# Nitrogen removal and use on a long-term fertilizer experiment

**Rob Norton[1]**, Charlie Walker[2], Craig Farlow[2]

1 International Plant Nutrition Institute, 54 Florence St, Horsham, Vic, 3400. rnorton@ipni.net
2. Incitec Pivot Fertilizers, PO Box 54, North Geelong, Vic 3214.

**Abstract**
The Dahlen nitrogen and phosphorus experiment was established in 1996 in the medium rainfall cropping zone of Victoria, Australia, and has been in a canola, wheat, barley and pulse rotation each year since then. The experiment has four rates of P (0, 9, 18, 36 P kg/ha) applied at sowing, and five rates of N (0, 20, 40, 80, 160 N kg/ha) either all at sowing or split. Crop and soil data has been collected for each crop year, which included two years where crops were sown but not harvested due to drought. A progressive N balance over the duration of the experiment has shown that N removal-to-fertilizer use ratios for the 9 kg P/ha/y were 2.96 (20 kg N/ha/y), 1.57 (40 kg N/ha/y), 0.92 (80 kg N/ha/y) and 0.47 (160 kg N/ha/y). Fixed N estimates were made based on pulse growth, checked with natural abundance measurements on site which ranged from 40 to 120 kg N/ha/crop depending on season. When fertilizer and legume N inputs are considered, the removal-to-supply ratios were 1.36 (20 kg N/ha/y), 1.04 (40 kg N/ha/y), 0.74 (80 kg N/ha/y) and 0.42 (160 kg N/ha/y). We conclude that this continuous cropping system was maintained as N neutral with the use of one pulse crop in 4 years, and the addition of 40 kg N/ha/y in the non-pulse crops. Soil organic carbon levels were unaffected by N application.

**Keywords**
Nitrogen use efficiency, cropping systems, removal-to-use, fixed nitrogen, rotations.

## Introduction
Efficient and effective use of N fertilizers is important in productive and sustainable farming systems (Stewart et al. 2005, Davidson et al. 2015). There are several ways to estimate N efficiency such as agronomic efficiency (AE) or recovery efficiency (RE) (Table 1), which are the marginal increases in yield or N removal to the added fertilizers. The difference indices rely on nil fertilizer checks, and are useful in identifying the relative contribution of soil and fertilizer nutrients, as well as giving a guide to the fate of nutrients not removed in products. They are most often reported from single year experiments, and may be done using tracers to estimate the nutrient recovery efficiency (RE). The use of $^{15}N$-labelled fertilizers in field experiments has shown RE in Australian wheat systems of 22-59% in the plant (Freney et al. 1992), whereas Ladha et al. (2005) estimated a mean "global" recovery from isotope studies of 44%.

However, there are few reports of nutrient balances over long-term nutrient management experiments. Analysing the balance of input, removal and changing nutrient stocks over time can identify the true nutrient efficiency of cropping systems as they face the vagaries of climate and the production of different crops in a rotation. This paper reports the nitrogen balance, expressed as Partial Nutrient Balance (BNP) from a long-term (19 years) fertilizer experiment and reports some of the changes in soil properties over that time. This updates an earlier report on the experiment from 1996 to 2010 (Norton et al. 2012).

## Methods
The Dahlen long-term nutrition experiment, 10 km west of Horsham Victoria, was established in 1996 to investigate the interaction of different rates of N and P within a minimum tillage and stubble retention cropping system. Since establishment, the site has been in a canola, wheat, barley and pulse rotation although an oaten hay crop was grown in 2011 to help manage herbicide tolerant weeds. The soil at the site is a Vertosol, which is the dominant cropping soil in the region. The mean annual rainfall (1891-2014) for the region (BOM site #079028, Longerenong) is 414 mm, but over the experimental period there were seven years of decile 1 or 2 rainfall, with mean rainfall over the duration of the experiment of 375 mm. The fertilizer treatments imposed are five rates of nitrogen (0, 20, 40, 80, 160 kg N as urea) and four rates of phosphorus (0, 9, 18, 36 kg P as triple super) applied annually over the past 19 years. No N is applied during the pulse phase of the rotation and but full applications of N and P occurred in drought years when no crop was harvested (2002, 2006). Prior to 2011, there were two series of N treatments; either all N at sowing or split 50:50 between sowing and stem elongation, and the results reported here are for where N was applied at only at sowing.

**Table 1. Dimensions of nutrient use efficiency (after Dobermann 2007).**

| Metric | Calculation | Range for N in cereal crops |
|---|---|---|
| Apparent Recovery Efficiency | RE = kg increase in uptake $kg^{-1}$ applied<br>= $(U - U_0)/F$ (whole plant)<br>= $(Ug-U_0g)/F$ (grain only) | 0.3 to 0.5 kg/kg; 0.5 to 0.8 in well managed systems, at low N use level or at low soil N supply. |
| Agronomic Efficiency | AE = kg yield increase $kg^{-1}$ nutrient applied<br>= $(Y-Y_0)/F$ | 10 to 30 kg/kg; >25 in well managed systems, at low N use or at low soil N supply |
| Partial Nutrient Balance (Nutrient Removal Ratio) | PNB = kg nutrient removed $kg^{-1}$ applied<br>= Ug/F | 0.1 to 0.9 kg/kg; >0.5 where background supply is high and/or where nutrient losses are low. |
| Partial Factor Productivity | PFP = kg yield $kg^{-1}$ nutrient applied<br>= Y/F = $(Y_0/F)$ | 40-80 kg/kg: >60 in well managed systems, at low N use or at low soil N supply |

*Y=crop yield with applied nutrients; $Y_0$=crop yield with no applied nutrients; F=nutirents applied; U=plant nutrient content of above ground biomass at maturity with applied nutrients; $U_0$=plant nutrient content uptake with no applied nutrients; Ug=grain nutrient content with applied nutrients; $U_0g$=grain nutrient content with no applied nutrients.*

Product samples were taken at harvest and yields are adjusted to 10% (cereals and pulses), 8% (canola) or 0% (hay) moisture contents. Product N content was assessed using NIR in each year. N removal (product of nutrient content and yield) and fertilizer input were used to construct nutrient balances for the period 1996 to 2014. The amount of N fixed during the legume phases (Ndfa) was estimated as the product of three times the grain yield (peak biomass) and 25 kg N/ha/t (Peoples et al. 2001). These estimates were validated against Ndfa measured using the natural abundance method on the lentil crop (2005).

After the 2014 canola crop, the whole site (120 plots) was sampled in the top 10 cm for Colwell P, mineral N, total soil N, C and P. In addition, all plots were sampled for mineral N to 90 cm. Soil tests were also available from prior to the first crop in 1996. These data were analysed using a factorial analysis of variance with four rates of P and 5 rates of N combined, although only selected combinations are presented here.

**Results and discussion**

The annual yields for the period 1996-2014 are summarized in Table 2. All the subsequent nutrient balances analyses include the two failed years (2002, 2006) where fertilizer was applied but no crop removed. Crop growing conditions were good for the first few years of the experiment, but low rainfall over the "Millennium Drought" saw low yields in comparison to long term values. In all but one year, N (lentils, 2005) and P (barley, 2008) treatments resulted in significant yield responses. There were interactions between N and P in nine of the 19 years, and the nature of this interaction was that there was no response to N when P was not applied.

Table 3 gives the soil test values for selected treatments following the 2014 canola crop. Mineral N concentration to 90 cm was significantly higher under the 160 kg N/ha/y treatment with an additional 230 kg N/ha accumulated compared to the lower rates. Previous samplings (Norton et al. 2012) showed there could be as much as an additional 300 kg N deeper than 90 cm under the highest application rate. In contrast, the moderate N rates showed similar mineral N concentrations to 90 cm, although there was a trend for the 80 kg N/ha/y rate to have more deep N than the lower rates. The occurrence of nitrate leaching is corroborated by the decline in soil pH (top 10 cm) by almost 0.5 pH units. So, very high rates of applied N can result in leached N, even though the soil is fine textured, and in general, the seasons have been relatively dry. The more common N rates in this region are 25 kg N/ha/y on cereals and 45 kg N/ha/y on canola, so that at those application rates the potential for leaching losses is low.

Soil organic C concentrations at the commencement of the experiment were 1.14±0.18% and this is similar to the organic C values for the N treatments. Soil organic C was significantly increased with higher P rates (data not shown) but N application caused no significant change in organic C. This contrast the report by Khan et al. (2007) from the long-term "Morrow" plots in the United States of America. Gove et al. (2009) suggest that the results from the Morrow plots are confounded by the use of inappropriate controls.

**Table 2. Mean site yields (t/ha) across all treatments and the level of significance of the yield response to N, P and the interaction of N and P. ns not significant (p>0.05); * p<0.05; ** p<0.01; *** p<0.001.**

| Year | Annual Rainfall (mm) | Crop | Site Mean (t/ha) | N response | P response | N*P response |
|---|---|---|---|---|---|---|
| 1996 | 458 | Barley | 3.26 | *** | *** | *** |
| 1997 | 311 | Chickpea | 1.62 | *** | *** | ns |
| 1998 | 393 | Canola | 1.58 | *** | *** | *** |
| 1999 | 401 | Wheat | 1.88 | *** | *** | ns |
| 2000 | 347 | Barley | 3.08 | *** | *** | *** |
| 2001 | 396 | Lentils | 0.90 | *** | *** | *** |
| 2002 | 245 | Canola | | Crop failure, drought | | |
| 2003 | 463 | Wheat | 3.68 | *** | *** | *** |
| 2004 | 303 | Barley | 1.00 | *** | *** | *** |
| 2005 | 391 | Lentil | 1.03 | ns | *** | ns |
| 2006 | 235 | Canola | | Crop failure, drought | | |
| 2007 | 417 | Wheat | 2.18 | ** | ** | ns |
| 2008 | 328 | Barley | 1.10 | *** | ns | *** |
| 2009 | 455 | Chickpea | 0.48 | *** | *** | ns |
| 2010 | 496 | Canola | 2.45 | *** | *** | ns |
| 2011 | 536 | Oaten Hay | 6.42 | ns | *** | ns |
| 2012 | 290 | Wheat | 4.75 | *** | *** | ns |
| 2013 | 400 | Barley | 4.34 | *** | *** | *** |
| 2014 | 256 | Canola | 0.82 | *** | *** | ns |

**Table 3. Mean yield (1996-2014), soil mineral N, organic carbon (OC) and soil pH levels after the 2014 crop. N balance (fertilizer+Ndfa) and partial nutrient balances (PNB) are also given. Values are for the 9 kg P/ha phosphorus treatment. LSD values are for the interaction N*P where significant (Yield, Min N), otherwise it is for the N responses alone (OC%, pH).**

| N Rate (kg/ha/y) | Yield (t/ha) | OC (0-10 cm) (%) | Min N (0-90) kg N/ha | pH (0-10 cm) ($CaCl_2$) | N balance (kg N/ha) | PNB (fert. alone) | PNB (fert.+ Ndfa) |
|---|---|---|---|---|---|---|---|
| 0 | 1.90 | 0.99 | 33 | 7.22 | -307 | - | 1.87 |
| 20 | 2.29 | 1.05 | 31 | 7.27 | -224 | 2.96 | 1.36 |
| 40 | 2.22 | 1.05 | 54 | 7.28 | -42 | 1.57 | 1.04 |
| 80 | 2.31 | 1.04 | 74 | 7.32 | 355 | 0.92 | 0.74 |
| 160 | 2.32 | 1.02 | 303 | 6.83 | 1454 | 0.47 | 0.42 |
| LSD ($p$<0.05) | 0.09 | ns | 89 | 0.25 | - | - | - |

Table 3 also contains estimates of N balances (removal less fertilizer and Ndfa inputs) and PNB over the duration of the experiment. Two estimates are used in estimating the PNB, one with the fertilizer inputs alone, and the other with the sum of fixed and applied N. The amount of Ndfa varied from year to year (mean values of 122 kg N/ha (1997), 67 kg N/ha (2001), 75 kg N/ha (2005) and 36 kg N/ha (2009)) in response to mean yields, and also in response to P application. The Ndfa rose from a mean of 59 kg N/ha/year to 82 kg N/ha/y where P was applied compared to nil P. The inclusion of Ndfa provides a more realistic assessment of the N balance of the system, rather than just considering a single year crop.

For this rotation that includes one crop in four as a pulse, the N balance including fertilizer and Ndfa for the nil N application was -307 kg N/ha and as N was added, the system removal and use approached a balance at 40 kg N/ha/y. If less than 40 kg N/ha/y was applied, N was being depleted from the system, although the topsoil mineral and the soil organic C (organic matter) do not necessarily reflect that decline. Data from 2010 a similar result was seen where N rate did not affect organic C, but there were significant declines where no P was used (Norton et al. 2012).

Table 4 shows the different metrics derived for this rotation over time. The first point to note is that all efficiency metrics are highest at the lowest N rate, as would be expected given the nature of a fertilizer response curve characterised by diminishing returns. Recovery efficiency in grain and PNB both give an assessment of the balance of nutrients, and the values at 40 kg N/ha/y for RE in grain indicate that half the applied N is not recovered but the PNB suggests that all the N, plus the contribution from Ndfa is recovered. The same data are used, and so this emphasises the importance of qualifying the metrics used when discussing nutrient use efficiency, especially as difference indices do give quite a different assessment of the situation. A similar comparison applies to the AE and PNB comparisons in Table 4.

**Table 4. Nitrogen fertilizer use efficiency metrics from the Dahlen long-term fertilizer experiment. All values are for the 9 kg P/ha rate and the metrics used are explained in Table 1.**

| N Rate (kg N/ha/y) | AE | RE | PFP | PNB |
|---|---|---|---|---|
| 20 | 22.4 | 0.54 | 141 | 1.36 |
| 40 | 11.4 | 0.47 | 71 | 1.04 |
| 80 | 7.9 | 0.37 | 38 | 0.74 |
| 160 | 3.1 | 0.19 | 18 | 0.42 |

During the first few years of the experiment, the progressive N balance for the 20 kg N/ha/y and 40 kg N/ha/y were close to balanced, but with the onset of the Millennium drought and relatively poor years, the 40 kg N/ha/y rate built up a surplus of around 150 kg N/ha, which was then drawn down in the better years from 2009 and was -42 kg N/ha by the end of 2014. Therefore at moderate N rates, in this environment unused N is essentially preserved from one season to the next, or even over several seasons. In these soils, providing application rates are moderate, leaching losses are small, and the dry soils mean denitrification is likely to be low. A long-term N strategy with rates that reflect the annual removals and include Ndfa is a reasonable starting point for a fertilizer strategy for these soils.

## Conclusion

This example represents a modern continuous cropping system using both fixed N and fertilizer N. Overall, N losses appear to be low when rates are less than 80 kg N/ha/y, and at 40 kg N/ha/y the system with one crop in four as a pulse seems in approximate N balance.

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