, they do change the NBI significantly, for example with the national N-NBI changing from -1.1 kg N/ha/y if all agricultural land is considered, to become -9.7 kg N/ha/y if the area fertilized is used. While not significant at a farm level, it does mean that national or regional reporting must be very clear on the denominator used in deriving the NBI.

Table 8. ABS values from farm surveys 2007-08 and 2009-10 for the areas of agricultural holdings, the area of holding used for agriculture, the area cropped and the area fertilized.

State	Area of holdings (kHa)	Area for Agriculture (kHa)	Area for Cropping (kHa)	Area Fertilized (kHa)
NSW	58,333	56,798	11,868	8,304
NT	59,787	58,897	30	13
QLD	135,559	133,340	4,108	2,085
SA	14,382	13,958	5,293	5,861
TAS	1,594	1,509	131	522
VIC	12,694	12,269	4,710	7,191
WA	93,713	90,886	10,262	16,513
Australia	376,063	367,656	36,402	40,489

The third area for concern is the variability in product nutrient concentrations. In this report, the data were derived from the tables provided by the late Dr D Reuter, and these were the values used in the Australian Agricultural Assessment 2001 report. Appendix 6 shows these values for the major agricultural commodities. It has been shown that grain nutrient concentrations of wheat (Norton 2012) and canola (Norton 2014) show large spatial and temporal variations. For example, the P concentration of wheat grain had a mean grain P concentration of 3.3 kg/t (0% moisture, equivalent to 3.0 kg/t at 10%

moisture) and this ranged from 2.9 kg/t in the Victorian North East, to 3.9 kg/t in the mid-north of South Australia. Over the survey population there were coefficients of variation of 20% for P, 14% for K and 13% for S. The N concentrations were – obviously - as variable as the grain protein concentration. This study also identified significant differences in grain P and S between the two cultivars tested (Yitpi and Gladius). The mean value is around 15% higher than the Reuter value. IPNI has developed a nutrient concentration application that has a wide range of products, but these are global means rather than regional values. For example, the P concentration for spring wheat is given here as 4.1 kg P/t of grain, 60% higher than the Reuter value. From this, it can be concluded that regional grain nutrient concentrations will provide a more accurate assessment of the regional or farm-gate nutrient balance than using default values.

Summary

- Nutrient balances can be estimated using existing census data but the values generated are means and disaggregation by region, nutrient, industry and crop requires assumptions to be made.

- The various studies over all agriculture show reasonable consistency in the size and distribution of partial nutrient balances for Australia. In general, Australian agriculture has a N-PNB near or slightly above unity, a P-PNB that is around 0.5, and a K-PNB that is much more than unity. As a consequence, soil P levels are likely to be increasing, while soil N and K levels are being depleted.

- These values show annual variations, with nutrient removals showing larger variations than nutrient inputs.

- The Australian grains industry on the whole shows a N and K balance more than unity and P balance less than unity 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).

- 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.

- Fertiliser use by crop data is not readily available to make industry level assessments at regional scales.

- 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 USE IN THE GRAINS INDUSTRY

Approximately 65% of the N, 60% of the P and 25% of the K used in Australia is applied to grain crops (Heffer 2009, 2013). Despite the importance of fertiliser use economically and environmentally, there is little public information on the rates or types of fertilisers used by different crops. The industry holds some good information about this based on their regional and commodity based sales but this is not generally available. The aim of this short section is to compile what is known from the surveys and is in the public arena on this topic.

Table 9 is derived from the 2001 small area farm survey data for average nutrient application rates on areas fertilized for all farming activities. Data in this format was derived from the now defunct AgStats statistical collection program. Mean N, P and K rates for Australia were 21.6 kg N/ha, 9.6 kg P/ha and 2.0 kg K/ha. These are rates are not disaggregated by crop or farming activity.

Table 9. The area fertilised, the average rate of Nitrogen (N), Phosphorus (P) and Potassium (K) applied within Statistical Local Areas (SLA) in 2001. Data are for all agriculture, divided by the area fertilized. Source ABS AgStats.

State	N kg/ha	P kg/ha	K kg/ha
NSW	31.0	11.0	1.1
QLD	36.8	5.0	2.1
SA	17.5	11.2	1.2
VIC	14.1	15.3	3.1
WA	13.4	5.5	2.9
Australia	21.6	9.6	2.0

The ABS Land Management statistics can be interrogated for fertiliser use rates, and a summary of two audit periods (2007-08 and 2014-15) is shown in Table 10. These data do provide interesting information on which products are being used at what rates, but not by which production sector. The uncertainties on deriving nutrient application rates (Table 6) have been mentioned earlier. There are also some questionable data areas here, with MAP and DAP included together, as are double - and triple- superphosphate and muriate and sulphate of potash products. In the surveys after 2012, muriate of potash is not included but potassium nitrate is listed despite being a minor fertilisers. Table 10 is interesting when comparing application rates between the two audit periods, and the rates for MAP/DAP and urea have increased by 22%. The data for 2014-14 suggest that ammonium sulfate was applied to 169,000 ha but no actual tonnage was cited, so the rate defaults to zero. These are the problems of up-scaling any survey data to estimate industry values and so relying on those data to develop robust industry nutrient performance indicators may need more careful assessments.

Despite these methodological issues, the data in Table 10 does seem reasonable and is consistent with what would be considered current industry practice. Even if the data are disaggregated by NRM zone, the rates seem to reflect what is industry practice. For example, urea rates in the Corangamite, Wimmera and Mallee of Victoria are estimated as 205, 68 and 78 kg urea/ha respectively. Similarly, MAP/DAP rates for those three regions are 83 kg/ha, 65 kg/ha and 75 kg/ha. It should be noted that these are rates across all crops, so the MAP/DAP values may have quite different values for wheat, barley, canola or pulses.

Table 10. Product application rates from ABS 2007-08 and 2014-15 Land Management and Farming Australia surveys.

2007-08	NSW kg/ha	Qld kg/ha	SA kg/ha	Tas kg/ha	Vic kg/ha	WA kg/ha	Australia kg/ha
2007-08							
MAP/DAP	70	60	70	260	80	70	69
Double/Triple superphosphate	70	90	70	270	110	80	82
Single superphosphate	130	170	130	220	150	110	134
MOP/SOP*	170	180	170	150	130	60	89
Potassium nitrate	140	170	120	90	160	70	122
Amm. Sulfate	150	150	90	280	80	100	105
Anhyd. ammonia	100	120	0	0	60	90	106
Urea	130	190	0	0	120	70	102
Urea ammonium nitrate	110	190	0	0	90	80	80
Animal manure	3600	6650	1510	3000	2240	1800	3187
2014-15							
MAP/DAP	94	72	81	227	93	73	84
Double/Triple superphosphate	81	64	90	253	126	97	102
Single superphosphate	143	211	109	234	172	107	144
Pot Nitrate	114	201	80	135	-	-	188
Amm. Sulfate	109	161	113	265	-	102	119
Anhyd. ammonia	134	112	-	-	-		124
Urea	144	161	110	271	156	81	124
Urea ammonium nitrate	53	89	39	65	40	53	52
Urea-Cont.Release	120	244	189	237	144	93	142
Animal Manures	1926	-	2204	2097	2310	1645	2217

* Muriate of Potash, Sulfate of Potash

The International Fertilizer Industry Association has published reports on fertiliser use by crop at a national level. These values are derived from various industry bodies in the countries, and in Australia, the data is compiled from estimates provided by the major fertiliser companies and Fertilizer Australia. Based on the reports by Heffer (2009, 2013), the mean nutrient application rates can be estimated from the area produced and the amount of fertiliser used.

Table 11. Fertiliser use by crop application rates as derived from the International Fertilizer Industry Association reports (Heffer 2009, 2013) grain crops (wheat, other cereals and oilseeds). The denominator is the area harvested (FAOSTAT).

Crop	N kg/ha	P kg/ha	K kg/ha
Wheat	24.7	10.4	1.9
Other Cereals	29.9	13.1	2.0
Oilseeds	60.0	18.4	4.8
Total*	29.9	12.4	2.1

Fertilizer Australia also collects data on products used from its member companies, but this is only loosely disaggregated. A summary of this is shown – with fertiliser use by product presented in Table 11. The data here substantiates that MOP is the major K source used, and that urea is by far the major N source used. Of interest fluid fertilisers, especially UAN, have become a significant part of the overall fertiliser market, increasing 4 fold since 2002.

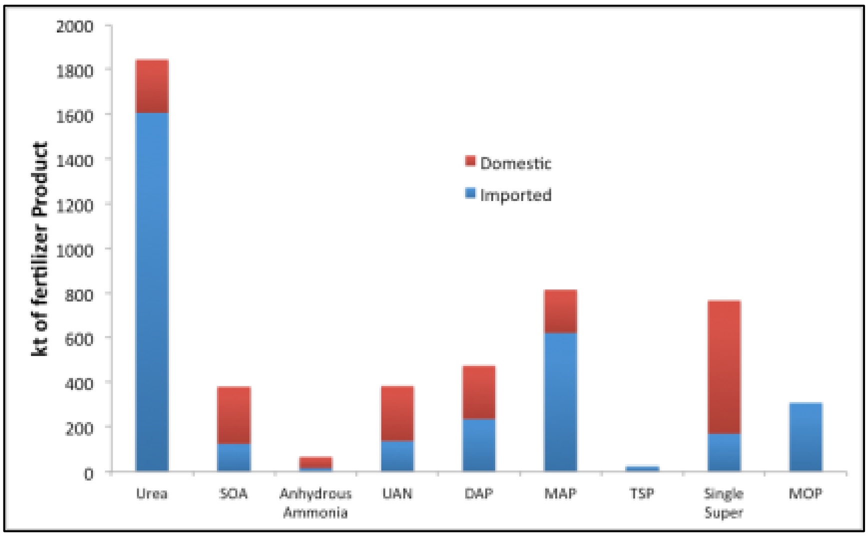

Figure 7. Fertiliser use in Australia by product (2014) showing the proportions of imported and domestic products. (Fertilizer Australia)

Given the uncertainties in application rates of products and nutrients by crop and region, it may be appropriate to consider an approach similar to the Dairy Industry with the Dairy Farm Monitor project, which collated data on inputs and productivity for dairy farms. The GRDC Paddock Survey project may serve this purpose, and the data coming from there could be very useful in gaining a better understanding of nutrient inputs.

Summary

- In combination, these data sets show some concordance, but each source has its own problems. The ABS data is not disaggregated by crop and the IFA data is only presented by region. The ABS does have some inconsistencies over time in the wording of particul ar questions concerning land management practices.

- Within the overall context of the project, the data collated does not give adequate coverage at crop, region and farming system to develop nutrient use benchmarks for growers.

- It is appropriate and encouraged that GRDC consider on-going assessments of field surveys such as the paddock survey.

NUTRIENT PERFORMANCE INDICATORS FROM SOUTHERN AUSTRALIAN GRAIN FARMS.

In Australia there have been national (Angus 2001) and regional assessments (National Land and Water Resources Audit 2001) of aggregate nutrient balances. Since that time there have been profound changes in farming systems including higher cropping intensity and increased use on all fertilisers. Earlier, regional nutrient balances were reported using data from farm surveys, but this assessment did not include BNF, fertiliser descriptions were imprecise and the data could not be disaggregated to region and crop type. Using IFA and FAO data, national values for PNB, PFP and NBI for N, K and K in cereal production systems could be developed and were presented in Table 2. Table 12 provides some guidelines from the literature on what values have been reported and how they can be interpreted and suggests that 80% recovery is a good general target to aim for, while PNB values vary among the different nutrients, lower with N and higher with P, reflecting the relative crop demand for these nutrients.

Table 12 Typical nutrient performance indicators for cereal crops when recommended management practices are employed and where soil available nutrient levels are within recommended ranges (Fixen et al. 2015).

Metric	N	P	K	Interpretation
PNB	0.7-0.9	0.7-0.9	0.7-0.9	Lower levels suggest changes in management could improve efficiency or soil fertility could be increasing, Higher levels suggest soil fertility may be declining.
PFP	40-90	100-250	75-200	Lower levels suggest less responsive soils or over application of nutrients which higher levels suggest that nutrient supply is likely limiting production.

While aggregated values are of interest, to further develop nutrient performance benchmarks as guides for farmers, data at farm or field level for nutrient acquisition and removal is required over multiple years to account for crop rotations. This survey data reports field level data collected to develop regional nutrient performance indicators PNB and PFP and their variability, against which growers can assess their nutrient management practices to guide future strategies.

Data Collection

In the GRDC prospectus, the call was for data to be collected from across all GRDC regions, but the task tendered for, and agreed to, was to investigate nutrient performance indicators from Southern Region farms. At the time of contracting, the southern region included southern New South Wales and data was included from that part of the now Northern region. The protocols developed could be adapted to collected and process data from other regions. Western Australia has several years of data at field level curated by Dr Geoff Anderson (DAFWA), and the GRDC supported National Paddock Survey (http://www.nationalpaddocksurvey.com.au) project may provide useful information. There are other opportunities to collect data, and single year field surveys have been undertaken for northern cropping and cotton regions (Professor Bell through DAQ00084). If these data have information from the same fields over multiple years then the data collected there could be harmonized with the information formatting presented here. For nutrient budgets though, data from the same field should be used particularly because nutrient management varies with different rotation systems.

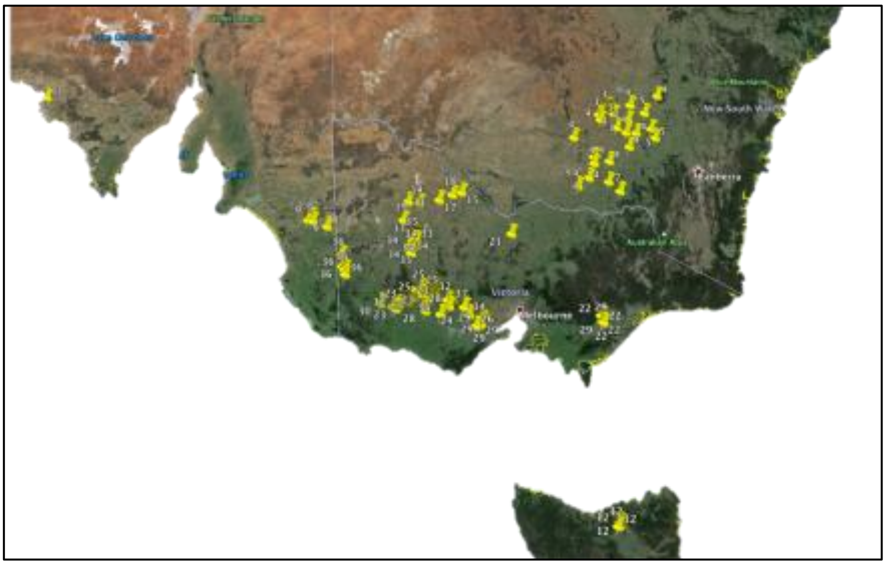

Figure 8, The geographical distribution of survey fields across southern Australia

Useable farm records for 514 fields from 125 growers covering over 35,000 ha over 4 or 5 years in south-eastern Australia (Figure 8) were accessed with a total of over 2500 annual field records where fertiliser, activity and crop yield was reported. An additional 300 incomplete records were accessed, that had fertiliser rates for only one or two years or did not provide yield data. This group of records was used to estimate fertiliser rates but not for calculating nutrient performance indicators. The data came from either consultants or directly from farmers. Consultants and farming systems groups in all parts of the southern region were personally contacted, but there were only scarce records from Tasmania and South Australia. Multiple requests (and commitments) were made from various South Australia groups but few delivered. The small datasets from Tasmania and South Australia were not analysed further.

It is readily acknowledged that the data is not representative of all regions and all farming systems. The collaborators were those who had farm records and were willing to share them.

Table 13. Summary of survey data collected from south-eastern Australia, including approximate annual rainfall for each region and relative areas of cereals, oilseeds and legumes (pulse and pasture).

Region	Annual Rainfall (mm)	No. of growers	No of fields	Area (ha)	% Cereal	% Oilseed	% Legume
High Rainfall Zone	>600	45	179	7,600	57	34	9
Southern New South Wales	450-600	33	66	5,300	56	34	9
Wimmera	450-350	17	68	4,200	46	14	34
Mallee	<350	23	171	17,800	70	11	16
Upper Eyre Peninsula	400-500	5	20	2,500	56	0	43
Tasmania	>700	2	12	600	40%	8	24

The data came from farms in four different agroecological zones with different rainfall distributions and land use patterns. The zones were the High Rainfall Zone of southern Victoria and south-eastern South Australia (HRZ), southern New South Wales (SNSW), the Victorian and South Australian Mallee, and the Victorian and South Australian Wimmera. A summary of the data collected is shown in Table 13. Thirty-seven precent of the fields surveyed with in wheat, while barley (21%), canola (20%), pulse crops (11%), annual pasture (6%) and fallow (2%) were the other land uses. In addition to the fields where yield and fertiliser use were reported, there were fertiliser use records collected from another 80 fields for shorter time periods and these data are use to report fertiliser use patterns but not to estimate nutrient performance indicators.

The farm records collected listed the annual inputs of fertilisers and the fertiliser nutrient concentrations were taken from industry sources and a summary is provided in Appendix 14. There were no manure applications to the fields in this survey. Nitrogen derived from symbiotic fixation (BNF) was estimated from pulse grain yield, and published values of pulse harvest indices, the shoot N%, %N derived from the atmosphere and shoot:root ratios (Peoples et al. 2008, Herridge et al. 2009). Values used for gross BNF were between 51 kg N/ha/t (chickpea) to 110 kg N/ha/t (vetch). A summary of the methods used and the rationale behind this is described in Appendix 13.

In the Mallee in particular, vetch is frequently used as a pasture, hay crop or green manure crop and to estimate the amount of N fixed, the amount of growth was indexed against wheat crops on the same property. Based on work of the author on green manuring in the Wimmera, it was estimated that 30 kg N/ha were fixed per tonne of wheat yield and this is based on a the vetch biomass being approximately 67% of the biomass of the wheat crop from nearby fields, with BNF of 20 kg N/t of vetch biomass (Peoples et al. 2001). Where an annual pasture phase was included, BNF estimated on the same basis as the BNF value derived for vetch.

Grain and hay yields were recorded in the farm records, and regional wheat grain nutrient concentrations for wheat (Norton 2012) and canola (2014) were used to estimate removal in grains. Other values were derived from the "Reuter" tables used in the National Land and Water Resources Audit (2001) and summarised in Appendix 11.

It was estimated that 80% of N and S and 40% of the P and K in the crop residue is lost when the residues are burned (Heard et al. 2006). The amount of crop residue was estimated from the harvest index (0.45 cereals, 0.28 canola) and seed yield, and nutrient concentrations in those residues were based on the values in Heard et al. (2006) which are reasonably consistent with the industry figures (e.g. in the GRDC Stubble Manual). Where residues were grazed it was estimated that 50% of N in the crop residue was removed due to grazing, but no estimates were made of nutrients removed in live animals when grazing occurred either in crop or from the residues.

The PNB, PFP and NBI for N, P, K and S were calculated from the summed from nutrient inputs and removals over a period or four or five years for each field. In calculating PNB, grain yields of all crops are included, with no adjustment for energy contents.

Results

Fertiliser use and estimated BNF

Fertiliser use was recorded for 91% of all the fields where crops or pastures were grown, and N, P, K and S were applied to 84%, 87%, 5% and 77% of fields over the audit period. Fields that received no fertiliser at all when farmed were more commonly, but not exclusively, in the low rainfall areas and typically on fields where pastures or green manure crops were reported. Farmer records of the rate and frequency of fertiliser product application are shown in Table 13. Mono-ammonium phosphate was the dominant P products used by growers, with DAP and SSP being less commonly used, with only about 5% of fields receiving those latter products. The most commonly used N sources were urea (44% of fields), ammonium sulfate (5% of fields) and urea/ammonium nitrate solutions (4% of fields). Muriate of potash was used on about one third of fields in the HRZ during the audit period. The application rates for MAP/DAP urea are in broad agreement with the ABS data (Table 10), but the ABS rate for sulfate of ammonia is around twice the rate from this survey.

Table 14. Fertiliser product type and application rate by region over the period 2010-2014. The numbers in parentheses are the number of fields that received that product.

Product	HRZ	Mallee	SNSW	Wimmera
MAP	89 (468)	42 (349)	66 (277)	57 (118)
MAP-S	102 (79)	-	-	53 (70)
DAP	91 (65)		105 (14)	70 (56)
SSP	111 (52)	82 (20)		133 (90)
Urea	146 (498)	57 (143)	117 (231)	97 (203)
SOA	71 (24)	44 (58)	88 (20)	67 (125)
UAN	23 (1)	74 (51)	25 (1)	58 (94)
MOP	80 (69)	-	-	68 (7)

Mean annual nutrient application rates and yields by crop and region are summarised in Table 14. There are higher N rates in the higher rainfall regions and higher rates generally on canola than cereals. The low rate of N for legumes was largely a consequence of the widespread use of MAP and DAP as at-seeding fertilisers which has N embedded in those products, but the main reason for the use of MAP/DAP is as a P source. P use on legumes was about half the rate used in cereals and one third the rate for canola, and similar to N, rates were higher in the higher rainfall regions. Practically all K use was in the HRZ on cereals and canola. This survey showed that little S was supplied to cereals, but both legumes and canola had relatively high rates of S applied, principally as gypsum (data not shown) and ammonium sulfate.

The rates recorded here of nutrient applications are higher than the rates in the ABS surveys reported earlier, and there are at least two reasons for this. Firstly, the cohort of farmers here is smaller than the ABS cohort, and the data we collected was from growers with good records, which may not be reflective of all growers. In addition, the data here are more focused on crop use and less on pasture, horticulture and other industries, so are more reflective of the actual use rates than the ABS data. When compared to the national figures reported by IFA (Table 11), the rates in Table 15 are higher, and this may be because not all states are reported in our Table 14 and rates for N (for example) are likely to be lower in areas such as the low rainfall regions of Western Australia.

The method of data collection enables more than the means to be assessed, and the population of data can be interrogated to assess the distribution of nutrient application rates within the various production regions. Figure 9 shows box-plot distributions for nutrient application of N and P for cereals and canola over the survey period. Comparing the N (Figure 9a) and P (Figure 9b) distributions, it is clear that N rates are more variable than P rates for all crops. Median rates for both crop types are lower in the low rainfall Mallee compared to the HRZ, but the median P rates are quite similar for both crop types. Because few field received K and S applications, the median values are less meaningful that for N and P, so box-plots for those nutrients are not presented. The inter-quartile range for N rates is higher than the variation on P rates (Figure 9), reflecting that N is largely applied tactically in response to seasonal conditions, while P is applied strategically and at sowing.

Table 15. Nutrient application rates in kg/ha for cereals, canola and legumes (pulse and pasture) for N, P, K and S for the four regions surveyed for the period 2010-2014.

Crop type & region	Average Yield (t/ha)	kg N/ha	kg P/ha	kg K/ha	kg S/ha
Cereal		38	12	1	4
HRZ	4.23	59	18	4	3
Mallee	1.96	21	8	0	3
SNSW	3.33	48	14	0	7
Wimmera	3.72	39	11	1	7
Canola		56	16	4	43
HRZ	2.15	66	20	8	50
Mallee	1.03	30	8	0	15
SNSW	1.75	57	14	0	39
Wimmera	2.08	51	15	0	64
Legume		5	7	0	8
HRZ	2.42	12	14	2	25
Mallee	1.04	2	3	0	2
SNSW	0.83	5	6	0	16
Wimmera	1.51	5	8	0	4
Mean		**35**	**12**	**2**	**13**

a) N rates b) P rates

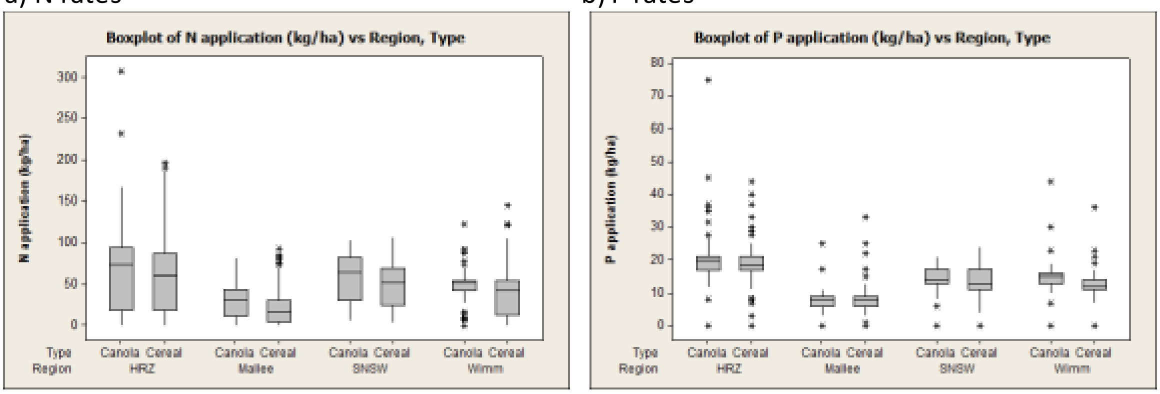

Figure 9. Box-plots of nutrient rate for four different regions in southern Australia, a) for N and b) for P for canola and cereals during the period 2010-2014.

BNF accounted for 16%, 29%, 14% and 50% of the N input for the HRZ, Mallee, SNSW and Wimmera respectively. These differences largely reflect the frequency of legumes in the crop rotations (Table 11). In the HRZ and SNSW fewer suitable pulse crops than the Wimmera in particular, which has favourable conditions for the cultivation of field peas (*Pisum sativum*), lentils (*Lens culinaris*) and chickpea (*Cicer arietinum*). Faba bean (*Vicia faba*) is the dominant legume in the HRZ.

Nitrogen nutrient performance indicators

The data collected and collated is presented as distributions of the relevant values, as the key aspect of these data is not just the mean or median value, but the distribution of the values. Furthermore, the statistical assessment and comparison of indices, such as comparing mean PNB or PFP values by analysis of variance is of questionable validity as those metrics are not normally distributed (see Figure 10. Understanding the distribution allows growers to identify where they sit within the population rather that being referenced to a single mean value or indexed number.

Summary statistics for the PNB, NBI and PNB calculated from the data collected are presented in Table 15. The aggregate N balance for the whole data set had a PNB of 1.14 kg N removed per kg N supplied but the data were skewed to the right, with more higher values than lower values (Figure 10) and there are differences among the regions where data were collected. For the whole data set, 67% of fields had N-PNB more than one. The median N-PNB ratio for all the fields within the four regions over the audit period is presented in Figure 10a. Values presented use BNF and N fertilisers as denominator in the metric.

Table 16. Descriptive statistics for the regional mean, standard error, median, upper and lower values and skewness for partial N balance (PNB), N nutrient balance intensity (NBI) and partial N factor productivity (PFP) from the survey.

Variable	Region	Mean	SE Mean	Q1	Median	Q3	Skewness	% <0.5	% >1
N-PNB	HRZ	1.55	0.10	0.93	1.16	1.60	3.14	2	68
	Mallee	2.09	0.17	0.99	1.44	2.17	3.53	20	39
	SNSW	1.20	0.07	0.81	1.09	1.47	1.27	8	59
	Wimm	1.21	0.11	0.75	1.04	1.40	2.73	16	50
N-NBI	HRZ	-13.1	2.0	-29.3	-12.7	5.2	-0.29		
	Mallee	-9.5	1.2	-20.3	-9.8	0.2	0.18		
	SNSW	-4.1	2.9	-24.4	-4.8	14.4	0.37		
	Wimm	-2.3	3.1	-14.7	-2.3	14.1	0.23		
								% <50	**%>200**
N-PFP	HRZ	71	6	36	46	67	4.17	59	6
	Mallee	105	10	44	69	103	3.54	35	25
	SNSW	50	4	32	40	54	2.36	71	3
	Wimm	46	4	28	43	57	2.25	68	0

PNB values differed among regions, with the data showing a positive skewness (Table 15). The data from the Mallee showed the largest deviation between the mean and median, indicating a large number of high PNB values in that region, so that more N is removed than is supplied. Thirteen 11% of fields surveyed in that region had PNB >2 but then 75% had values less than 1. In the HRZ, there were 70% of fields with N-PNB less than unity, while the values for the Wimmera and Mallee were 50% and 60% respectively. The distributions for each region are shown in Appendix 15.

The patterns for N-NBI are all less skewed that the N-PNB and approximate to a normal distribution. All regions showing negative N balances but there was a relatively small negative N balance for the Wimmera reflects the higher proportion of pulses grown and so the impact of BNF in reaching a balance. The mean value from this survey is less than the value calculated from the ABS data, which is largely expected, as the latter does not include BNF. In aggregate, all these data indicate that most fields are net exporters on N, and that N is being derived from the mineralisation of organic N or from some other sources such as non-symbiotic N fixation, nitrate in rainfall or from atmospheric deposition.

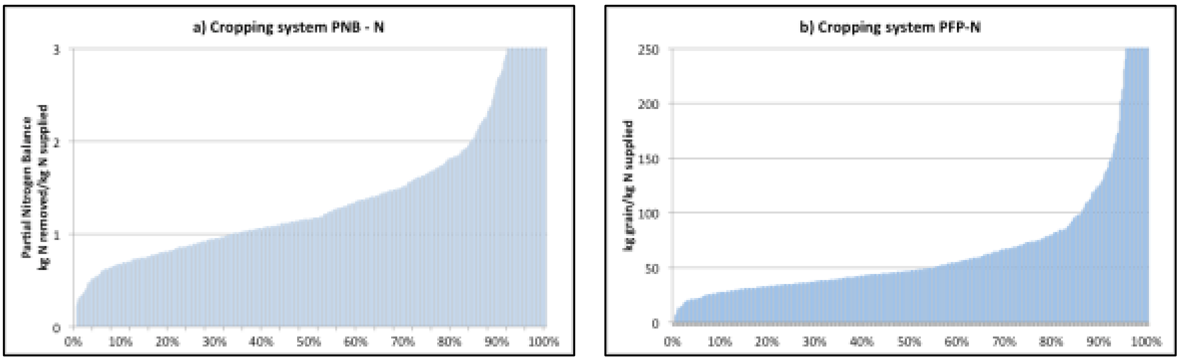

Figure 10. Cumulative distributions of nitrogen nutrient performance indicators for south-eastern Australian cropping systems, a) Partial factor productivity and b) Partial nutrient balance.

Figure 10 and Table 15 also shows the partial factor productivity for N use in the survey farms. In some ways, these values represent the productivity of the N used or fixed on these farms. The values are not normally distributed and are skewed to the right, and the whole data set has a mean value of 77 kg grain per kg N supplied. The values are not corrected for the differences in energy concentration between different species (eg wheat versus canola) but are aggregate values. The “returns” on the N supplied (as expressed by the PFP) in the Mallee are higher than the other regions, which may be a consequence of the generally lower background N fertility in this region, a consequence of the low soil organic C levels. The lower N status means crops are likely to be more responsive to additional N than where native soil N is higher.

Figure 11 is an alternative way to present the data collected on N performance. Similar to figure 1 it plots the N excess or deficit against the removal of N – which is a surrogate for yield. This method of presentation indicates the magnitude of the excess over removal as well as indicating system productivity. The data indicate that higher yields are often associated with larger nutrient deficits – or that growers aiming for higher yields are “mining” the soil N (in this case). This observation is not necessarily restricted to a particular region although trend-lines could be fitted to these data (with very low coefficients of determination) that indicate a negative slope for the Wimmera, Mallee and HRZ – where higher yields mean more depletion - but the SNSW has a positive slope – with higher yields meaning less depletion. The veracity of the trends is poor but the observations can be made.

For growers, this type of representation of the data would seem useful as it provides a target – which is close to the abscissa and as far along that axis as the environment permits. This also is quite clear in showing the magnitude of the depletion or enrichment (N-NBI) relative to the yields. In some regions, the concept of “N surplus” is widely used as a target for N management – a surplus of 25 kg N/ha is the target for certain New Zealand dairy farms, and this is assessed through modelling using Overseer. In Germany, N surplus of 60 kg N/ha is permitted, assessed by grower records, but there is a suggestion that this value will be significantly decreased in line with developing EU environmental regulations.

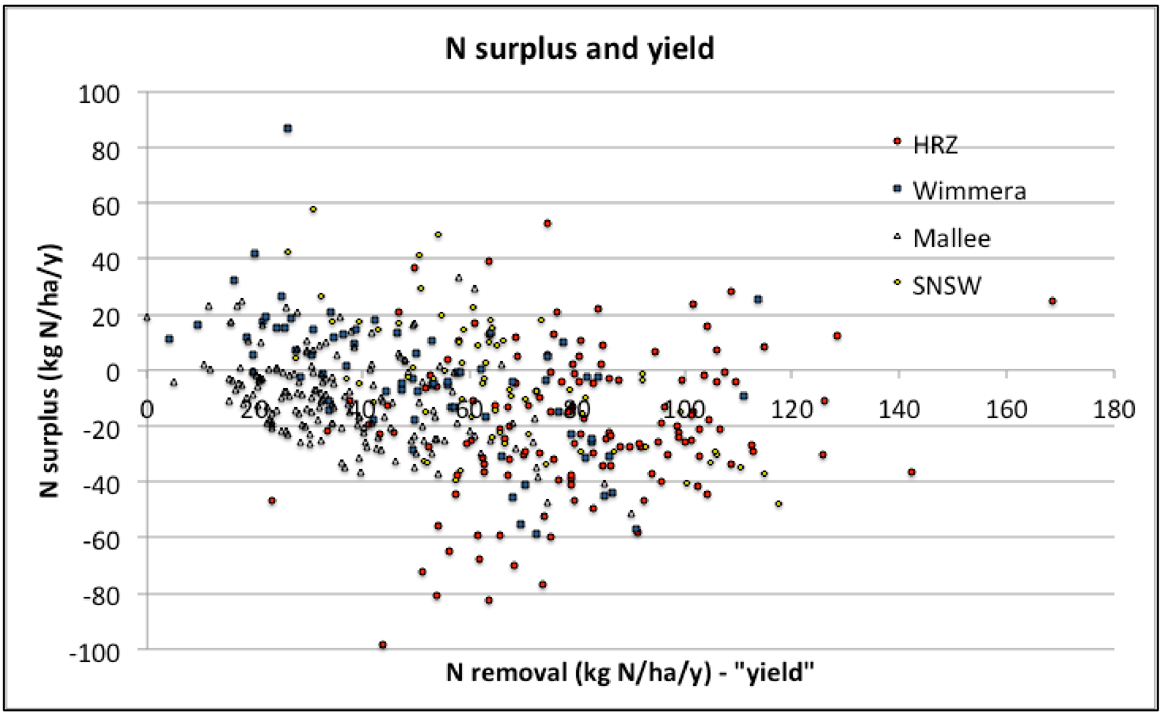

Figure 11 Nitrogen surplus (N-NBI) graphed against N removal for the 503 fields surveyed in the period 2010-2014.

Phosphorus nutrient performance indicators

The P-PNB overall had a mean of 0.69 kg P removed per kg of P applied, and 80% of fields had more P applied than removed, however the data are not normally distributed (Figure 12). The balance expressed either as P-PNB or P-NBI indicate that P removals are less than P supplied, and the imbalance is smallest in the Mallee and largest in the HRZ (Table 16). Even so, the P-PNB for the HRZ is nearly normally distributed, and there were only 6% of fields where P application was >1, while there were 38% of fields in that category in the Mallee. In SNSW and the Wimmera there were 5% and 37% of field with P-PNB>1 respectively (Table 16). The fate of that surplus P is not known but it is more likely immobilized through various soil reactions rather than lost through erosion or leaching. It should be noted that the audit years in the Wimmera and Mallee were not very favourable years due to various climatic stresses. As a consequence, growers fertilizing with P to an “average” year may have been oversupplying P to those fields, where mean P rates are 8 and 11 kg P/ha (Table 14).

Weaver and Wong (2011) reported the median P-PNB values for the cropping industries of 0.48 which is about 50% lower than the value reported from these case study fields. They too noted the large range of values, spanning an order of magnitude for the cropping industries. Weaver and Wong (2011) noted that lower P-PNB were associated with higher soil P levels and that P-PNB values greater than 1 imply P accumulation, and the degree to which this accumulation occurs is a function of soil characteristics such as the P buffering index.

The P-PFP values are higher than the N-PFP values as the demand for P is less than the demand for N so the response function – with a similar shape – has a different value. Lower PFP values are likely to occur where the background P values are higher, simply because of the diminishing returns nutrient response function. The median P-PFP from these data was 227 kg grain/kg P applied, with a trend that higher PFP values occur in regions where rainfall was lower, such as in the Mallee compared to the HRZ.

Table 17. Descriptive statistics for the regional mean, standard error, median, upper and lower values and skewness for partial P balance (PNB), P nutrient balance intensity (NBI) and partial N factor productivity (PFP) from the survey.

Variable	Region	Mean	SE Mean	Q1	Median	Q3	Skewness	%<0.5	%>1
P-PNB	HRZ	0.70	0.01	0.57	0.69	0.82	0.50	15	6
	Mallee	0.97	0.04	0.67	0.87	1.16	4.01	13	38
	SNSW	0.73	0.05	0.59	0.66	0.76	6.34	9	5
	Wimm	0.83	0.08	0.46	0.88	1.10	2.74	29	37
P-NBI	HRZ	6.2	0.4	3.0	5.0	9.0	1.30		
	Mallee	0.7	0.2	-1.1	0.7	2.4	-0.18		
	SNSW	4.4	0.3	2.7	4.0	6.0	0.12		
	Wimm	2.4	0.6	-0.9	1.2	5.5	0.46		
								% <150	**% >250**
P-PFP	HRZ	184	4	154	177	213	2.57	23	6
	Mallee	287	13	197	258	333	4.41	12	53
	SNSW	195	15	158	178	204	6.40	17	6
	Wimm	217	17	122	209	278	3.77	35	25

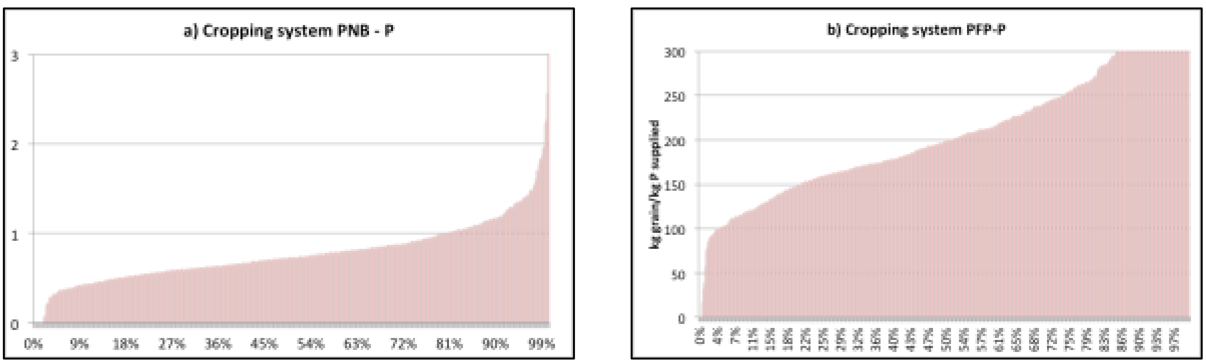

Figure 12. Cumulative distributions of phosphorus nutrient performance indicators for south-eastern Australian cropping systems, a) Partial factor productivity and b) Partial nutrient balance.

Figure 13 presents the same data as in Figure 12 but in the format of Figure 1 where a nutrient surplus or deficit is scaled against the nutrient removal. Similar to the data presented for N in Figure 11, the P data shows a wide range of recoveries that do not necessarily relate to yield. The Mallee data shows the closest cluster to a trend line – with most falling between a surplus of ±5 kg P/ha. In general, the HRZ is largely in P surplus as suggested by the P-PNB data.

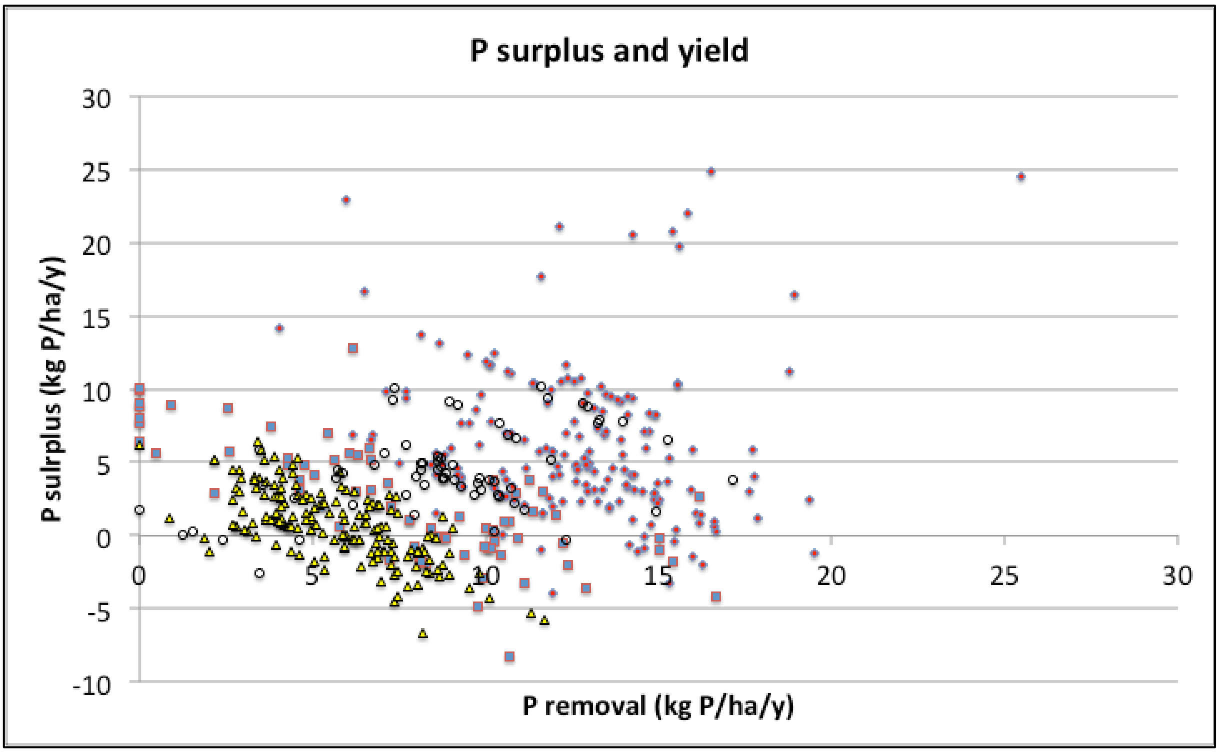

Figure 12 Phosphorus surplus (P-NBI) graphed against P removal for the 503 fields surveyed in the period 2010-2014.

Potassium nutrient performance indicators

The use of K on fields in this survey was largely restricted to the HRZ, where about 9% of the crops received K. As a consequence K-PNB and K-PFB can be calculated for only 60 fields from the survey fields, as the denominator -fertiliser applied - is zero. The nutrient balance data collected is displayed in Figure 12, graphed as applied and removed K. On the 91% of fields that did not receive K, removals ranged from nil to over 250 kg K/ha. In all except 6 fields the K balance was negative – that is more K was added than removed. This includes fields where K was applied at rates that were mostly sufficient to replace removals. The K-PNB could be calculated, the values were of little use as the population from which they were drawn was relatively small (<60 fields) and often reflected only a few growers. The K-PFP values, where calculated were generally in the range of 150-300 kg grain/kg K applied.

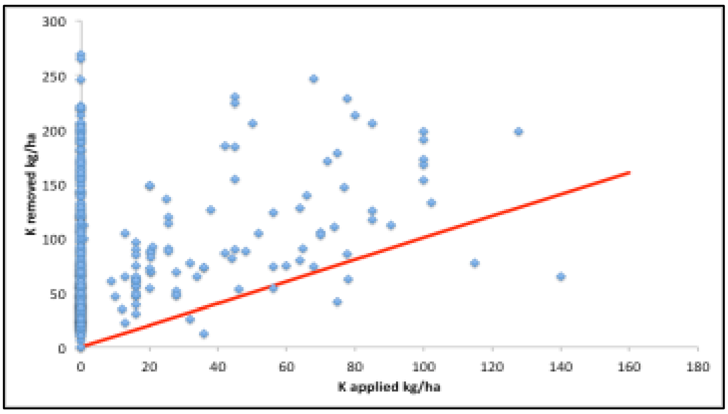

Figure 12. Potassium removal and application in surveyed fields in south-eastern Australia over the period 2010-2014. A 1:1 line is shown for reference.

Sulfur nutrient performance indicators

The data collected for S showed that 52 fields did not have S applied, while the mean rate of S where supplied was 54 kg/ha although 189 fields had rates less than 20 kg S/ha which was essentially S incidentally contained in other fertilisers. Figure 13 shows the S-PNB by region with the main groupings around a PNB of 2, with the high balance values a consequence of gypsum applications that occurred in the audit period. Figure 14 is an alternative way of presenting these data, showing the application and removal rates similar to Figure 12. Figure 13 does not include the nil-S application rates as the derivation of an S-PNB (and S-PFP) would defy the rules of arithmetic.

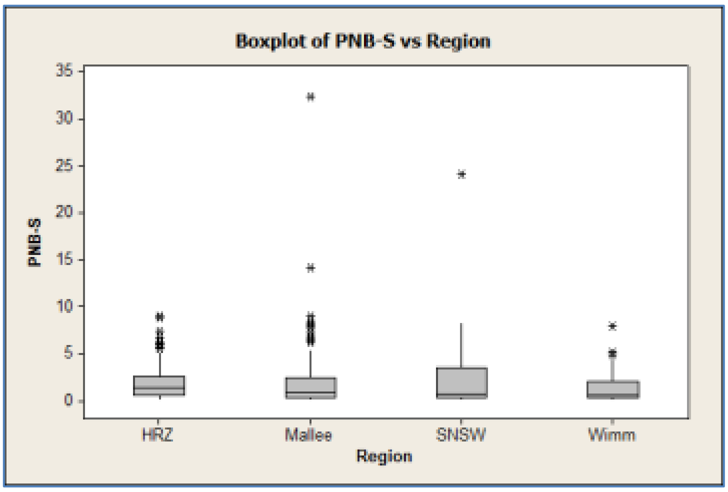

Figure 13. Boxplot of S partial nutrient balance for each of the regions where adequate data were collected. Outliers were largely the consequence of gypsum application during the audit period. Fields where no S was applied are not considered in this presentation.

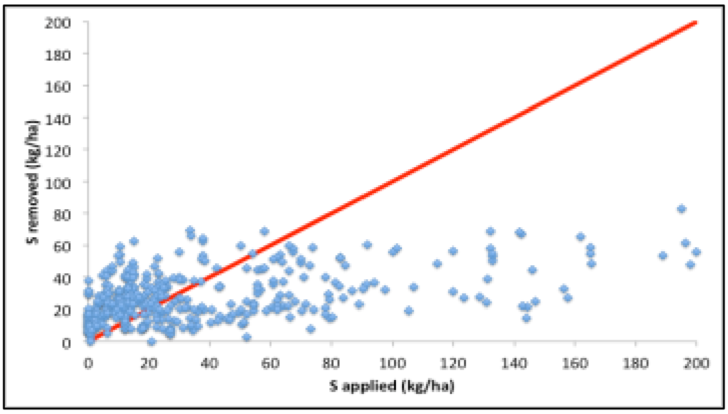

Figure 14. Sulfur application rates and sulfur removal in products for cropping fields for the period 2010-2014. The high rates of S application were largely a consequence of gypsum application during the audit period

Discussion and interpretation

It is possible to derive nutrient performance indicators of PNB, NBI and PFP using farm field records. These indicators do show a wide variation among regions and also among fields and the derivation of the indicators has important implicit assumptions. These assumptions are about the actual nutrient concentration of the products and also the crop residues, both of which will vary among fields and farms. Crop residues nutrient concentrations are variously reported, and this may be a consequence of when the residues were collected – those collected later are likely to be lower in soluble nutrients than residues collected soon after harvest. Even so, many growers would have access to the sorts of data that would allow them to make these calculations at a farm or field level, but the critical aspect is interpreting what the values mean and what interventions could be deployed to improve the indicators.

The interpretation of the indicators is not just to focus on a single number as being the "target" as the value estimated should be viewed in the light of several other issues. High or low values for PNB or PFP do not mean the systems being evaluated are inherently efficient or inefficient. Similarly, the magnitude of the deficit or surplus of nutrient (NBI) should be viewed in relation to the productivity of the system – for example a 5 kg N/ha deficit in a low rainfall area with low soil organic matter may be more significant than the same deficit in a high rainfall area with higher soil organic matter.

The absolute value of PNB should be considered with measures of soil nutrient storage such as N, P or K tests. A high PNB – where more nutrients are removed than added may be a reasonable strategy to adopt and this is the case with many of the values estimated for K-PNB from the survey. Soil test K levels are generally high and so removal is usually much greater than additions. Even so, over time soil K levels will be depleted although it is uncertain when interventions will be needed to supplement this supply. Conversely, a low PNB – where more nutrient is removed than is added – does not immediately mean that there is an environmental issue with nutrient pollution. The fate of the nutrient is not described and for immobile nutrients such a P, where soil erosion is negligible, the P is most likely retained in the soil and soil test values will increase.

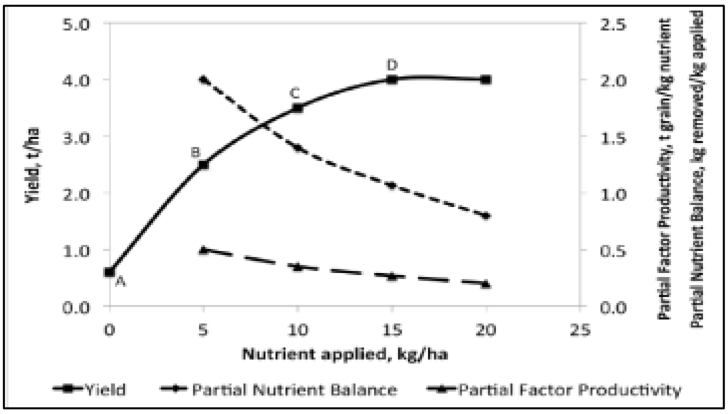

Figure 15. A hypothetical example of crop yield, and the consequent Partial Nutrient Balance and Partial Factor Productivity from the nutrient additions. The nutrient balance illustration is based on a nutrient concentration of 4 kg nutrient per tonne of product.

Because of the nature of the response of crops and pastures to applied/supplied nutrients, a high PFP indicates that the field is highly responsive. Figure 15 shows that adding nutrient results in lower PNB and PFP because the marginal response decreases. If decisions about optimal rates were to be developed using PNB alone, then very low or no nutrients would be applied as the lowest rate has the highest PNB and PFP. The highest efficiency on the yield response curve occurs where yield is lowest, but in reality effectiveness should not be sacrificed for efficiency. For farmers, fertiliser rates are fundamentally an economic decision on marginal costs and marginal returns, moderated by their attitude to risk.

Summary

- 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.
- The data from the 500 fields reported here, N-PNB is generally higher than 1.0, while P-PNB is generally lower than 1.0. The N-PNB is higher than 1 for over half the fields assessed in all regions except the Mallee where 39% were above 1. The P-PNB value reported in this study are lower than the values mentioned in Table 16. 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.

NUTRIENT PERFORMANCE INDICATORS FROM FIELD EXPERIMENTS

Field experiments are often used to present information concerning fertiliser use efficiency, and the most common indicators are Agronomy Efficiency (AE) and Recovery Efficiency (RE) which are the marginal values that can be assessed where there are nil fertiliser treatment to which the fertiliser application treatments can be evaluated (Table 1). This section of the project sought to collect, calculate and compare the four nutrient performance indicators (AE, RE, PNB and PFP) to provide as assessment of the veracity of the farm field data and to assess if additional or different information can be gleaned on performance indicators from these experiments.

Ladha et al. (2005) reported on common nutrient performance indicators are derived from 93 field experiments for maize, wheat and rice grown in different regions of the world. Those authors reported N-AE as 18 kg grain yield increase per kg N, N-RE as 0.57 and N-PFP as 45 kg grain per kg N applied. Values for these indicators were general higher PFP and AE for maize and rice compared to wheat and there were differences among regions. Whether experiments are on farmer's fields or on experimental stations, high yielding cereal systems tend to have higher AE than systems at lower yield levels. This is not surprising as the higher nutrient requirements of crops at higher yield levels is likely to exceed the nutrient supply capacity of low fertility to a greater extent than at lower yield levels.

Methods

Nutrient performance indicators AE, RE, PNB and PFP were calculated for N, P and K using data from a range of field experiments conducted mainly in south-eastern Australia. The experiments investigated fertiliser rate for a single year in wheat crops. The N experimental was data from Incitec Pivot Ltd field experiments between 2001 and 2011, and the P and K experiments drawn from the Better Fertiliser Decisions for Crops database. The data covered 47 N experiments which allowed 3791 entries when replicates are counted as separate entries, 1224 P experiments (means used) and 172 K experiments (means used). The nutrient performance indicators were calculated as per Table 1 and presented as frequency distributions in the Appendix 17 to Appendix 21. Because the N values are for single year experiments, there was no fixed N included in any of the calculations.

Results

Across Australia, the metrics used to estimate N efficiency for wheat varied greatly, with the ranges of agronomic efficiency (N-AE), recovery efficiency (N-RE), partial factor productivity (N-PFP) and partial nutrient balance (N-PNB) being –63 to 47, –1 to 1, 0 to 424, and 0 to 7, respectively (Table 17). The corresponding ranges of phosphorus efficiency were –226 to 430, –1 to 1, 0 to 4298 and 0 to 13, and potassium efficiency were –27 to 105, –0.1 to 0.4, 1 to 429 and 0 to 2 (Table 17). The nutrient performance data calculated from these experiments was generally normally distributed (Appendix 17) unlike the data from the field survey.

Table 17 Values of NUE, PUE and KUE for wheat grown in Australia

	Nitrogen Use Efficiency			
	N-AE	N-RE	N-PFP	N-PNB
Mean	6.7	0.19	77	1.39
SD	9.8	0.17	53	0.91
Range	-63.2 to 46.9	-0.76 to 1.10	0 to 425	0.01 to 6.97
	Phosphorus Use Efficiency			
	P-AE	P-RE	P-PFP	P-PNB
Mean	25.9	0.08	186	0.55
SD	33.1	0.10	197	0.59
Range	-226.0 to 430.0	-0.69 to 1.29	0 to 4298	0.0 to 12.9
	Potassium Use Efficiency			
	K-AE	K-RE	K-PFP	K-PNB
Mean	10.7	0.04	85	0.34
SD	14.2	0.06	67	0.27
Range	-26.9 to 104.6	-0.11 to 0.42	1 to 429	0.0 to 1.7

Because of the way the values are calculated, AE is usually smaller than PFP and RE is smaller than PNB. This is because the marginal increases in yield or nutrient recovery are smaller than the total yield or nutrient recovery. The data in Table 17 can be compared to the field level data collected and reported in Table 15. The PNB values from both methods show N=PNB as 1.76 and 1.39 and P-PNB as 0.55 and 0.64. The PFP values are N-PFP are 77 kg grain/kg N when determined by both methods, and the P-PFP values are 227 and 186 kg grain/kg P. The field experimental values are more variable than the farmer collected data, maybe because a wider range of sites was used for the experiments.

These nutrient performance indicators were then disaggregated based on various agroecological zones (Tables 18-20). All four indicators were generally higher in the New South Wales North West and Queensland South West (NSWNW/QLDSW), the New South Wales and Victoria slopes (NSWVIC Slopes), South Australian Mid-North and the Yorke and Eyre Peninsulas (SAMN/YEP), and the Victorian high rainfall zone (HRZ), than the other regions (Table 18). As expected, the AE values were all lower than the PFP values and the RE values were smaller than the PNB values. The Mallee and the Wimmera were the least responsive regions for N, but the PFP values were similar across all regions. Both metrics reflect background soil fertility but do so in different ways.

When compared to the data from the field surveys presented in Table 15, these experimental values for PNB and PFP are ±10% for the HRZ and the Wimmera, but higher in SNSW when derived from experimental values, but lower in Mallee from the experimental data. The survey PNB and PFP values are multi-year and take account of the added input of BNF and the experimental data set is most likely taken from more N responsive sites, as these are the sites that are generally reported – not sites where there was no response.

Table 18 Nitrogen performance indicators across agroecological zones in New South Wales, Queensland, South Australia and Victoria

Agroecological zone		NSWNE/QLD SE	NSWNW/QLD SW	NSW/VIC Slopes	SAMN/YEP	Wimmera	Mallee	HRZ
N-AE	Mean	7.5	12.9	11.3	8.4	2.9	2.0	7.8
	SD	*7.3*	*2.9*	*7.9*	*9.5*	*7*	*6.9*	*14.4*
	Range	*-5.9-29.3*	*5.0-19.1*	*-14.9-37.8*	*-7.5-46.9*	*-15.0-23.7*	*-37.4-21.5*	*-63.2-45.3*
N-RE	Mean	0.18	0.26	0.22	0.30	0.15	0.12	0.22
	SD	*0.18*	*0.08*	*0.14*	*0.13*	*0.16*	*0.16*	*0.2*
	Range	*-0.16-1.10*	*0.06 -0.43*	*-0.19-0.73*	*0.07-0.79*	*-0.33-0.49*	*-0.37-0.77*	*-0.76-0.70*
N-PFP	Mean	73	97	98	83	61	66	85
	SD	36	30	59	43	44	80	48
	Range	33-299	77to 152	24-303	22-313	0-197	7-425	6-365
PNB	Mean	1.41	1.51	1.77	1.45	1.28	1.15	1.42
	SD	*0.71*	*0.41*	*0.98*	*0.69*	*0.81*	*1.32*	*0.8*
	Range	*0.57-6.97*	*1.20-2.32*	*0.59-4.83*	*0.39-4.43*	*0.01-3.97*	*0.14-6.72*	*0.12-6.39*

For P efficiency metrics (Table 19) AE and PFP were higher in NSW Central and NSW/VIC Slopes than the other regions, whereas RE and PNB were higher in NSW Central, the Wimmera, and SAMN/YEP (Table 19). The single year P PNB values were lower in the experimental data set than the values from the survey by 12 to 50%. The survey data suggested that the Wimmera mean P-PNB was in approximate P balance, while the single year P experimental data suggests that up to half to P supplied was not removed. The difference could reflect the residual effect that carry-over P has from year to year, and this has been noted in long term fertiliser experiments, where P recovery is around 60% or more over the long term and the balance being largely accounted for in increasing soil P test values (Norton et al. 2012).

Table 19 Phosphorus performance indicators across agroecological zones in New South Wales, Queensland, South Australia and Victoria

Agroecological zone		NSW Central	NSWNE/QLD SE	NSWNW/QLD SW	NSW/VIC Slopes	QLD Central	SAMN/YEP	Wimmera	Mallee
AE	Mean	52.4	28.2	22.5	38.8	12	19	17.5	17.3
	SD	*59.3*	*29.3*	*24.7*	*32.4*	*21.4*	*30.9*	*29.6*	*35.2*
	Range	*-13.4-430.0*	*-46.0-206.0*	*-16.7-91.7*	*-54.0-196.7*	*-23.4-88.6*	*-226.0-365.5*	*-80.0-117.3*	*-214.0-414.0*
RE	Mean	0.16	0.08	0.07	0.12	0.04	0.06	0.06	0.05
	SD	*0.18*	*0.09*	*0.07*	*0.12*	*0.09*	*0.1*	*0.09*	*0.1*
	Range	*-0.04-1.29*	*-0.14-0.62*	*-0.05-0.28*	*-0.69-0.88*	*-0.06-0.67*	*-0.68-1.10*	*-0.24-0.35*	*-0.64-1.24*
PFP	Mean	228	216	178	169	135	228	247	171
	SD	*276*	*168*	*136*	*146*	*114*	*246*	*259*	*254*
	Range	*22-2150*	*9-1273*	*13-642*	*14-1180*	*22-540*	*5-2491*	*21-1170*	*6-4298*
PNB	Mean	0.68	0.64	0.55	0.51	0.40	0.68	0.73	0.50
	SD	*0.83*	*0.6*	*0.42*	*0.44*	*0.33*	*0.73*	*0.77*	*0.74*
	Range	*0.07-6.45*	*0.03-3.82*	*0.038-1.93*	*0.04-3.54*	*0.08-1.40*	*0.00-7.47*	*0.06-3.51*	*0.02-12.89*

Table 20 Potassium performance indicators across agroecological zones in New South Wales, South Australia, Victoria and Western Australia

Agroecological zone		NSW VIC Slopes	SAMN/YEP	WA Central/Northern	WA Eastern	WA Mallee/Sandplain
AE	Mean	9.3	39.2	10.2	16.1	9.4
	SD	*19.6*	*28.4*	*12.6*	*20*	*12*
	Range	*-16.0-63.6*	*9.0-104.6*	*-26.9-81.1*	*-2.5-39.2*	*-6.9-53.3*
RE	Mean	0.04	0.16	0.04	0.06	0.04
	SD	*0.08*	*0.11*	*0.05*	*0.08*	*0.05*
	Range	*-0.06-0.25*	*0.04-0.42*	*-0.11-0.32*	*-0.01-0.16*	*-0.03-0.21*
PFP	Mean	54	66	85	77	98
	SD	*50*	*56*	*71*	*29*	*55*
	Range	*13-290*	*12-201*	*1-429*	*50-113*	*17-228*
PNB	Mean	0.21	0.27	0.34	0.31	0.39
	SD	*0.2*	*0.23*	*0.28*	*0.11*	*0.22*
	Range	*0.05-1.16*	*0.05-0.80*	*0.00-1.72*	*0.20-0.45*	*0.07-0.91*

For potassium use efficiency metrics, the highest AE and RE was observed in SAMN/YEP, whilst the highest PFP and PNB in WA Mallee and Sandplain (Table 20) regions that are recognised as being K responsive. There were no data available for Victoria on K responses.

The frequency distribution of these nutrient performance indicators and the relationship between the indicators by region were examined for and those data are summarised in the Appendix 17. In general, the AE and RE for N, P and K use followed a normal distribution. However, similar to the data from the field survey PFP and PNB were skewed to the right for P and K use, and the means were greater than the medians of the population. This skewness is the result of some very high values for PFP and PNB.

Discussion

The reason for undertaking this part of the study was to estimate efficiency indicators using experimental data and to the see if the use of marginal estimates of nutrient performance (AE and RE) convey more information to the user. The calculation of AE and RE requires zero-fertiliser strips, plots or treatments, and therefore may not be practical for farmers but these check plots do help explain the background nutrient supply against which a response to the applied nutrient can be assessed. Because of this, the difference between the experimentally derived values for PFP and PNB are expected to be different from the survey PFP and PNB, as the former group generally do not include nil response sites, and the latter group has been derived from data collected over 4 or 5 years rather than one.

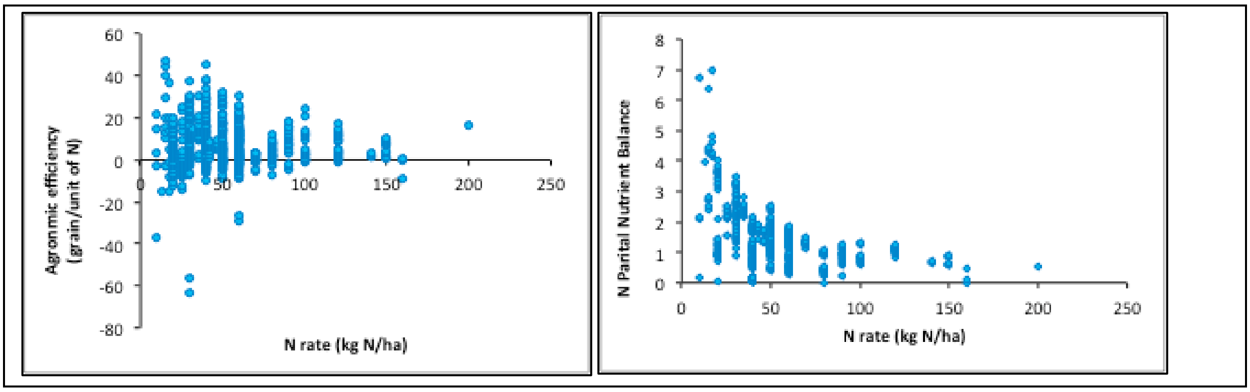

Figure 16. The distribution of the responses of a) agronomic efficiency and b) partial nutrient balance to N fertiliser rates.

Summary

- Irrespective of the source of the data the PNB is a reliable indicator of whether a particular nutrient is being mined.
- 67% of N-PNB measures were > 1, meaning 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 (Figure 16) 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.
- The lower the nutrient input, the larger the variation in the performance indicator and the efficiency metrics are highly variable even at the same rate.

EFFECTS OF MANAGEMENT PRACTICES ON N PERFORMANCE INDICATORS: A META-ANALYSIS

There are numerous studies investigating how to improve fertiliser N use efficiency in major wheat growing regions in south-eastern Australia. These results of the studies can be interrogated for the effects of best management guiding principles on the performance indicators AE, RE, PNB and PFP. The findings of individual studies can be inconclusive due to the complex interactions among climatic conditions, soil properties, and fertiliser management practice, so in this section, a more robust assessment of previous research on N performance measures on management practice is presented. The objective here is to assess the capacity of these indicators to assess performance against the "4R" nutrient stewardship principles and compare the information provided by each indicator. The 4R approach is simple and universally applicable, and addressed applying the Right nutrient source, at the Right rate, provided at the Right time and presented in the Right place to meet crop demand.

Methods

A meta-analytic technique was used to quantitatively synthesise the data available. A meta-analysis combines results from different studies to identify patterns among study results. It is a useful tool in this case because (i) it has the potential to overcome some of the limitations of low statistical power in individual experiments; and (ii) it has the advantage of testing whether responses are general across experiments.

The database was compiled from published and unpublished results from field experiments conducted by Incitec Pivot Fertilisers and its research partners on both experimental farms and on growers' fields. The experiments were conducted under rainfed conditions between 2001 and 2011 in the major wheat-producing areas in Victoria, New South Wales and South Australia with three or four replications. All experiments included in the database had a zero-N plot with N rate in the treatment plots ranging from 10 to 160 kg N ha^{-1}. These experiments were designed to investigate a single or combination of the effects of N management practices on wheat growth and N uptake. These practices include the 4R aspects of nutrient stewardship. From the dataset on wheat yield and N uptake, the four N use efficiency indicators were calculated, *viz*. agronomic efficiency (AE), recovery efficiency (RE), partial factor productivity (PFP) and partial nutrient balance (PNB).

In the meta-analysis, we treated urea (the most commonly used N fertiliser source) as a control and the other fertilisers as treatments. Enhanced efficiency fertilisers were classified into fertilisers added with urease inhibitor or with nitrification inhibitor. For fertiliser application rate (kg N ha^{-1}), we calculated the factor of application rate relative to the lowest N rate (x), and was grouped into $1 < x \leq 2$, $3 < x \leq 4$, and $x > 5$. The rates used in the various experiments differed due to yield potential, so that lower yielding sites had lower base N rates (20 kg N/ha) while higher yielding locations has base rates of 40-40 kg N/ha. Location of fertiliser application included banding of fertilisers relative to surface application (control). Fertiliser application time was categorised by wheat growth stage (DC0 as control vs. DC15 (early), DC31-41 (middle) or DC51-61 (late)). A total of 800 observations were included in the meta-analysis, with 231 observations for fertiliser source, 136 for urease inhibitor and 137 for nitrification inhibitor, 155 for N application rate, 34 for deep placement and 107 for growth stage.

The response ratio ($r=\bar{x}^T/\bar{x}^C$) is the ratio of treatment group to the control group and it can be used to estimate the effect as a proportionate change due to experimental manipulation (Rosenberg et al. 2000). For each of the four NUE indicators, we used the natural log transformed response ratio as a metric for analyses (Hedges et al. 1999):

$$In\, r = In\left(\frac{\bar{x}^T}{\bar{x}^C}\right)$$

where $\bar{x}^T$ is the mean of the treatment group, and $\bar{x}^C$ the mean of the control group. Results are reported as the percentage change of the indicators under treatment effects ((r–1) × 100). Negative percentage changes mean the treatment decreased NUE when compared to control whereas positive changes indicate an increase in NUE due to treatment. In our analysis, the following weighting function was used for the effect size:

$$\text{Weight} = (n_C \times n_T)/(n_C + n_T)$$

where n_C and n_T are the number of replicates of the control and treatment respectively (van Groenigen et al. 2013). For meta-analyses that included multiple non-independent observations, we divided the weighting by the number of multiple observations to reduce bias that may occur otherwise.

The meta-analysis was conducted using MetaWin version 2.1 (Rosenberg et al. 2000). Mean effect sizes and 95% confidence intervals were generated by bootstrapping (4,999 iterations) (Rosenberg et al. 2000). A fixed-effects model or a mixed-effects model is technically not applicable for non-parametric meta-analytic procedures based on weighting by replication. However, to perform a correct bootstrapping using MetaWin, a fixed-effects model had to be selected. The effects of the mitigation strategies were considered significant if the 95% CI did not overlap with zero.

Negative values were observed for AE and RE for some studies because the yield or N uptake of the treatment was lower than that of the control. These negative values resulted in invalid or misleading results when the metric of the response ratio was used, and were excluded from the meta-analysis.

Results

Consistently, the ranges of the responses of AE and RE to improved management practices (4Rs and enhanced efficiency fertilisers) were much greater than those of PFP and PNB (Figs. 1-6). This is because the agronomy parameters yield and N uptake of the zero-N plots were incorporated into the calculations for AE and RE, respectively, but not for PFP or PNB. In other words, the smaller the difference in these agronomy parameters between the zero-N plots and the experimental plots, the larger the gap between the responses of AE and PFP, and those between RE and PNB.

Another point worth noticing in evaluating the practicality of nutrient performance indicators is that while AE and RE generally require a zero-N plot, negative values occur when the yield or N uptake of a treatment plot was lower than that of the zero-N plot. In this case, it is not meaningful and could be misleading to examine the response ratio.

The effect of nutrient source

Overall, compared to urea, the use of other fertilisers did not significantly affect any of the NUE indicators (Figure 17a). Nonetheless, NUE tended to decrease when fertilisers other than urea were used, especially under high N input conditions. The urease inhibitor and nitrification inhibitor tended to increase both AE and RE (by 5-19% and 3-8%, respectively), although the effect was not significant (Figures 17b and 17c). The effects of these inhibitors on PFP and PFP were minimal. While urease and nitrification inhibitors show promise in decreasing NH_3 and N_2O emission in Australia and other parts of the world, their average effect on yield is not consistent. This is largely because the processed affected by the inhibitor – ammonia volatilization or nitrate leaching – are not always present, so that loss pathway is not addressed.

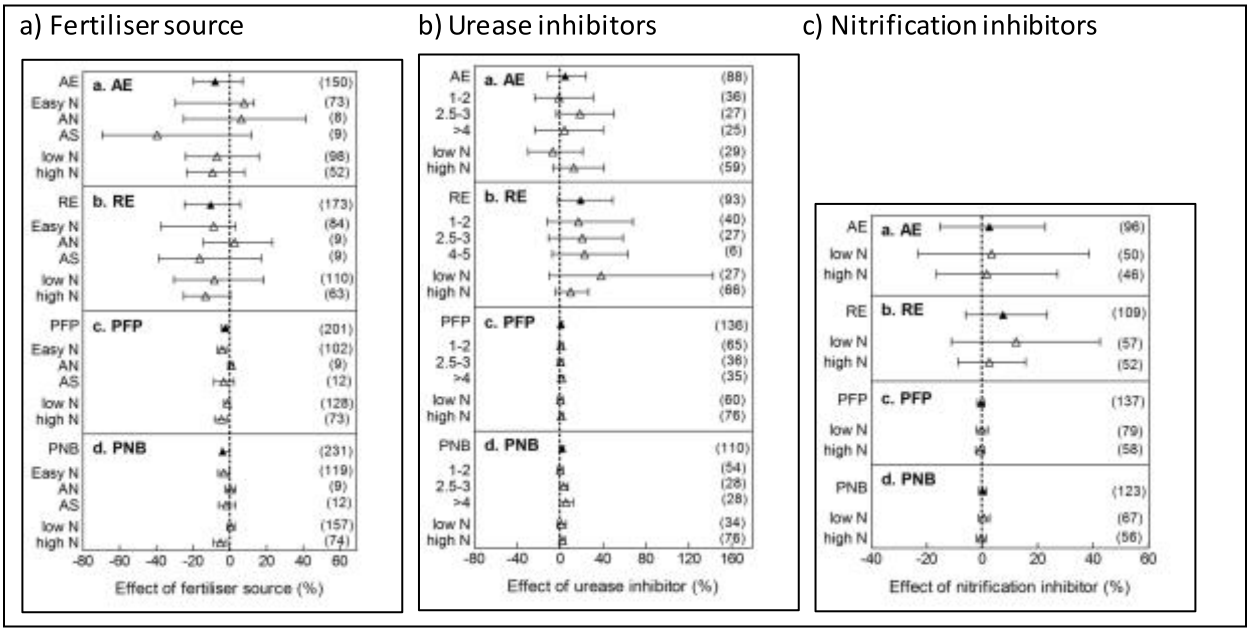

Figure 17 Effect of a) fertiliser source, b) urease inhibitors and c) nitrification inhibitors on N performance indicators. Means and 95% confidence intervals are depicted. Numbers of experimental observations are in parentheses. For a) the individual responses for fertilisers other than the commonly used ones (Easy N, ammonium sulphate (AS) and ammonium nitrate (AN)) were not listed but their responses were included in the overall effect size. For b) The application rates of the urease inhibitor were categorised into 1-2 L, 2.5-3 L and >4 L High N: N rate >50 kg N ha^{-1}; Low N: N rate ≤ 50 kg N ha^{-1}.

Response to nutrient rate

As would be expected from the way the indicators are calculated, higher rates of N resulted in lower N indicators. This is a consequence of the diminishing response functions seen in these types of production functions, where the marginal increase due to the addition of a unit of input reduces for each additional unit of input. Increased N application rate decreased all performance indicators by 20-55% (Fig. 4) and the higher the N rate compared to control, the greater the reduction in the indicators. The size of the differences due to rates is smaller between the marginal indicators (AE and RE) and the absolute indicators (PFP and PNB). Despite these differences the patterns seen among the indicators are similar, although the variability in the marginal indicators is larger than for the absolute indicators.

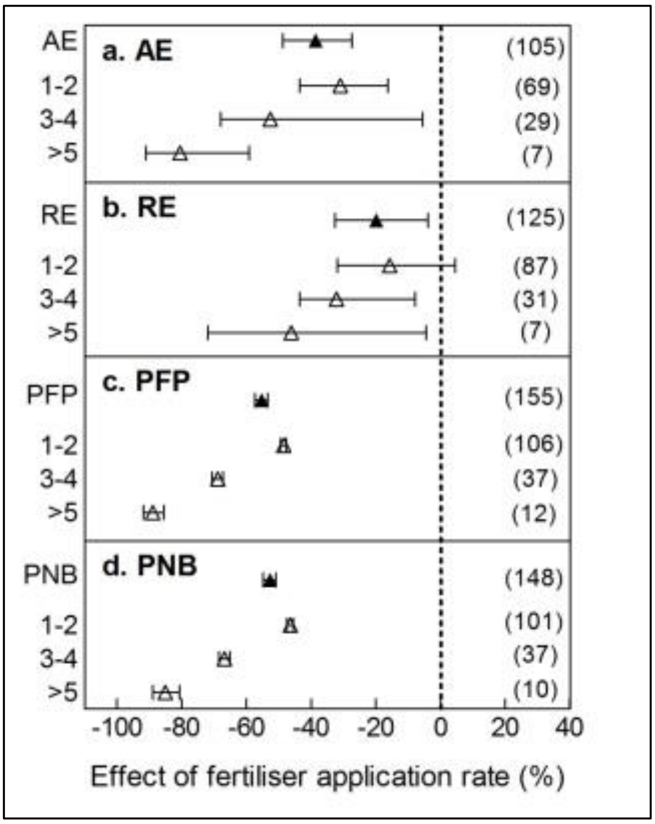

Figure 18 Effect of fertiliser application rate on NUE indicators. Means and 95% confidence intervals are depicted. Numbers of experimental observations are in parentheses. The application rates were categorised according to the factor of application rate relative to the lowest N rate (x), and was grouped into $1 < x \leq 2$, $3 < x \leq 4$, and $x > 5$.

Response to nutrient timing and placement

All the nutrient performance indicators were reduced by 5-32% when fertiliser N was applied at a later growth stage than at sowing (Figure 19a). This decrease was in RE was larger when N application was delayed between DC31 (middle) and DC41 (late) compared to when it was supplied at nearer to seeding (early). Fertiliser N application at DC15, DC51 or DC61 did not affect any of the performance indicators. The amount of N input did not interact with the time of fertilisation (Figure 19a). PNB and PFP were far less discriminating than AE or RE in detecting responses to the timing of N application.

Regardless of N input, no significant effects of banding on of the performance indicators were observed although the range of responses was large (Figure 19b). While it is expected that banding of fertilisers would decrease ammonia volatilisation through slower ammonification from the concentrated band, the N saved does not always translate into improvement in N uptake, growth or yield. None of the four indicators were responsive to N placement.

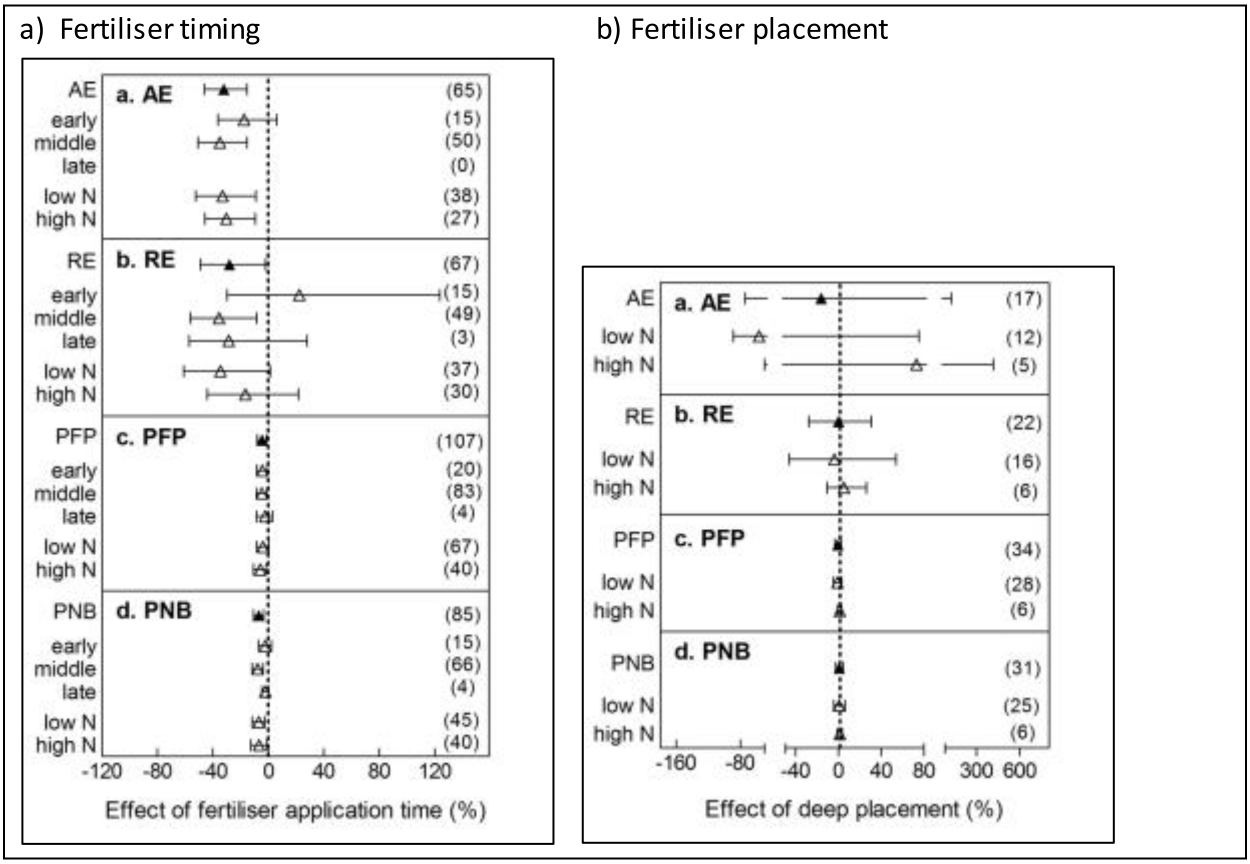

Figure 19 Effect of fertiliser a) application time and b) placement on N performance indicators. Means and 95% confidence intervals are depicted. Numbers of experimental observations are in parentheses. Early: growth stage DC15; middle: growth stage DC31-41; and late: growth stage DC51-61. High N: N rate >50 kg N ha^{-1}; Low N: N rate $\leq$ 50 kg N ha^{-1}.

Summary

- 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 such as in Figure 10, with the position the growers data occupies highlighted. Expanded discussions on values as outlined in Table 12, 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 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 selection, 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 needs to given to 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.

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The Grains Research and Development Corporation supported this project financially. Ms Elaina vanderMark spent countless hours collecting the information presented in the farm level performance indicators and her enthusiasm, persistence and professionalism is acknowledged. The data on national nutrient performance indicators was partially undertaken by Dr Robert Edis, with funding support from IPNI. Dr Shu-kee Lam developed the protocol to estimate biological nitrogen fixation and also undertook the estimation and analysis of nutrient performance indicators from research data, some derived from Incitec Pivot, and from the Better Fertiliser Decisions for Crops database. During the project, Ms vanderMark was employed through Southern Farming Systems, and Dr Lam through The University of Melbourne and I would thank their supervisors Mr Jon Midwood and Professor Deli Chen for their support of this project.

Finally, the collection of the data to estimate field level nutrient performance indicators was only possible because of the co-operation of the farmers and consultants who supplied that information and their contribution is duly acknowledged and greatly appreciated.

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APPENDICES

Appendix 1. Cereal area and mean cereal yield, mean nitrogen application rate, and the performance indicators of Partial Nutrient Balance (kg nutrient removed/kg nutrient applied) and Partial Factor Productivity (t yield/kg nutrient applied). The Partial Nutrient Balance is based on a weighted cereal grain N content of 1.58% (*as is basis*).

	Cereal Area (Mha)	Cereal Production (Mt)	Mean cereal yield t/ha	Mean N rate kg/ha	N PNB kg grain N /kg N fert	N PFP kg grain /kg N fert	Mean P rate kg/ha	P PNB kg grain P /kg P fert	P PFP kg grain /kg P fert	Mean K rate kg/ha	K PNB kg grain K /kg K fert	K PFP kg grain /kg K fert
Argentina	9.24	40.68	4.37	57	1.21	77	4.1	1.12	328	0.4	78.94	14619
Australia	18.37	26.45	1.39	27	1.02	52	11.9	0.44	128	1.8	3.91	724
Bangladesh	11.18	46.95	4.02	93	0.57	44	2.5	1.36	399	10.4	2.03	376
Brazil	18.42	67.16	3.63	54	0.88	67	6.9	0.58	171	36.2	0.55	101
Canada	15.95	47.11	3.26	74	0.89	45	2.7	1.14	335	6.8	2.08	386
Chile	0.59	3.58	6.41	179	0.63	36	5.8	0.61	179	26.2	1.26	233
China	83.14	473.94	5.48	172	0.47	32	3.8	0.82	242	20.3	1.54	286
Egypt	2.99	20.98	7.01	252	0.45	28	1.7	2.33	685	4.9	7.79	1442
EU27	58.04	277.82	4.85	104	0.90	47	2.4	1.54	454	19.4	1.38	256
India	99.24	255.31	2.56	95	0.43	28	5.2	0.56	165	8.8	1.23	227
Indonesia	15.13	75.43	4.62	99	0.59	46	1.2	2.96	870	10.4	2.28	422
Iran	8.70	22.33	2.47	66	0.71	38	5.3	0.78	228	7.0	8.22	1523
Malaysia	0.67	2.39	3.52	123	0.37	29	8.7	0.38	113	62.4	0.29	53
Mexico	10.01	33.54	3.36	79	0.62	42	1.6	2.05	603	2.0	7.53	1394
Morocco	5.59	8.54	1.60	22	1.52	74	3.7	0.97	285	1.9	3.81	706
Pakistan	12.93	33.92	2.58	124	0.38	21	6.7	0.56	164	1.6	10.26	1900
Philippines	6.73	21.78	3.21	45	0.90	71	0.9	3.22	948	2.1	6.50	1203
Russia	40.54	68.06	1.87	25	1.78	84	1.6	1.76	518	3.0	3.05	565
South Africa	2.99	12.07	3.65	77	0.66	48	5.0	0.93	272	8.0	4.05	750
Thailand	11.32	37.27	3.00	43	0.90	73	1.4	2.69	792	3.8	5.16	955
Turkey	13.04	33.70	2.68	68	0.81	39	4.6	0.76	223	1.5	8.25	1527
USA	52.86	370.00	6.69	144	0.64	47	3.5	0.89	262	40.9	0.96	178
Vietnam	8.36	42.16	4.96	106	0.60	47	5.3	0.69	204	29.0	0.98	182
World	679.1	2355	3.43	81	0.68	43	3.5	0.96	281	12.2	1.50	278

Appendix 2. Cereal production PNB-N by country. Data were derived from FAOSTAT (Crop production and area sown), IFA (Fertilizer use by crop) and IPNI (Crop product nutrient concentrations). Neither biological N fixation nor manure applications are considered in this example and crop removal is estimated using mean values rather than regionally relevant data.

Country	Wheat	Maize	Rice	Other Cereals	All Cereals	Soybean	Palm	Other Oilseeds	Sugar
Argentina	1.28	0.99	2.26	1.67	1.21	1.20	-	3.23	2.17
Australia	1.10	1.06	2.60	0.86	1.02	-	-	0.63	0.93
Bangladesh	1.27	1.06	0.56	-	0.57	-	-	1.01	0.89
Brazil	0.99	0.85	0.97	0.87	0.88	1.20	0.55	1.02	1.83
Canada	0.86	0.70	-	1.05	0.89	1.18	-	0.94	-
Chile	0.63	0.51	0.83	0.81	0.63	-	-	1.08	-
China	0.54	0.40	0.47	0.66	0.47	0.80	0.32	0.41	0.38
Egypt	0.59	0.26	0.53	0.64	0.45	0.74	-	0.19	0.44
EU27	0.96	0.53	0.86	1.09	0.90	1.13	-	0.95	-
India	0.46	0.36	0.40	0.50	0.43	0.90	-	0.49	0.64
Indonesia	-	0.43	0.65	-	0.59	0.94	0.86	-	1.07
Iran	0.78	0.46	0.48	0.79	0.71	1.05	-	0.43	0.26
Malaysia	-	0.38	0.37	-	0.37	-	0.69	11.68	1.07
Mexico	1.22	0.39	0.60	5.12	0.62	-	0.08	0.94	1.29
Morocco	1.78	0.53	0.55	1.30	1.52	-	-	0.33	0.13
Pakistan	0.40	0.30	0.34	0.53	0.38	-	-	1.26	0.39
Philippines	-	0.75	0.97	-	0.90	-	0.46	0.05	2.08
Russia	1.63	0.46	0.71	2.79	1.78	1.08	-	4.87	-
South Africa	1.46	0.54	-	1.70	0.66	1.20	-	1.25	0.79
Thailand	-	0.64	0.94	0.88	0.90	1.12	0.71	0.26	1.20
Turkey	0.73	0.46	0.84	1.30	0.81	0.93	-	0.55	-
USA	0.73	0.61	0.55	0.77	0.64	1.22	-	0.60	0.43
Vietnam	-	0.36	0.65	-	0.60	0.74	-	0.05	0.62
World	0.77	0.55	0.56	1.26	0.68	1.15	0.81	0.73	0.89

Appendix 3. N applied and removed by specific types of farming business in Australia, 2007/8 and 2009/10.

Type of Business	Area of holding 2007/8 (kha)	Nin 2007/8 (kt)	Nout 2007/8 (kt)	N-PNB 2007/8	Area of holding 2009/10 (kha)	Nin 2009/10 (kt)	Nout 2009/10 (kt)	N-PNB 2009/10
Vegetable Growing (outdoors)	570	12.6	8.3	0.65	938	16.4	9.4	0.58
Grape Growing	1,345	6.0	3.7	0.62	509	6.1	3.7	0.62
Apple and Pear Growing	91	0.7	0.6	0.89	438	1.2	0.3	0.22
Stone Fruit Growing	103	0.5	0.3	0.65	18	0.2	0.1	0.31
Citrus Fruit Growing	171	1.6	0.7	0.43	87	2.5	0.8	0.31
Sheep Farming Specialised	43,192	22.6	33.2	1.47	39,450	10.8	16.8	1.56
Beef Cattle Farming (specialised)	270,592	31.5	104.7	3.32	250,534	31.8	92.5	2.91
Sheep-Beef Cattle Farming	31,109	7.7	20.7	2.70	28,206	6.7	16.9	2.52
Grain-Sheep or Grain-Beef Cattle Farming	21,610	107	175	1.64	22,054	132	220	1.66
Rice Growing	128	1.1	0.9	0.83	294	3.4	3.5	1.04
Other Grain Growing	26,876	335	474	1.42	28,568	386	704	1.82
Sugar Cane Growing	697	24.7	26.8	1.08	727	31.1	26.3	0.84
Dairy Cattle Farming	2,432	62.1	62.2	1.00	2,786	80.6	58.9	0.73
Cotton Growing	651	24.2	12.4	0.51	980	38.5	21.0	0.54

Appendix 4. N applied and removed by specific types of grain related farming business in Australia, 2007/8 and 2009/10.

Business types	Area of holding 2008 (kha)	N-PNB 2008	N-NBI kg/ha 2008	Area of holding 2010 k(ha)	N-PNB 2010	N-NBI kg/ha 2010
Grain-Sheep or Grain-Beef Cattle Farming and area of holding >= 1000 ha	16,689	1.6	-2.7	15,182	1.9	-4.3
Grain-Sheep or Grain-Beef Cattle Farming and area of holding < 1000 ha	4,921	1.7	-4.7	6,872	1.4	-3.2
Other Grain Growing and > 50% of farm used for wheat and area of holding >= 1000 ha	13,850	1.5	-4.3	15,067	2.0	-10.3
Other Grain Growing and > 50% of farm used for wheat and area of holding < 1000 ha	2,780	1.5	-6.2	4,035	1.7	-9.8
Other Grain Growing and > 50% of farm used for canola and area of holding >= 1000 ha	84	0.8	6.0	180	1.5	-10.3
Other Grain Growing and > 50% of farm used for canola and area of holding < 1000 ha	4	1.0	1.5	46	1.3	-7.8

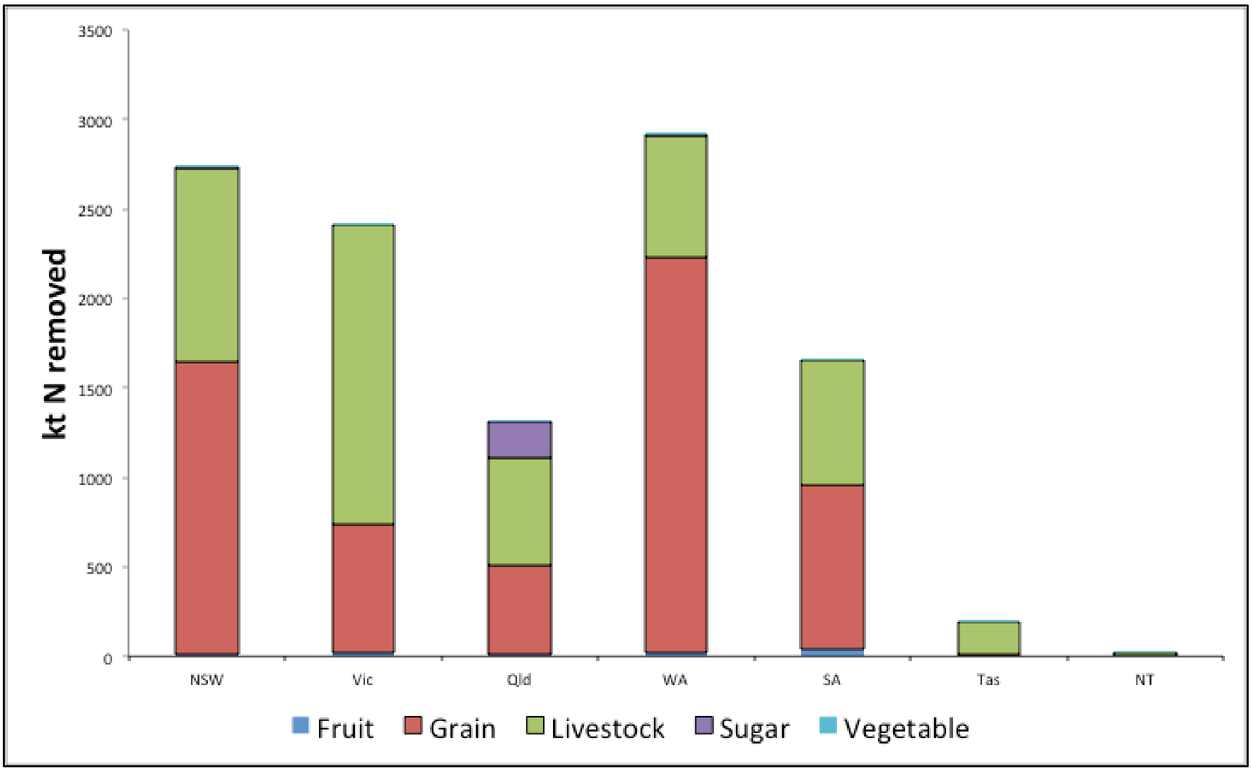
Appendix 5. P applied and removed by specific types of business in Australia, 2007/8 and 2009/10.

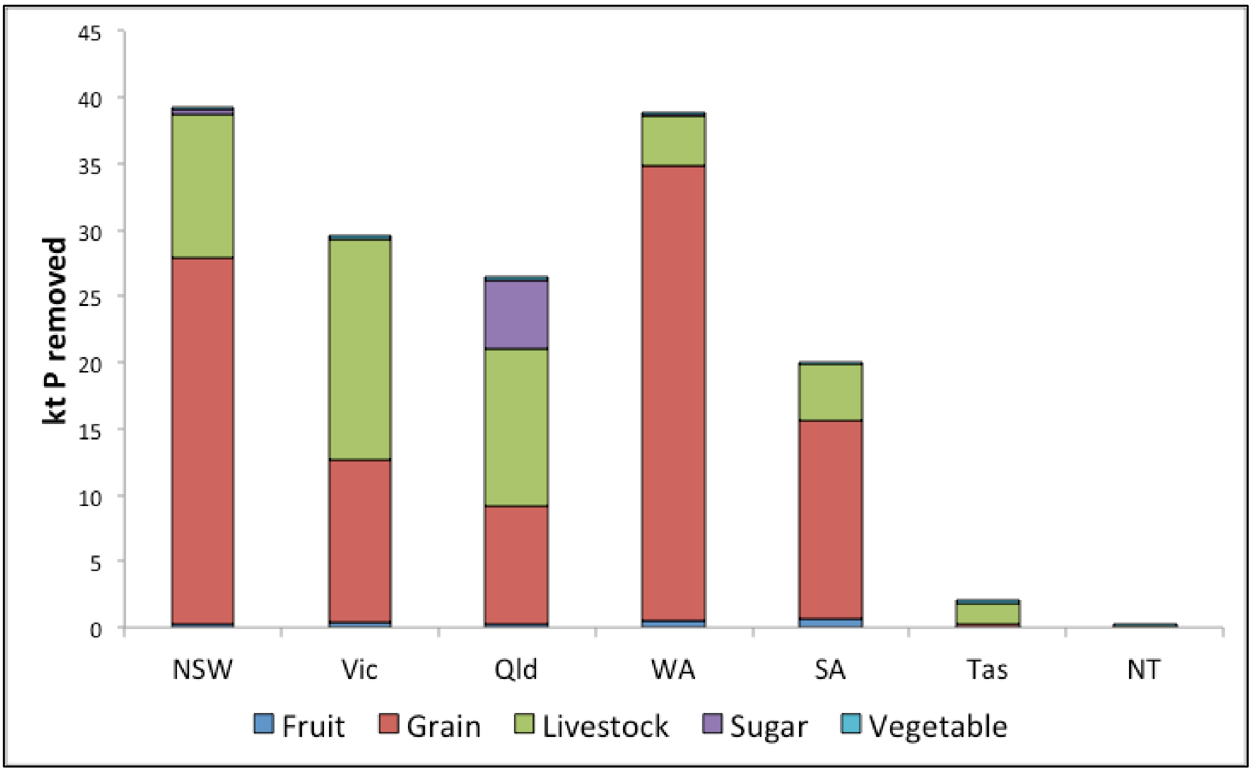
Type of Business	Area of holding 2008 (kha)	Pin 2008 (t)	Pout 2008 (t)	P-PNB	Area of holding 2010 (kha)	Pin 2010 (t)	Pout 2010 (t)	P-PNB
Vegetable Growing (outdoors)	570	5,237	1,325	0.25	938	6,615	1,471	0.22
Grape Growing	1,345	2,066	691	0.33	509	2,213	636	0.29
Apple and Pear Growing	91	457	94	0.21	438	177	55	0.31
Stone Fruit Growing	103	221	56	0.26	18	21	12	0.57
Citrus Fruit Growing	171	379	104	0.27	87	323	111	0.34
Sheep Farming Specialised	43,192	23,623	5716	0.24	39,450	18,058	3,098	0.17
Beef Cattle Farming specialised	270,592	31,931	26408	0.83	250,534	25,156	24,055	0.96
Sheep-Beef Cattle Farming	31,109	14,505	4598	0.32	28,206	13,893	3,791	0.27
Grain-Sheep or Grain-Beef Cattle Farming	21,610	66,959	22257	0.33	22,054	77,140	26,521	0.34
Rice Growing	128	375	130	0.35	294	940	569	0.61
Other Grain Growing	26,876	133,863	53810	0.40	28,568	145,536	75,385	0.52
Sugar Cane Growing	697	1,663	4565	2.74	727	1,591	4,474	2.81
Cotton Growing	2,432	3,354	1573	0.47	2,786	2,295	2,510	1.09
Dairy Cattle Farming	651	17,671	11,117	0.63	980	20,625	10,407	0.50

Appendix 6. P balance of selected types of business and selected sizes and principal commodities.

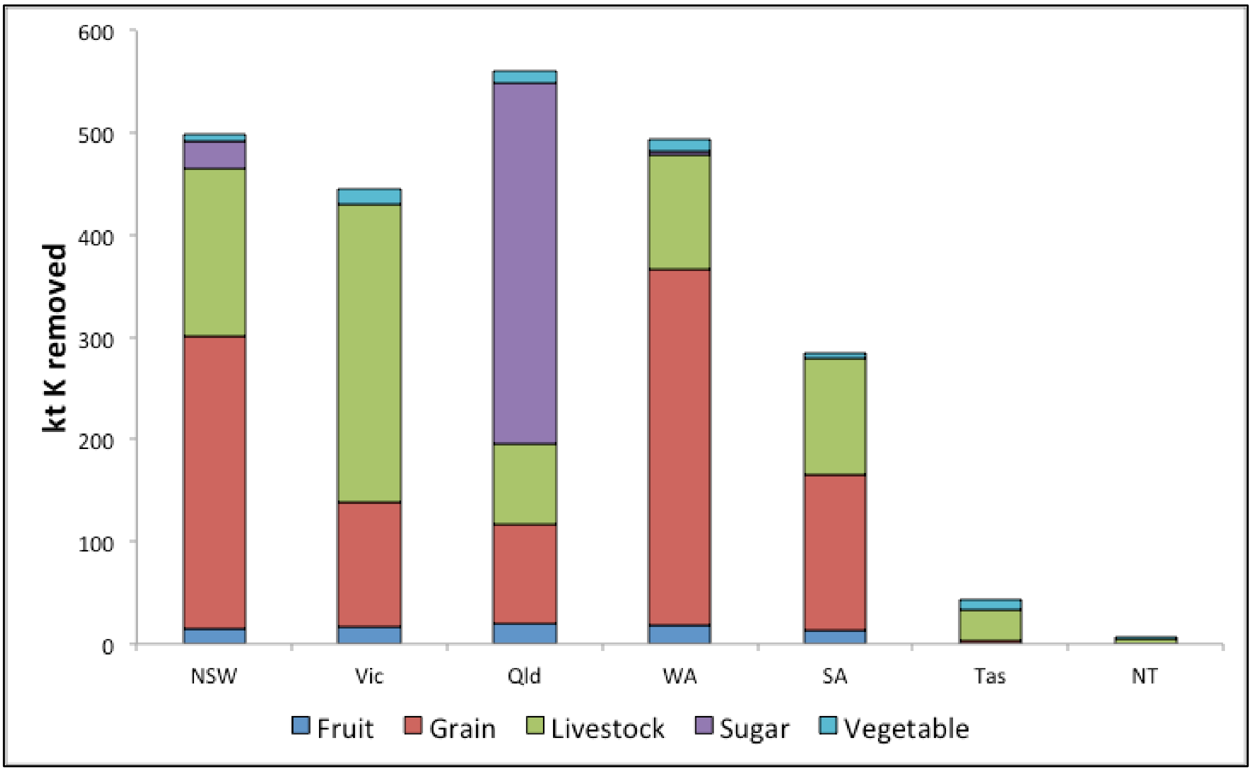
Business types	Area of holding 2008 (kha)	P-PNB 2008	P-NBI kg/ha 2008	Area of holding 2010 (kha)	Pout/Pin 2010	P balance kg/ha 2010
Grain-Sheep or Grain-Beef Cattle Farming and area of holding >= 1000 ha	16,689	0.34	1.75	15,182	0.37	1.79
Grain-Sheep or Grain-Beef Cattle Farming and area of holding < 1000 ha	4,921	0.33	3.14	6,872	0.30	3.41
Other Grain Growing and > 50% of farm used for wheat and area of holding >= 1000 ha	13,850	0.33	2.71	15,067	0.48	2.29
Other Grain Growing and > 50% of farm used for wheat and area of holding < 1000 ha	2,780	0.32	4.03	4,035	0.50	2.49
Other Grain Growing and > 50% of farm used for canola and area of holding >= 1000 ha	84	0.35	6.78	180	0.48	4.75
Other Grain Growing and > 50% of farm used for canola and area of holding < 1000 ha	4	0.46	6.24	46	0.56	3.99

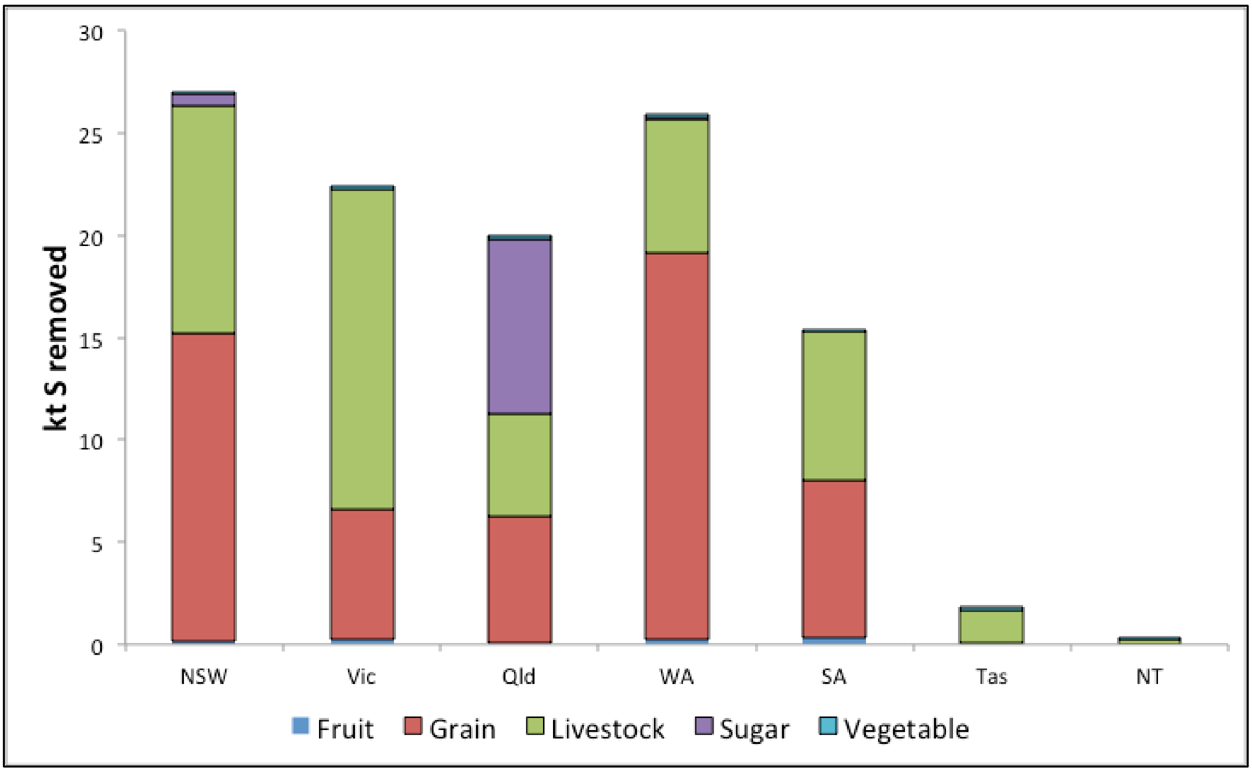
Appendix 6. Nutrient removal by industry and state for Nitrogen (top) and Phosphorus (bottom).





Appendix 7. Nutrient removal by industry and state for Potassium (top) and Sulfur (bottom).



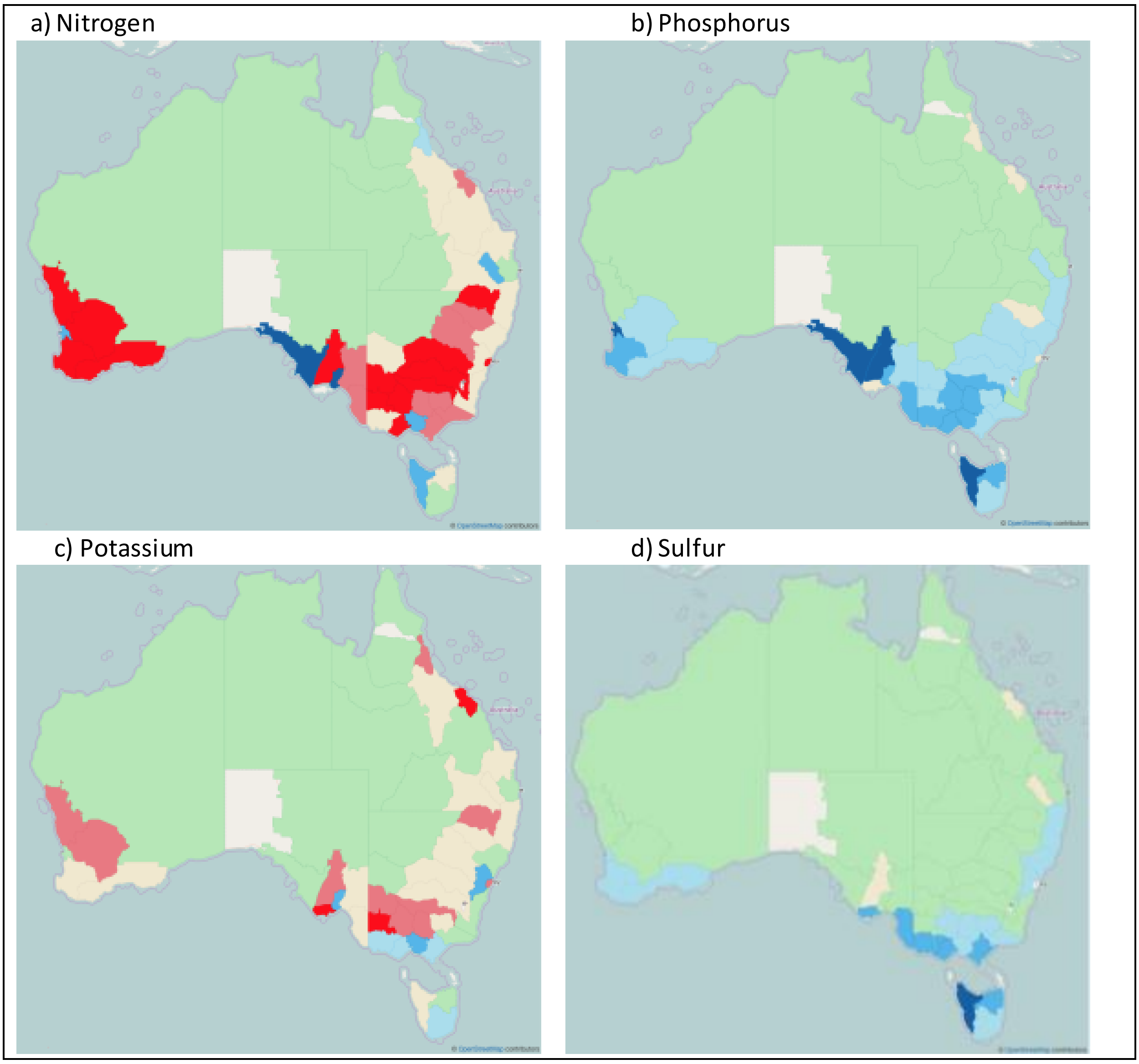


Appendix 8. N, P, K and S partial nutrient balances for each Natural Resource Management region for the period 2007-08 and 2009-10.

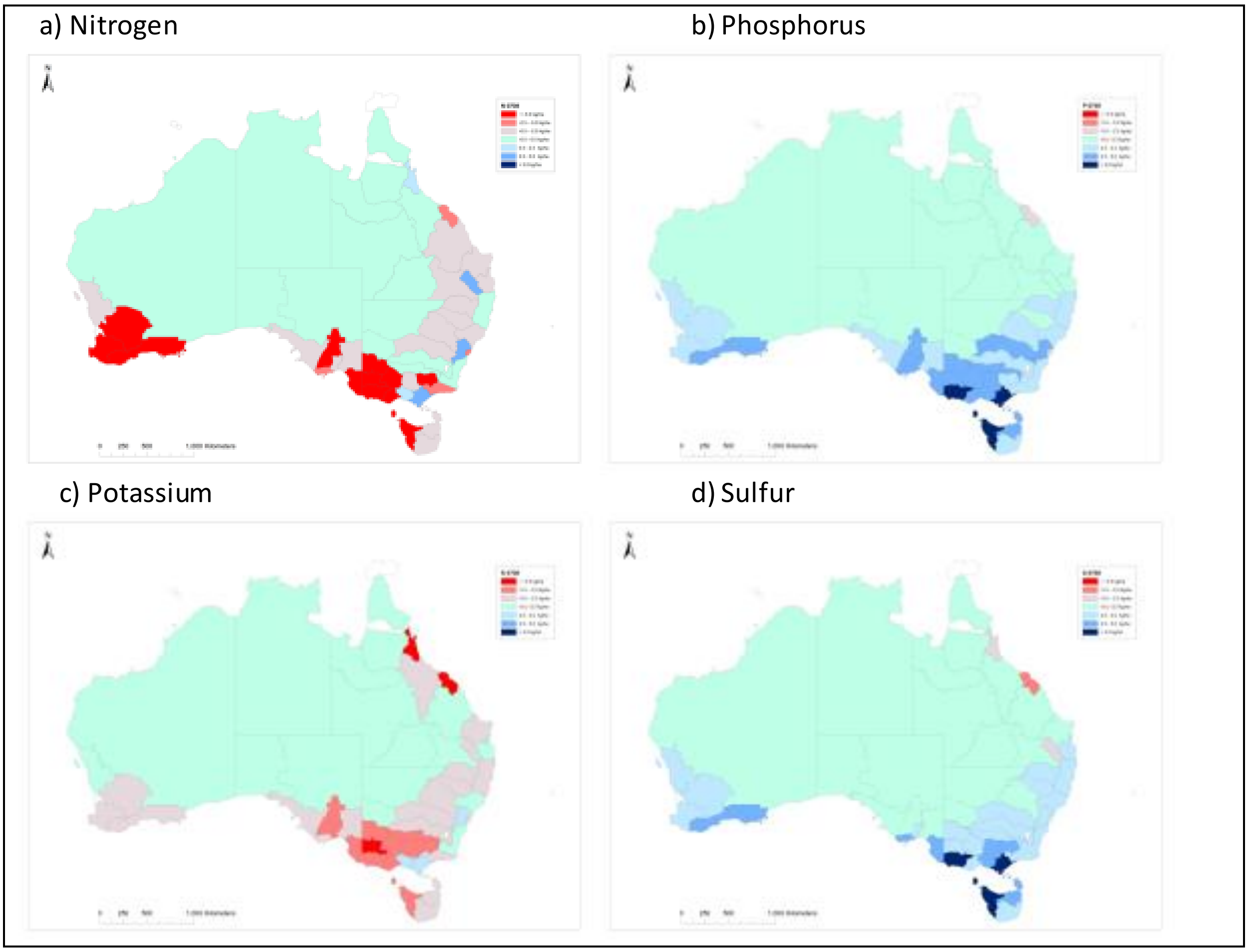
Regional NRM PNB (2008-2010)		N PNB		P PNB		K PNB		S PNB	
		Mixed	Grains	Mixed	Grains	Mixed	Grains	Mixed	Grains
NSW	Border Rivers Gwydir	0.49	1.81	4.64	9.68	18.33	-	1.34	6.34
NSW	Central West	3.84	1.77	1.12	2.49	68.71	-	0.65	1.33
NSW	Hawkesbury Nepean	0.87	-	2.35	-	-	0.30	-	0.08
NSW	Hunter Central Rivers	4.87	-	2.45	-	-	-	-	0.14
NSW	Lachlan	1.34	1.22	0.52	0.79	-	2.71	0.65	0.59
NSW	Lower Murray Darling	8.23	7.44	3.38	4.51	-	-	0.92	17.35
NSW	Murray	0.80	1.15	0.70	0.96	16.99	19.16	0.48	0.68
NSW	Namoi	0.62	1.58	3.28	19.64	9.80	2.54	0.64	0.98
VIC	Corangamite	1.59	1.92	1.40	4.95	7.31	2.18	1.44	1.13
VIC	Glenelg Hopkins	2.51	0.84	1.19	2.48	16.90	17.82	1.34	0.57
VIC	Goulburn Broken	1.55	1.11	0.73	1.34	-	-	0.44	1.12
VIC	Mallee	0.21	3.57	1.44	2.16	46.02	-	0.10	1.31
VIC	North Central	1.56	1.57	1.09	1.77	45.46	2.54	0.92	0.91
VIC	North East (VIC)	4.30	4.52	1.98	7.20	-	-	5.97	1.63
VIC	Port Phillip and Westernport	16.09	2.03	2.46	-	-	-	15.87	0.21
VIC	West Gippsland	-	20.65	-	-	-	-	-	-
VIC	Wimmera	1.67	4.46	1.44	4.69	-	-	0.28	3.46
QLD	Burdekin	53.76	15.02	-	70.84	-	-	65.69	-
QLD	Burnett Mary	2.35	2.79	2.72	8.32	1.13	2.85	1.40	3.14
QLD	Condamine	0.23	1.51	10.09	13.11	2.18	5.48	0.99	10.43
QLD	Fitzroy	3.43	4.10	30.65	79.01	69.64	7.01	10.19	11.54
QLD	South East (QLD)	1.69	-	19.60	-	-	6.30	-	5.48
SA	Eyre Peninsula	0.48	2.73	1.11	1.95	-	-	0.26	2.29
SA	Kangaroo Island	0.77	8.95	0.83	1.60	-	-	0.82	4.74
SA	Adelaide and Mount Lofty Ranges	0.39	2.31	-	3.84	6.18	-	0.31	4.42
SA	Northern and Yorke	0.71	3.04	1.62	2.62	43.49	-	0.42	1.15
SA	SA Murray Darling Basin	1.99	2.46	1.09	2.23	15.08	16.94	0.64	0.70
SA	South East	2.95	1.99	0.94	3.87	12.98	18.99	0.46	0.86

	(SA)								
WA	Avon	0.43	2.63	3.17	5.39	29.78	2.22	0.24	1.16
WA	Northern Agricultural	0.32	1.87	1.93	2.45	1.69	3.55	0.20	1.19
WA	South Coast	0.59	1.76	0.97	4.89	2.90	0.85	0.14	0.81
WA	South West	1.97	1.11	2.76	6.62	2.52	2.28	0.40	0.43
WA	Swan	0.87	14.79	3.30	6.85	5.46	3.72	9.16	1.00
TAS	North (TAS)	1.16	-	0.92	-	-	1.75	0.18	0.13
TAS	South (TAS)	6.80	-	1.32	-	-	-	-	0.07
Australia		**0.80**	**2.03**	**1.40**	**3.39**	**5.53**	**3.07**	**0.37**	**1.11**

Appendix 9. 2011-2012 nutrient balance intensity for N (a), P (b). K (c) and S (d) across different natural resource management regions across Australia. In general, the red regions indicate where nutrient removal is more than nutrient supply, and the scales are provided on the individual graphics.



Appendix 10 2007-2008 nutrient balance intensity for N (a), P (b). K (c) and S (d) across different natural resource management regions across Australia. In general, the red regions indicate where nutrient removal is more than nutrient supply, and the scales are provided on the individual graphics.



Appendix 11. Produce nutrient concentrations, as used the Australian Agricultural Assessment 2001 (Reuter, pers. comm). All values are in kg/t of material at the moisture content stated.

Species	Grain Moisture (%)	N	P	K	S	Ca	Mg
CEREALS							
Barley	11	*	2.7	4.3	1.2	0.37	1
Cereal rye	11	14	*3.4*	*4.6*	0.9	*0.62*	*1.2*
Maize	10	13	2.3	2.7	1.1	0.11	1.2
Millet / Canary seed	11	20	3.3	3.9	1.3	1.2	3.8
Oats	11	16	2.7	4	1.4	0.6	1.2
Rice (grain & hulls)	14	10.3	2.4	2.9	0.85	0.22	0.86
Sesame	*5*	*34*	*7.2*	*5.7*	*2.1*	*6.7*	*3.7*
Sorghum	10	17	2.3	3.3	2.4	0.5	1.4
Triticale	11	16	2.4	4.4	1	0.31	1
Wheat	11	*	2.6	3.6	1.4	0.38	1.2
GRAIN LEGUMES							
Chickpea	10	33	3.8	9.1	1.8	1.5	1.4
Cowpea	10	39	6.9	9	1.9	0.6	2
Faba bean	10	38	3.6	9.7	1.6	1.1	1.1
Field pea	10	35	3.6	9	2.1	0.8	1.5
Lablab	11	36	10	3.8	1.7	0.8	1.9
Lentil	10	37	3.3	8.2	1.4	0.9	1.4
Lupin (Sweet)	9	48	3.2	8.3	2.6	2.3	1.8
Lupin (Albus)	9	55	3	8.8	2.4	2	1.5
Lupin (Sandplain)	8	51	3.8	8.8	3.1	1.7	1.7
Lupin (Yellow)	9	64	4.2	9.5	4.4	2.2	2.4
Mung bean	9	41	7.7	4.7	1.9	1	1.8
Green Mung bean	9	42	7.2	4.1	2	1	1.8
Black Mung bean	10	40	6	5.3	1.8	0.9	1.7
Narbon bean	11	39	4.4	9.9	3.2	1.4	1.1
Navy bean	10	39	4.5	13.5	2.1	1.7	1.5
Pigeon pea	10	31	7.6	6.1	1.5	1	1.3
Vetch (common)	10	42	4.2	9	1.9	0.8	1.1
PASTURE LEGUMES							
Lucerne seed		60	6.8	11	2.5	1.3	2.2
Medic seed	10	64	6.8	8.9	2.7	1.3	2
Serradella	10		4.9		2.8	16.7	
OILSEED CROPS							
Canola / Rape	8.5	31	5.1	7.4	5	3.9	2.8
Cottonseed		31	4.4	13.4	2.9	1.5	3.8

Species	Moisture (%)	N	P	K	S	Ca	Mg
Linola	w/w	31	4.2	6.5	1.9	1.7	2.7
Linseed / Flax	8.5	30	4.2	6.6	2	1.8	2.8
Mustard	8.5	35	6.5	5.8	9.3	3.8	2.7
Peanut	10	36	3.2	10	2.3	0.9	2.4
Safflower	8.5	29	3.1	6.1	1.7	1.7	1.8
Soybean	8.5	62	5.5	18.5	3.5	2.3	2.6
Sunflower	8.5	30	7.8	*5.9*	*1.7*	*1.1*	*2.3*
OTHER CROPS							
Hops	0	54	7.4	61	3.6		
Lavender	30	4.5	0.45	3.6	2	3.9	
Poppy	11.5	21	5.7	18	2.7	14.3	2.6
Pyrethrum		17	2.2	15	1.8	7	2.9
Tobacco (cured leaves)		*39*	2.5	32	3.5	20	3.6
STRAW, HAY AND SILAGE							
Legume hay (clover or medic)	89	22	1.7	18	1.6	8.6	2.3
Lucerne hay	87	30	2	24	2.6	9.9	2.7
Legume / Grass hay	88	21	2	18	1.7	5.3	1.9
Oaten hay	90	13	1.6	17	1.1	2.3	1.2
Pasture hay	88	18	1.8	15	1.6	5	1.8
Grass silage	44	24	2.8	24	2.2	5.3	2.1
Maize silage	62	12	1.9	15	1	2.1	2.4
Pasture silage	48	26	2.8	26	2.3	5.9	2.1
Oaten silage	45	20	2.5	23	1.8	3.7	1.7
Cereal	10	10	3	31	2	-	-
Canola	10	4	2	70	4.8	-	-
Legume	10	10	4	17	2.7	-	-
VEGETABLES							
Artichoke (edible)	84	4.3	0.77	4	0.23	0.48	0.47
Asparagus	94	2.2	0.41	2.1	0.35	0.14	0.12
Beans (all types)	91	3.8	0.39	2.8	0.24	0.44	0.32
Beetroot	91	2	0.3	2.2	0.13	0.09	0.16
Broccoli (all types)	90	5.4	0.82	4	0.81	0.37	0.18
Brussel sprouts	88	5.9	0.86	4.6	1.2	0.18	0.21
Cabbage (all types)	92	3.4	0.6	3.3	0.41	0.54	0.19
Capsicum	92	2.2	0.31	2.9	0.23	0.14	0.23
Carrot	89	1.6	0.4	2.3	0.15	0.45	0.16
Cassava	66	2.6	*0.4*	2.9	0.06	0.18	0.09

Species	Moisture (%)	N	P	K	S	Ca	Mg
Cauliflower	91	3.1	0.59	3.6	0.6	1.3	0.23
Celery	95	1.3	0.29	2.8	0.13	0.49	0.25
Chicory (roots)	*80*	*2.2*	*0.61*	*2.9*	0.12	*0.41*	*0.22*
Chilli (red)	82	2.2	*1.2*	3	0.23	0.16	0.28
Chilli (green)	81	4.5	*1.2*	2.8	0.38	0.12	0.11
Chives	90	2.4	*0.51*	2.1	0.5	0.9	0.12
Chokos		2.1	0.56	2.7	0.19	0.26	0.2
Cucumber	96	1.4	0.26	1.9	0.16	0.3	0.12
Egg plant	*93*	*1.8*	*0.25*	*2.1*	0.19	*0.07*	*0.16*
Fennell	*94*	*1.5*	*0.26*	*4.4*	0.15	*0.24*	*0.08*
Garlic (bulbs)	61	8.2	1.7	5.3	1.7	0.2	0.25
Gherkin	*93*	*2.2*	*0.38*	*2.9*	0.18	*0.26*	*0.32*
Ginger	89	1.8	0.4	2	0.23	0.23	0.28
Horse Radish	*76*	*7.2*	*0.8*	*5.8*	*2.2*	*1.1*	*0.62*
Leek	*91*	*2*	*0.19*	*2*	*0.44*	*0.73*	*0.11*
Lettuce	96	1.9	0.37	2.7	0.1	0.35	0.1
Mushroom	*91*	*6*	*0.8*	*4.2*	*0.48*	*0.05*	*0.12*
Okra (edible portion)	*90*	*3.1*	*0.6*	*3*	0.26	*0.74*	*0.57*
Onion	89	1.9	0.42	1.9	0.37	0.28	0.1
Parsley	83	5.8	0.7	8.3	0.41	2.2	0.46
Parsnip	*81*	*3.8*	*0.88*	*5.1*	*0.77*	*0.47*	*0.29*
Peas	75	11.2	1.33	2.7	0.54	0.32	0.42
Peas (snow)	88	4.8	3.6	4.2	2.1	0.25	0.36
Peppers	74	5.9	0.78	*2.8*	*0.21*	0.29	*0.22*
Potato	80	3	0.42	4.4	0.28	0.14	0.12
Potato (sweet)	76	2.4	0.53	3.7	0.22	0.31	0.2
Pumpkin	90	2.1	0.56	2.7	0.19	0.26	0.2
Radish	93	3.5	0.31	2.2	0.55	1.9	0.41
Rhubarb	*95*	*1.3*	*0.17*	*3.1*	*0.06*	*0.84*	*0.11*
Silverbeet	93	2.9	0.42	4.4	0.27	0.7	0.63
Squash	92	3.9	0.34	1.6	0.33	0.13	0.12
Spinach	*93*	*3.2*	*0.3*	*4.7*	*0.32*	*0.88*	*0.59*
Swede	*91*	*1.1*	*0.4*	*1.7*	*0.39*	*0.53*	*0.09*
Sweet corn (ears)		*3.9*	*0.56*	*2.1*	1.1	0.11	1.2
Tomato	94	1.6	0.33	2.4	0.19	0.13	0.12
Turnip	93	1.9	0.5	3.1	0.51	0.28	0.14
Zucchini	94	2.9	*0.28*	1.9	*0.24*	0.16	0.15
FRUIT							
Apple	84	0.32	0.08	1.1	0.02	0.04	0.04
Apricot	83	2.3	0.32	3.6	0.09	0.17	0.17
Avocado	63	4.1	0.76	6.1	*0.4*	0.72	0.77
Babaco	94	2.1	0.24	1.4	0.14	0.11	0.06
Banana (NSW)		2.4	0.64	8.8	*0.13*	0.31	0.31

Species	Moisture (%)	N	P	K	S	Ca	Mg
Banana (QLD) (whole bunch and stalk)		1.6	0.2	5.2	*0.13*	0.17	0.21
Berries		1.7	0.28	1.6	0.11	0.29	0.15
Black currant	80	1.8	0.34	3.6	*0.32*	0.5	*0.27*
Blackberry	84	1.9	0.22	1.8	*0.09*	0.41	*0.27*
Blueberry	85	*1.1*	*0.13*	*0.8*	0.06	*0.15*	*0.05*
Cantaloupe/ melon	87	1.9	0.59	4.5	0.21	0.33	0.33
Carambola	91	1.2	*0.17*	1.1	0.08	0.03	0.03
Casimiroa	80	1.4	0.2	2.4	0.08	0.1	0.29
Cherry	80	1.5	0.21	2.2	0.08	0.15	0.12
Citrus fruit		*2.9*	*0.4*	*6.3*	*0.3*	*2.6*	*0.5*
Coffee		46	3.4	3.2	2.1	2.4	2.3
Cranberry	88	*0.5*	*0.1*	*0.6*	*0.08*	*0.12*	*0.07*
Currants	82	2.2	0.48	2.9	0.29	0.46	0.18
Custard apple		2.6	0.3	2.6	0.14	0.7	0.34
Date	21	*3.6*	*0.46*	*6.5*	*0.7*	*0.4*	*0.39*
Fig	83	2.2	0.28	1.9	0.17	0.44	0.09
Gooseberry	87	1.3	0.35	1.4	*0.13*	0.2	*0.1*
Grape (table)	~80	1.3	0.27	2.1	0.08	0.22	0.1
Grape (wine berries)		1	0.26	3.1	0.11	0.46	0.14
Grapefruit	89	*1.1*	*0.21*	*1.6*	*0.12*	*0.33*	*0.11*
Guava	83	1.2	0.26	2.3	0.07	0.16	0.11
Kiwifruit	~84	*1.5*	*0.21*	*3.2*	*0.2*	*0.32*	*0.15*
Lemon & Limes	87	*1.9*	*0.15*	*1.5*	*0.12*	*0.6*	*0.12*
Longan	72	*1.6*	*0.06*	2.4	0.09	*0.02*	0.29
Loganberry		*2.8*	*0.24*	*2.6*	*0.18*	*0.35*	*0.25*
Lychee		2	0.4	2.4	0.11	0.24	0.42
Mandarin		*1.6*	*0.16*	*1.4*	*0.13*	*0.37*	*0.13*
Mango: NSW	79	1.1	0.19	1.5	0.13	0.18	0.18
Mango: QLD		0.8	0.2	2.1	0.09	0.3	0.2
Mangosteen	85	0.8	0.2	2.1	0.09	0.1	0.2
Mulberry	89	3.5	*0.38*	3.1	0.27	0.2	0.12
Nectarine	86	1.4	0.22	2.3	0.06	0.06	0.1
Olive	55	2.3	0.39	4	0.24	0.32	0.18
Orange	82	*1.3*	*0.18*	*1.8*	*0.11*	*0.6*	*0.16*
Passionfruit	81	*2.8*	*0.32*	*3.9*	*0.28*	*0.27*	*0.2*
Pawpaw		*1.3*	*0.3*	*3.2*	0.09	*0.43*	*0.3*
Peach/Peacharine	86	1.2	0.2	1.9	0.06	0.04	0.1
Pear	85	0.24	0.03	0.33	0.01	0.01	0.01
Pepino	93	1	0.33	1.2	0.19	0.05	0.08
Persimmon		1	*0.22*	1.7	*0.1*	0.14	0.08
Pineapple		*0.78*	*0.07*	*2*	*0.07*	*0.13*	*0.09*

Species	Moisture (%)	N	P	K	S	Ca	Mg
Plum	86	1.5	0.19	1.6	0.09	0.05	0.09
Quince		0.32	0.08	1.1	0.02	0.04	0.04
Rambutan		1.6	0	1.4	0	0.08	0.1
Raspberry	84	1.8	0.29	1.7	0.14	0.36	*0.15*
Stone fruit		1.3	0.21	2.1	*0.06*	0.05	0.1
Strawberry	91	1.9	0.26	1.5	*0.11*	0.19	0.08
Tangelo		2.9	0.4	6.3	0.3	2.6	0.5
Tea (pluck leaves)		*40*	*4*	*20*	2.6	*4.9*	*2.5*
Watermelon	94	1.5	0.25	2.2	0.09	0.11	0.12
NUT CROPS							
Almond* (whole fruit)	12	13.2	1.9	17.6	0.68	2.1	1.4
Cashew		14	2	6.5	0.7	1	1.6
Chestnut (whole fruit)	23	9.2	0.88	6.3	0.65	0.62	0.83
Hazelnut / Flibert		25	3.1	5.6	0.7	1	1.6
Macadamia		11	1.6	9.2	1.3	0.41	0.82
Pecan		10	2.3	4.5	0.67	3.7	0.6
Pistachio (whole fruit	52	8.6	1.5	9.4	0.6	0.43	0.38
Walnut		26.6	3.6	4.7	1.8	0.8	1.5
LIVESTOCK							
Sheep Merino greasy fleece	kg/t	119	0.3	15	0.59	22	1.8
Sheep Xbred greasy fleece	kg/t	125	0.3	35	0.43	23	1.5
Sheep Live, shorn, ex farm gate	kg/t	23	5.9	2.1	0.4	1.4	11
Cattle Whole milk (cow)	kg/kL	5.3	0.93	1.6	0.10	0.3	1.2
Cattle Live, ex farm gate	kg/t	26	7.2	2.0	0.4	1.4	12
Poultry Whole egg	kg/t	16.8	2.63	1.20	0.61	1.45	48.5
Poultry Live broiler, ex farm gate	kg/t	31.8	6.1	2.9	0.38	2.6	9.1
Pigs Empty body	kg/t	24	5.6	2.2	0.37		9.2
PASTURE							
Temperate grasses	g/kg DM	17.7	3.5		1.8		3.7

Species	Moisture (%)	N	P	K	S	Ca	Mg
Temperate legumes	g/kg DM	28.0	3.7		2.4		14.2
Tropical grasses	g/kg DM	15.2	2.2		3.6		3.8
Tropical legumes	g/kg DM	27.2	2.5		2.4		10.1
PASTURE SEED							
Lucerne seed		60	6.8	11	2.5	1.3	2.2
Medic seed (WA)	10		4.3-7.1		2.5-3.1	2.6-3.1	
Medic Seed ISA)	10	64	6.8	8.9	2.6	1.3	2
Serradella	10		3.8-5.5		2.7-2.9	14.4-16.2	
SUGAR							
Cane	kg/t FW	0.67	0.11	0.76	0.15	0.15	0.19

Appendix 12, Regional nutrient concentrations for wheat and canola used in the estimation of nutrient performance indicators. Data were taken from Norton (2012) and Norton (2014).

Crop	Region	N	P	K	S
Wheat	SE NSW	from Ptn	3.6	5.1	2
	SW NSW	from Ptn	2.7	4.2	1.7
	SA Lower Eyre	from Ptn	3.1	4.5	1.5
	SA Mid North	from Ptn	3.9	4.7	1.8
	SA Murray Mallee	from Ptn	3.5	4.5	1.8
	SA South east	from Ptn	3.5	4.9	1.8
	SA Upper Eyre	from Ptn	3.2	4.8	1.8
	SA Yorke	from Ptn	3.8	4.4	1.7
	Vic Mallee	from Ptn	3.1	4.3	1.6
	Vic North Centra	from Ptn	2.9	4.3	1.8
	Vic Wimm	from Ptn	4.1	5.0	1.7
	Vic SW	from Ptn	3.3	4.5	1.7
	Vic North East	from Ptn	3.0	4.6	1.7
Canola	SE NSW	44	3.9	6.2	4.8
	SW NSW	54	5.5	6.3	3.7
	SA Lower Eyre	41	6.3	7.4	3.2
	SA Mid North	41	5.8	7.2	4.1
	SA Murray Mallee				
	SA South east	45	5.1	7.0	3.9
	SA Upper Eyre	37	7.8	7.4	3.1
	SA Yorke	46	6.2	7.5	3.7
	Vic Mallee	43	6.5	6.9	4.3
	Vic North Centra	40	5.4	6.7	4.0
	Vic Wimm	38	5.8	6.7	3.7
	Vic SW	34	5.2	6.8	3.3
	Vic North East	35	5.5	6.6	3.6

Reference:

Norton RM. 2012. Wheat grain nutrient concentrations for south-eastern Australia. "Capturing Opportunities and Overcoming Obstacles in Australian Agronomy". Edited by I. Yunusa. *Proceedings of 16th Australian Agronomy Conference 2012*, 14-18 October 2012, Armidale, NSW. http://www.regional.org.au/au/asa/2012/nutrition/7984_nortonrm.htm

Norton RM. 2014. Canola seed nutrient concentrations for southern Australia. In Ware AH and Potter TD 2014 18th Australian Research Assembly on Brassicas (ARAB 18). Tanunda, 2014. Proceedings. Australian Oilseed Federation, p 1-6.

Appendix 13. How much N is contributed by grain legume N fixation for every tonne of grain produced?

Biological nitrogen (N_2) fixation is an important source of N in cropping systems. Globally, the amount of N fixed by crop legume-rhizobia symbioses is estimated to be 20–22 million tonnes per year (Herridge et al. 2008). The percentage of N derived from the atmosphere (Ndfa) can be determined by non-isotopic (N balance, N difference, ureide and acetylene reduction) and isotopic (^{15}N natural abundance, ^{15}N isotope dilution and $^{15}N_2$ gas) methods (Unkovich et al. 2008). Nonetheless these methods are more or less impractical or cost-ineffective for growers to estimate how much N is fixed by their crops. Simple relationships between aggregated data on legume shoot dry matter production and N_2 fixation provide a pragmatic approach to estimating N_2 fixation (Unkovich et al. 2010a), but the assessment of net N contribution of N_2 fixation to the system's N budget would also require the amount of N fixed in roots and nodules as well as that removed in grains.

Here we first present three methods adopted in the literature for estimating N_2 fixation from shoot dry matter of legumes. Using estimated data on shoot N fixation, root N fixation and grain N removal, we then assess the net contribution of legume N under different harvest indices for the major crop legumes (chickpea, faba bean, field pea, lentil, narrow-leaf lupin and vetch) grown in Australia on a basis of per tonne of grain yield.

Estimation of N_2 fixation by legume shoot dry matter

1. Consolidation of existing data for all crops

Crop legumes generally fixed 15–25 kg shoot N for every tonne of shoot dry matter (Herridge et al. 2008), or an average of 21 kg (Unkovich et al. 2010a).

2. Regression analysis for individual crop

Unkovich et al. (2010a) assembled published and unpublished data on legume N accumulation and N_2 fixation from Australian field studies into a database. Linear regressions have been fitted between the aggregated datasets of legume shoot dry matter production and shoot N fixed for each crop (Table 1).

Table 1 Linear regression analysis and adjusted r^2 for crop shoot dry matter (x, t/ha) and shoot N fixed (y, kg/ha)

Legume	Regression equation	r^2	kg N fixed/tonne of shoot dry matter (when x = 1)
Chickpea	$y = -1.05 + 10.7\,x$	0.50	9.7
Faba bean	$y = -1.5 + 23\,x$	0.79	21.5
Field pea	$y = -1.73 + 20.6\,x$	0.53	18.9
Narrow leaf lupin	$y = 4.03 + 14.2\,x$	0.76	18.2

Source: Unkovich et al. (2010a)

3. <u>Determination of %Ndfa for individual crop</u>

The relationships between shoot dry matter and N_2 fixation can also be estimated using data on shoot %N and %Ndfa for individual crop (Unkovich et al. 2010a) by the equation:

- **Shoot N fixed (kg/ha) = shoot dry matter (kg/ha) × shoot %N × %Ndfa**

The average values for the shoot %N and %Ndfa of the crops are presented in Table 2.

Table 2 Shoot %N and %Ndfa for the estimation of shoot N fixation

Legume	Shoot %N	%Ndfa	kg N fixed/tonne of shoot dry matter
Chickpea	2.40	41	9.84
Faba bean	2.83	65	18.40
Field pea	2.40	66	15.84
Lentil	2.57	60	15.42
Narrow leaf lupin	2.49	75	18.68
Vetch	3.24	80	25.92

Source: Unkovich et al. (2010a)

Net N contribution by legumes to N budget

Net contribution of legume N = whole plant legume N fixed – grain N removed

= shoot N fixed + root N fixed – grain N removed

The estimation of shoot N fixed is presented above. Root N fixed can be calculated using a 'root N factor' for individual crops as listed in Table 3. To account for the amount of N removed in grains, we use data on grain %N reported by Patterson and Mackintosh (1994).

Table 3 Shoot N: root N, root factor, grain %N and removal for different crop legumes

Legume	Shoot N: root N	Root factor [a]	Grain %N	kg N removed in grain/tonne of grain yield
Chickpea	1.25	1.80	3.54	35.4
Faba bean	2.13	1.47	3.84	38.4
Field pea	2.10	1.48	3.83	38.3
Lentil	1.80	1.56	4.88	48.8
Narrow leaf lupin	3.78	1.26	5.15	51.5
Vetch	2.10	1.48	5.00	50.0

[a] The 'root N factor' is 1 + 1/(shoot N: root N),
Source: Patterson and Mackintosh (1994); Unkovich et al. (2010a)

Variation in N_2 fixation of crops is closely related to dry matter production. To provide a more practical assessment on the net N contribution by legumes, we calculated net N change based on a range of harvest indices as described in Herridge et al. (2008) (Table 4).

Table 4 Net N contribution (kg/ha) per tonne of grain yield under a range of harvest indices calculated by the three methods (Method 1: consolidation of existing data; Method 2: regression analysis; Method 3: %Ndfa).

Crop	Net N contribution (kg/ha) per tonne of grain yield									
	Method	Harvest index								
		0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
Chickpea	1	342.7	153.7	90.7	59.2	40.3	27.7	18.7	11.9	6.7
	2	155.4	59.1	27.0	10.9	1.3	–5.1	–9.7	–13.2	–15.8
	3	141.8	53.2	23.7	8.9	0.1	–5.8	–10.0	–13.2	–15.7
Faba bean	1	270.3	116.0	64.5	38.8	23.3	13.1	5.7	0.2	–4.1
	2	297.5	128.4	72.1	43.9	27.0	15.7	7.7	1.7	–3.0
	3	232.0	96.8	51.7	29.2	15.7	6.7	0.2	–4.6	–8.4
Field pea	1	272.6	117.2	65.4	39.5	23.9	13.6	6.2	0.6	–3.7
	2	264.1	111.6	60.8	35.4	20.2	10.0	2.7	–2.7	–6.9
	3	196.2	79.0	39.9	20.4	8.6	0.8	–4.8	–8.9	–12.2
Lentil	1	278.8	115.0	60.4	33.1	16.7	5.8	–2.0	–7.8	–12.4
	2	NA	NA	NA	NA	NA	NA	NA	NA	NA
	3	191.8	71.5	31.4	11.4	–0.7	–8.7	–14.4	–18.7	–22.1
Narrow leaf lupin	1	213.1	80.8	36.7	14.7	1.5	–7.4	–13.7	–18.4	–22.1
	2	132.5	43.1	13.2	–1.7	–10.6	–16.6	–20.8	–24.0	–26.5
	3	183.8	66.2	27.0	7.4	–4.4	–12.3	–17.9	–22.1	–25.3
Vetch	1	260.8	105.4	53.6	27.7	12.2	1.8	–5.6	–11.2	–15.5
	2	NA	NA	NA	NA	NA	NA	NA	NA	NA
	3	333.6	141.8	77.9	45.9	26.7	13.9	4.8	–2.0	–7.4

NA: regression equation not available

The higher the harvest index, the lower the net contribution of crop legumes to N budget (Table 4, Fig. 1). Crop legumes may add up to 300 kg N/ha per tonne of grain yield (when the harvest index is 0.1) or remove around 30 kg N/ha per tonne of grain yield (when the harvest index is 0.9). This suggests that excessively vegetative crops with low seed yield may have compensatory benefits in terms of N input to the cropping system.

Summary

- The average harvest index of major crop legumes grown in Australia is between 0.3 and 0.4 (Unkovich et al. 2010b), which represents an input of 7–65 kg N fixed/ha for every tonne of grain produced depending on species.

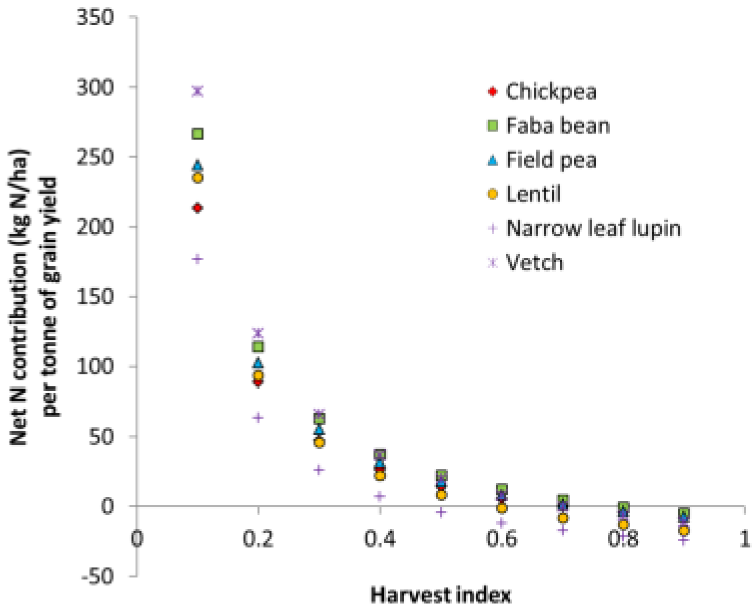


Figure 1 Net N contribution by major crop legumes grown in Australia under various harvest indices (average across the three methods listed in Table 4)

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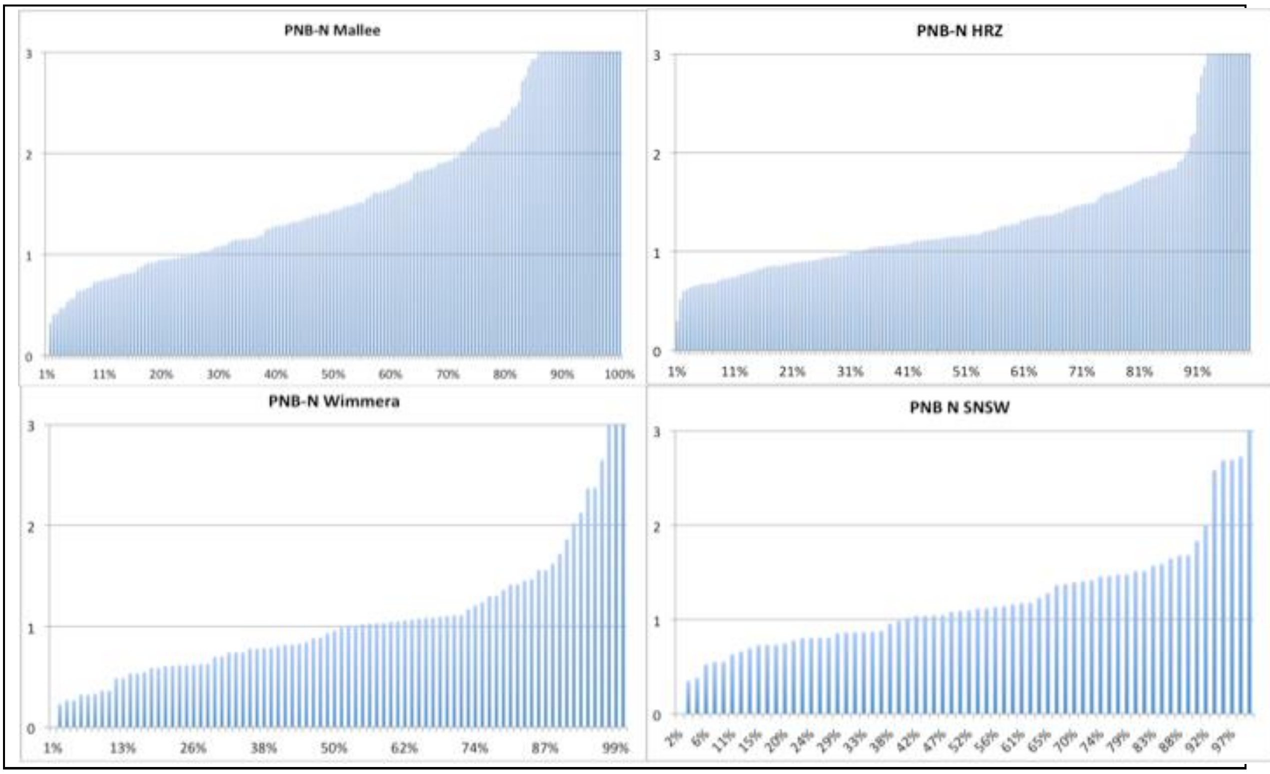
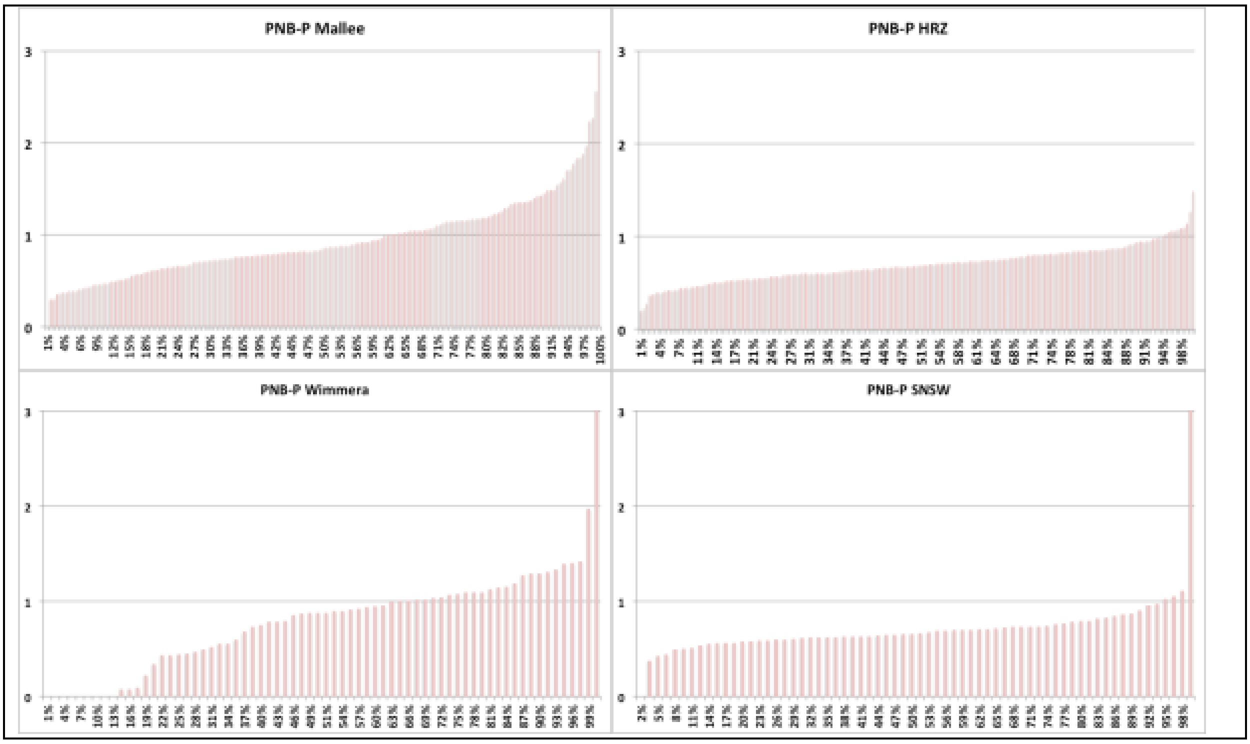
Appendix 14 Nutrient concentrations in fertilizers reported in the farm survey data. In addition to the named product listed here, some products reported were cited by their N:P:K:S composition (eg 10:17:13:2, which is 10% N, 17% P, 12% K and 2% S).

Fertiliser	N	P	K	S
19:13:0:9 DAP/SOA mix	19%	13%	0%	9%
Anhydrous ammonia	82%	0%	0%	0%
Animal manure	3%	1%	2%	0%
Copper Sulphate	0%	0%	0%	35%
Diammonium Phosphate (DAP)	18%	20%	0%	0%
Double superphosphate	0%	18%	0%	2%
Easyzinc 100	10%	15%	0%	0%
Goldphos 10	0%	18%	0%	10%
Grain legume super + Zn	0%	15%	0%	7%
Granulock Z	11%	22%	40%	10%
Gypsum (Grade 2 used)	0%	0%	0%	13%
Life Force Blend	2%	26%	2%	1%
Mallee Mix 8	10%	21%	0%	2%
Manganese Sulphate	0%	0%	0%	19%
Monoammonium Phosphate (MAP)	11%	22%	0%	2%
MAP Zn 1%	11%	22%	0%	2%
MAP ZN.05	11%	22%	0%	2%
MAP+cu+zn	11%	22%	0%	2%
MES 10/MESZ	12%	18%	0%	10%
Muriate of potash (MOP)	0%	0%	50%	0%
N Rich 22	22%	15%	0%	10%
Nitram	35%	0%	0%	0%
N-Rich 26	26%	15%	0%	10%
Nutri-phos Soft Rock	0%	90%	0%	0%
Omni boost K	6%	13%	3%	3%
Pivot 27-12-0-1	27%	12%	0%	1%
Potassium nitrate	13%	0%	38%	0%
Single superphosphate/Superfect (SSP)	0%	9%	0%	11%
Sulfate of ammonia (SOA)	21%	0%	0%	24%
Sulfate of potash (SOP)	0%	0%	42%	17%
Super M	10%	16%	0%	18%
Thumper	13%	19%	0%	7%
Triple superphosphate (TSP)	0%	20%	0%	12%
Ureas-ammonium nitrate (UAN/Easy N)	32%	0%	0%	0%
Urea	46%	0%	0%	0%
Urea 38.0.0.7	38%	0%	0%	7%
Vigor Lig + N	10%	2%	7%	1%
Zincstar	11%	22%	0%	2%
Zincstar 10	11%	22%	0%	2%

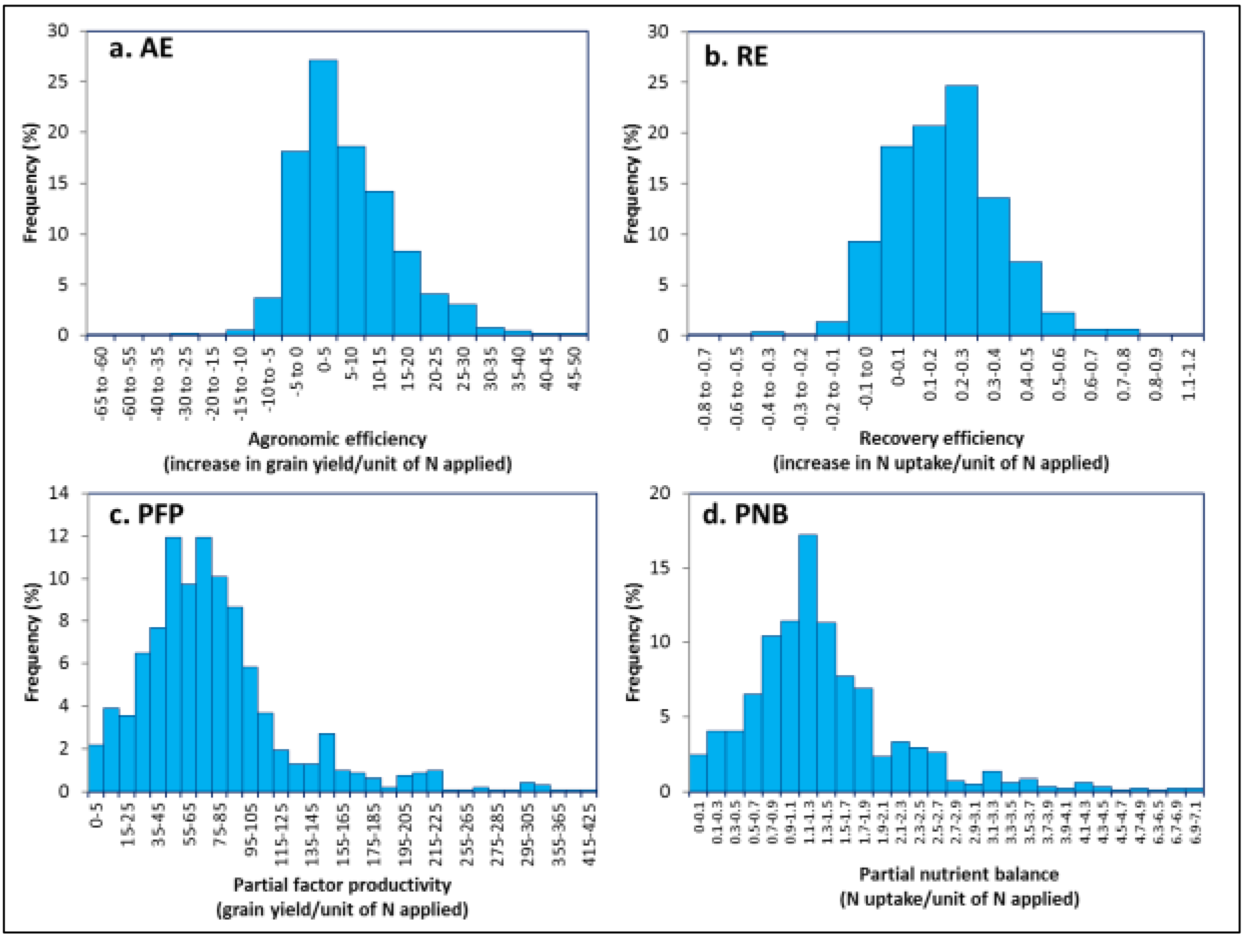
Appendix 15 Nitrogen PNB for the Mallee, HRZ, Wimmera and SNSW.



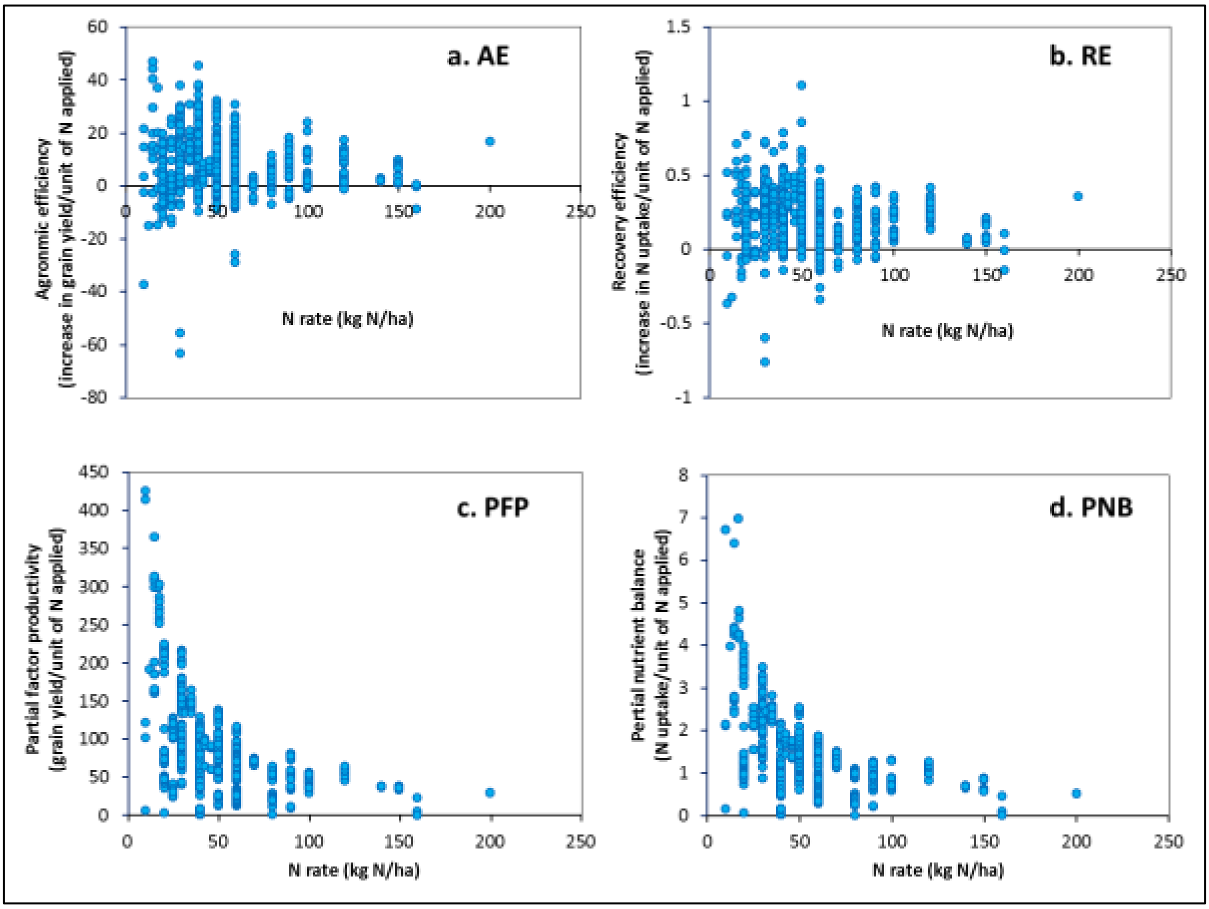
Appendix 16 Phosphorus PNB for the Mallee, HRZ, Wimmera and SNSW.



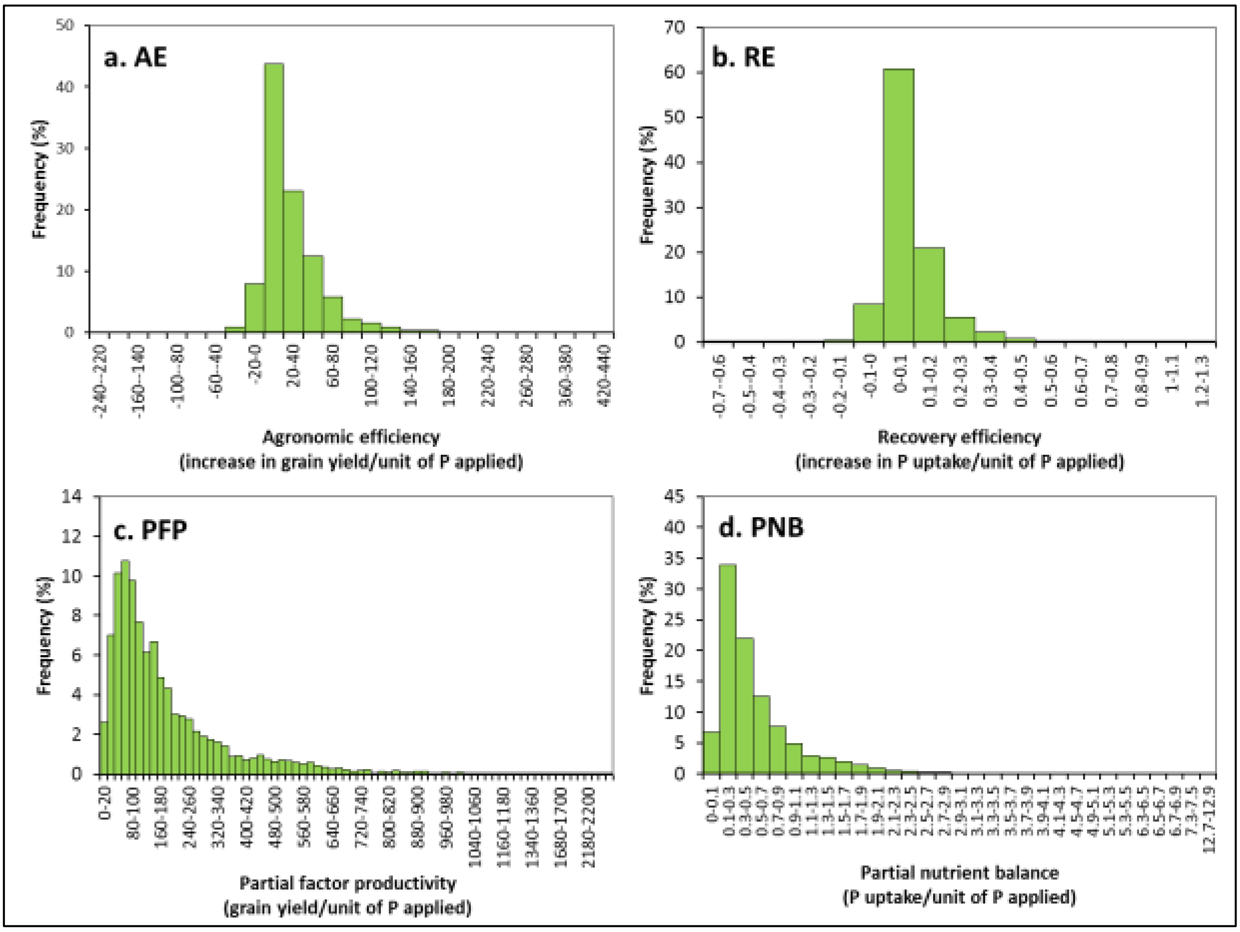
Appendix 17 Frequency distribution of (a) agronomic efficiency, (b) recovery efficiency, (c) partial factor productivity, and (d) partial nutrient balance for N use in Australian wheat cropping systems



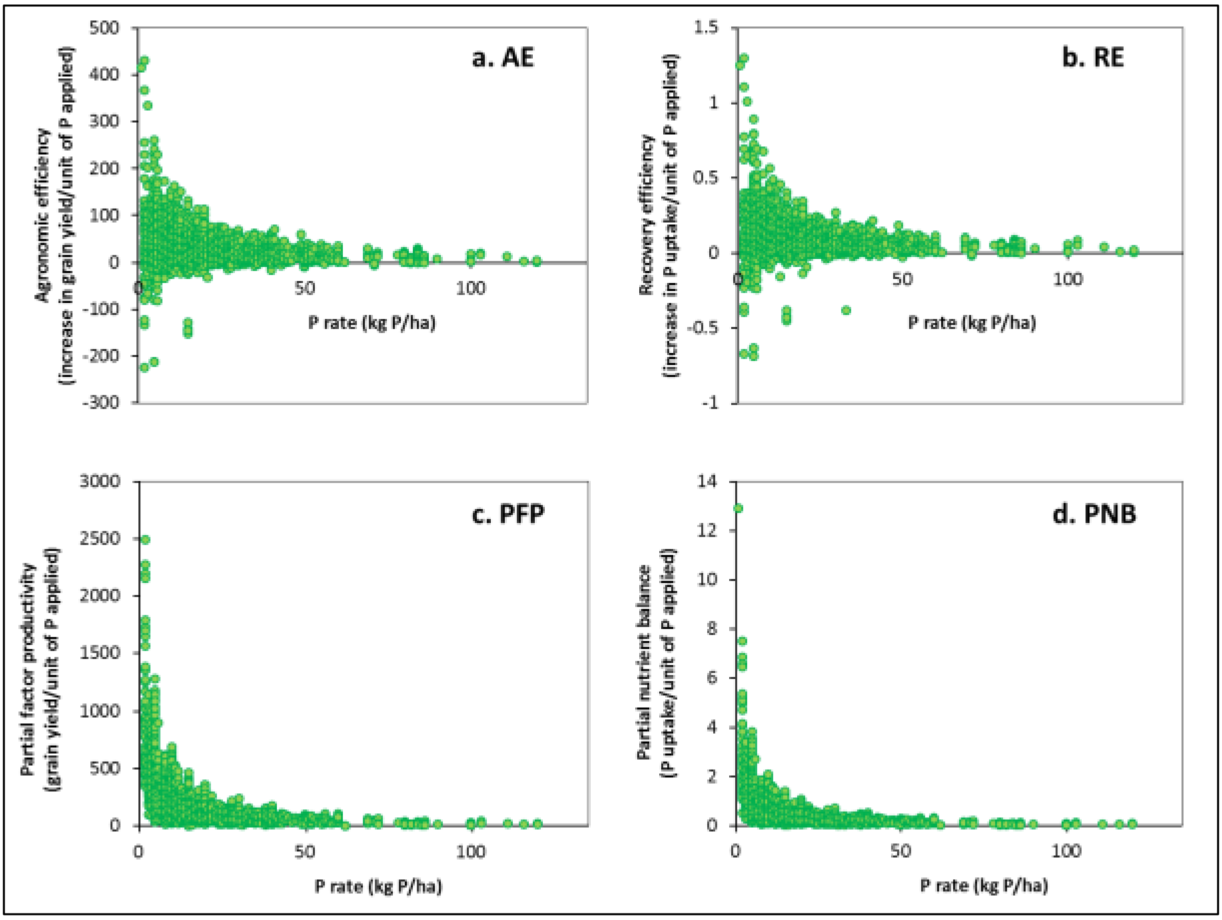
Appendix 18 The relationship between N application rate and (a) agronomic efficiency, (b) recovery efficiency, (c) partial factor productivity, and (d) partial nutrient balance in Australian wheat cropping systems



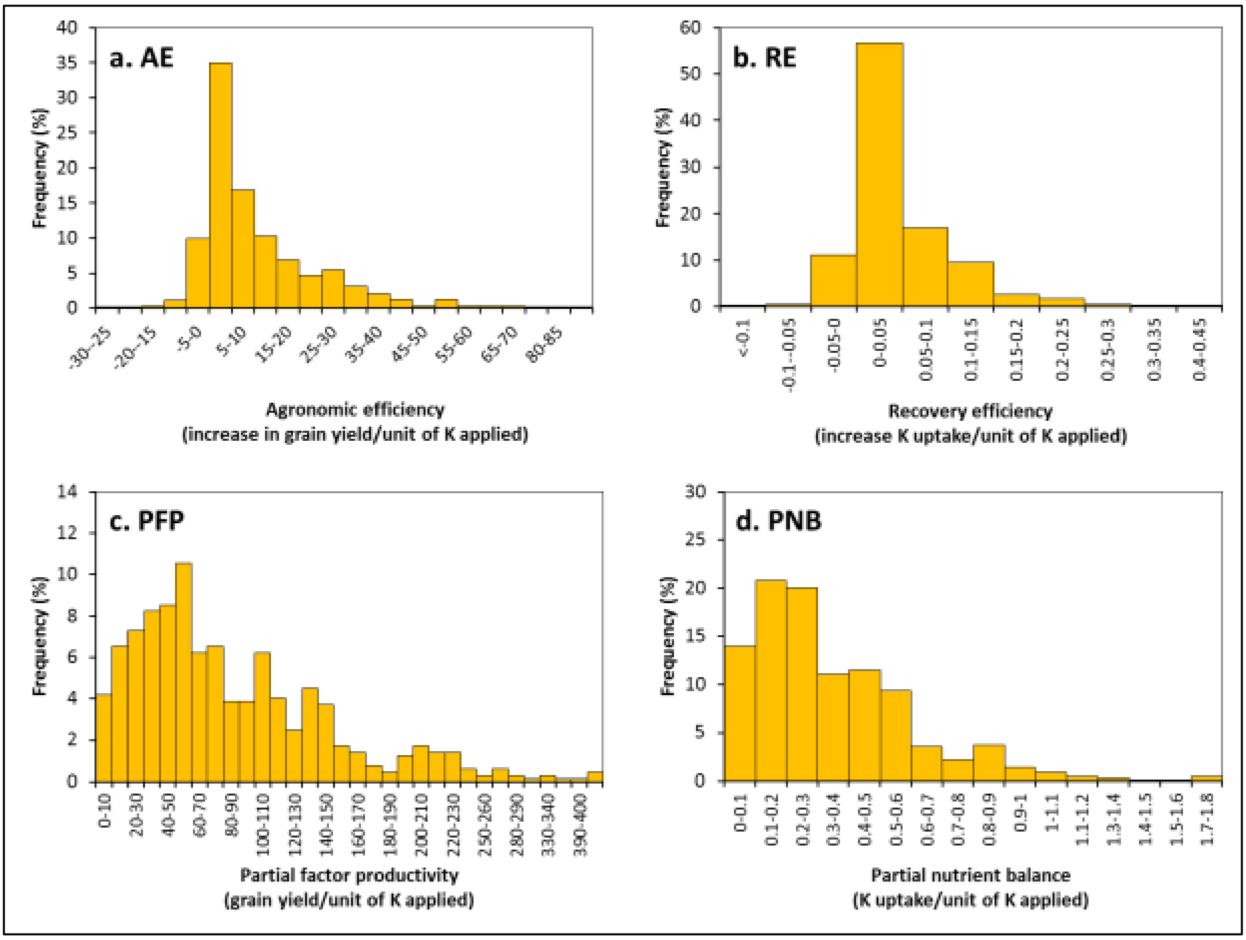
Appendix 19 Frequency distribution of (a) agronomic efficiency, (b) recovery efficiency, (c) partial factor productivity, and (d) partial nutrient balance for P use in Australian wheat cropping systems.



Appendix 20 The relationship between P application rate and (a) agronomic efficiency, (b) recovery efficiency, (c) partial factor productivity, and (d) partial nutrient balance in Australian wheat cropping systems.



Appendix 21 Frequency distribution of (a) agronomic efficiency, (b) recovery efficiency, (c) partial factor productivity, and (d) partial nutrient balance for K use in Australian wheat cropping systems



Appendix 22 The relationship between K application rate and (a) agronomic efficiency, (b) recovery efficiency, (c) partial factor productivity, and (d) partial nutrient balance in Australian wheat cropping systems