NITROGEN: USING LEGUMES TO GROW YOUR OWN

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Take home messages

- The amounts of N fixed by legumes are usually related to plant growth with around 20-25 kg of shoot N being fixed for every tonne of above-ground dry matter produced.
- However, 30-60% of the legume's total plant N may be below-ground associated with roots and nodules. Consequently crop legume residues can still contain significant amounts of fixed N even after a large amount of N is removed in grain at harvest.
- The conversion of legume organic N into inorganic N is mediated by microbes and only a fraction of the N in legume residues becomes available as mineral N in the first year.
- Release of mineral N is influenced by soil water content, temperature and pH, the amount of residues returned to the soil after a legume phase, the 'quality' (particularly C:N ratio) of those residues, and the length of the fallow period between the end of the legume phase and sowing the next crop.
- The efficiency of N uptake from fertilizer can be more than twice that of legume sources; however, the impact of legumes on crop N dynamics may be much greater than predicted from the direct uptake of legume N. The N benefit from legumes can also last for more than one year.
- Legume roots and nodules could be a more important source of N for crops than shoot residues.
- Direct effects of legumes on soil N fertility are not necessarily the main source of rotational benefits for following crops.

How much N do legumes fix?

Measurements of N fixation undertaken on 140 pastures and 59 pulse crops growing at various locations in Victoria or southern and central NSW indicate that legumes have the potential to fix more than 100-200 kg N/ha across a wide geographic area (see Table 1).

Table 1. Estimates of the amounts of shoot N fixed by various legumes growing at different locations in SE Australia.

Location	Legume species	Amount of shoot N fixed[A] (kg N/ha per year)	
		Range	Mean
Victoria			
Horsham	Faba bean	82-174	128
	Lentil	60-110	90
	Field pea	85-166	138
	Vetch	72-160	116
	Annual medic	2-90	39
	Lucerne	19-90	43
Rutherglen	Lupin	59-244	150
	Sub-clover	99-238	160
NSW			
Junee	Field pea	133-183	160
	Sub-clover	21-118	56
	Lucerne	103-167	128
Stockinbingal/Temora	Faba bean [2002]	112-146	123
	Lupin/field pea [2008]	12-83	45
Condobolin	Lupin	26-93	51
	Field pea	35-111	58
Trangie	Lucerne	13-82	37

[A] The data set includes experimental trials and on-farm measures collected from commercial crops and pastures. Source: Peoples *et al.* (2001) Plant & Soil 228: 29-41, and includes unpublished data of Cela, Angus, Swan, Crews & Peoples.

The amount of N fixed by a legume in any environment is regulated by two factors. The amount of N present in the legume's products of growth, and the proportion of that N derived from atmospheric N_2 (%Ndfa) as a result of symbiotic N fixation by rhizobia in the legume's nodules:

Amount N fixed = Legume N x (%Ndfa)/100

The N accumulated by a legume is in turn determined by the amount of dry matter (DM) produced and N content (%N) of that biomass:

Legume N = Legume DM x (%N)/100

Major factors influencing %Ndfa

Rhizobia In the absence of the appropriate rhizobial species in the soil %Ndfa will be zero (ie no symbiosis can be formed), and %Ndfa may be less than optimal if the rhizobial strains in the soil are poorly effective. This can generally be rectified by inoculation.

Soil nitrate Legumes are similar to all other plants in that they can utilise forms of mineral N in soil (ammonium and nitrate) for growth (albeit generally not quite as efficiently as cereals or grasses; see Herridge *et al* 1995 Soil Biol Biochem 27: 545-551). Since soil nitrate and N fixation are complementary in meeting the N requirements for growth by a legume crop, nitrate effectively inhibits nodulation and N fixation processes. In other words, a legume's reliance upon N fixation (ie %Ndfa) will decline with increasing concentrations of mineral N in the legume's root zone. High concentrations of soil nitrate can occur as the result of excessive tillage, heavy summer and autumn rainfall (provided weeds are controlled), a long fallow which might be used to build-up and conserve soil water (eg such as in the cropping zones of northern NSW, Schwenke *et al* 1998 Aust J Expl Agric 38: 61-70), or after a series of failed or droughted crops (eg %Ndfa of several different legume crops grown at Stockinbingal between Temora and Cootamundra in southern NSW in 2008 ranged from just 8-29% compared to measurements of >70% in the same district in 2002; unpublished data of Cela, Angus, Swan, Crews and Peoples). Experimentation with pea in France indicated that nitrate inhibition of N fixation was absolute (i.e. seasonal %Ndfa = 0) when soil mineral N at sowing exceeded 380 kg nitrate-N/ha, and N fixation was not initiated until soil mineral N concentrations dropped below 56 kg N/ha (Voisin *et al* 2002 Plant & Soil 243: 31-41). Similarly, research trials undertaken with productive chickpea crops in Queensland showed that little or no N_2 was fixed once the soil contained >350 kg nitrate-N/ha (Doughton *et al* 1993 Aust J Agric Res 44: 1403-1413), although data collected from commercial chickpea crops with lower biomass in northern NSW suggest the critical value may be closer to 200 kg nitrate-N/ha (Schwenke *et al* 1998). While the NSW results for chickpea may have been complicated by low rainfall, it was noteworthy that neighbouring faba bean crops sampled on the same farms maintained much higher levels of %Ndfa than chickpea at equivalent concentrations of soil nitrate (Schwenke *et al* 1998).

Impact of legume growth

With the exception of the 2008 data from Stockinbingal in Table 1 above, the %Ndfa values for most legumes ranged between 60-90% (mean %Ndfa of about 75% for both pulses and pasture legumes) and the amounts of shoot N fixed were closely related to the amount of biomass production, with around 20-25 kg of shoot N being fixed for every additional tonne of shoot dry matter produced (Fig. 1). So although the levels of %Ndfa are important, provided there are adequate numbers of effective rhizobia in the soil and concentrations of soil mineral N are not too high, N_2 fixation is overwhelmingly regulated by legume growth rather than by %Ndfa. Apart from climatic extremes almost every other factor that has been identified as influencing N fixation has done so through a direct impact on legume growth potential (e.g. nutrition, weed control, disease, pests, or cropping sequence and intensity), and consequently can potentially be addressed or manipulated by a farmer through management.

Therefore, basic improvements in crop agronomy probably hold the greatest promise as a means of enhancing inputs of fixed N through increasing legume biomass. A significant strategy involves the use of legume genotypes adapted to the prevailing soil and environmental conditions.

Contributions of residual fixed N to soil

With pasture legumes the fixed N in foliage tends to be returned to the soil either in urine or faeces following grazing, or via senesced and fallen materials that might remain unconsumed by livestock. But in the case of crop legumes, much of the N in the shoot is harvested in the high protein grain.

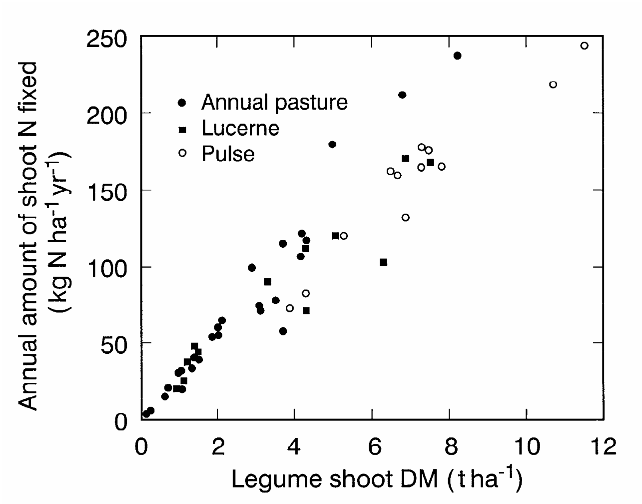

Figure 1. The relationship between shoot dry matter (DM) accumulation and estimates of the annual amounts of shoot N fixed by rainfed annual pasture legumes, lucerne, or pulse legume crops growing in SE Australia (Peoples *et al.* 2001 Plant & Soil 228: 29-41).

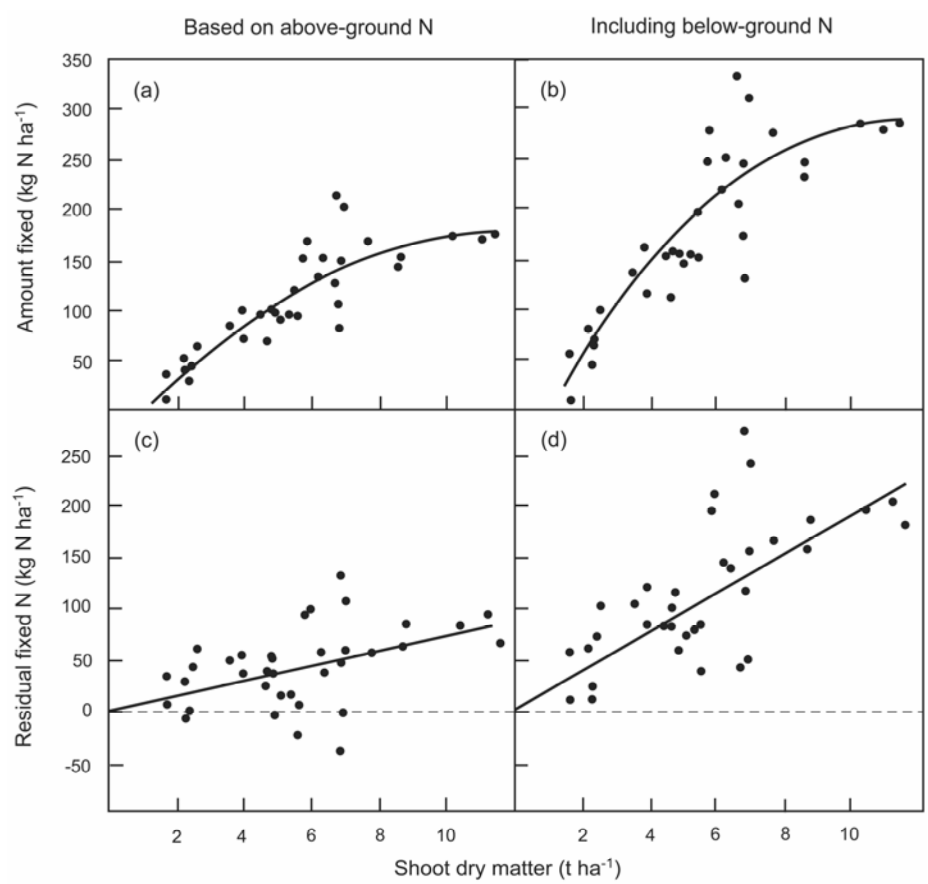

Figure 2. Data obtained from irrigated commercial faba bean crops in northern NSW illustrating the consequences of (i) ignoring the contribution of below-ground N (a,c), or (ii) including the contribution of below-ground N (b,d) on determinations of amounts of N_2 fixed (a,b) and residual fixed N remaining after grain harvest (i.e. fixed N – seed N removed). Calculations of positive measures of residual fixed N indicate a net input of fixed N, while negative values represent a net export of N from soil. The broken line represents the situation where the estimate of the amounts of N_2 fixed equals the seed N removed. Data modified from Rochester *et a*l. (1998) Aust J Expl Agric 38: 253-260.

Often it is assumed that because such large amounts of N are removed from the field in grain that legume pulse crops might not return much fixed N to the soil for the benefit of following crops. However, the values such as those presented in Table 1 have usually been determined solely from measures of legume shoot biomass. Below-ground contributions of fixed N have often been ignored. Field research now suggests that N associated with nodules and roots may represent between 30% and 60% of the total N accumulated by legumes (e.g. Rochester *et al* 1998 Aust J Expl Agric 38: 253-260; Khan *et al* 2003 Aust J Agric Res 54: 333-340; McNeill and Fillery 2008 Plant & Soil 302: 297-316). Therefore, total inputs of fixed N by pulses are likely to be much greater than had previously been believed from shoot-based determinations (e.g. compare Fig. 2a with 2b). It follows that, when below-ground contributions of fixed N are included in N budgets compared to when they are not, different conclusions would be drawn about the potential for legume crops to return fixed N to soil following grain harvest (e.g. Fig. 2c, 2d; see also Peoples et al., 2001).

Patterns of N release for crops

It should not be assumed that all of the N fixed by legumes will immediately be available to crops following either a pulse or a pasture phase. The N in legume organic matter decomposes to produce ammonium and a specialised group of microorganisms (nitrifiers) convert the ammonium N to nitrate. Both ammonium and nitrate can be utilised by plants for growth, but many plants prefer nitrate. Since the conversion of organic N into inorganic N (i.e. the process of mineralisation) is mediated by soil microbes only a portion of the N in legume root and shoot residues will become available for plant uptake in the short-term and this can be influenced by:

- Soil water content and temperature - Peak rates of mineralisation in autumn or a favourable spring where soil water and temperatures are optimal are about 1.0-1.2 kg N/ha/day. Winter temperature of around 7°C reduces the rate to about 0.2 kg N/ha/day, but the rate essentially falls to zero in a dry soil.
- Soil pH - Low soil pH inhibits the activity of nitrifiers. In acid soils the conversion of ammonium to nitrate might be restricted to the top few cm where the soil pH is likely to most favourable due to the buffering capacity of organic matter near the soil surface.
- The 'quality' of the residues - Decomposition studies of shoot and root residues indicate that differences in patterns of N release are strongly linked to tissue C:N ratios. Residues with a low C:N ratio decompose fastest, and those with a high C:N ratio can actually lead to a reduction in mineral N by absorbing N mineralised from the soil organic matter (this process is called immobilisation). Not all legume residues are the same. For example, the quality (C:N ratio) of shoot residues and the rate of mineralisation will differ if a legume crop is grown for grain or used as green manure since the mature, senesced vegetative residues remaining after grain harvest have a much higher C:N ratio than young foliage material either green or brown manured earlier during growth. Similarly stems and pods of pulses tend to decompose more slowly than leaves for the same reason.

At the end of a growing season roots are likely to represent the single largest pool of legume N for mineralisation. In the case of the roots of species such as sub-clover the breakdown is usually rapid because of the low C:N ratio (around 13:1), and is often complete by the second or third year of a following cropping phase (eg Table 2). The C:N ratio for lucerne roots, on the other hand, is 25-30:1 and this results in an initial transient immobilisation of N followed by a slow mineralisation of lucerne residues (see Bolger *et al.* 2003 Biol Fertil Soils 38:296-300). This may partly explain why there is sometimes N deficiency in crops immediately after lucerne. However, the slower initial mineralisation and larger pool of lucerne N in the soils means that the supply of N after a lucerne pasture is likely to continue much longer into the cropping phase than following sub-clover (eg Table 2).

Factors that can influence concentrations of inorganic after a pasture include:

- The botanical composition of the pasture and the amount of legume grown during the pasture phase - Generally mixed legume-grass pastures decompose more slowly than pure legume stands. However, data from different pastures at two locations that differed in total average annual rainfall (550mm at Junee, and 430mm at Ardlethan) suggest that concentrations of soil nitrate and subsequent crop response following a pasture phase tend to be related to the cumulative amount of legume biomass grown, with on average an additional 15 kg nitrate-N/ha being accumulated over and above background mineralisation of soil organic N for every additional t of legume dry matter (DM) accumulated (Fig. 3).
- Grazing intensity - High grazing pressure results in greater concentrations of mineral N as a much higher proportion of the N in the foliage of pasture legumes is consumed by livestock to be excreted as urine, which in turn is rapidly converted to ammonium and nitrate in the soil.
- The timing of lucerne removal of prior to cropping - On-farm experimentation near Junee in southern NSW indicated that concentrations of soil mineral N measured at sowing following a wheat crop and its impact on crop N uptake and grain yield were closely related to the time of removal of the lucerne pasture prior to cropping (Table 3). In this particular experiment soil mineral N was increased by around 0.75 kg N/ha of every additional day of fallowing, or by 0.5 kg N/ha per mm of rainfall over the fallow period.

Table 2. Grain yield of wheat harvested in 2001 grown in the absence of fertilizer N for different periods after either subterranean clover- or lucerne-based pasture phases.[A]
Values followed by the same lower case letter are not significantly different at P=0.05.

Sequence of pastures or crops					2001 Yield
1997	1998	1999	2000	2001	(t/ha)
Barley	Canola	Wheat	Canola	Wheat [B]	2.8a
Barley	Subclover	Subclover	Canola	Wheat	3.4b
Barley	Subclover	Subclover	Subclover	Wheat	4.2c
Lucerne[C]	Canola	Wheat	Canola	Wheat	3.9c
Lucerne[C]	Lucerne	Wheat	Canola	Wheat	4.1c
Lucerne[C]	Lucerne	Lucerne	Canola	Wheat	4.1c
Lucerne[C]	Lucerne	Lucerne	Lucerne	Wheat	4.1c

[A] Unpublished data (Angus, McCallum, Peoples and Swan) from an on-farm trial site located near Temora in southern NSW.
[B] Wheat yield of the continuous cropping control involving a rotation of canola and cereals in 2001 was increased to 3.4 t/ha with the addition of 60kg fertilizer N/ha applied as urea.
[C] The farmer's lucerne pasture was 4 years old at the commencement of experimentation.

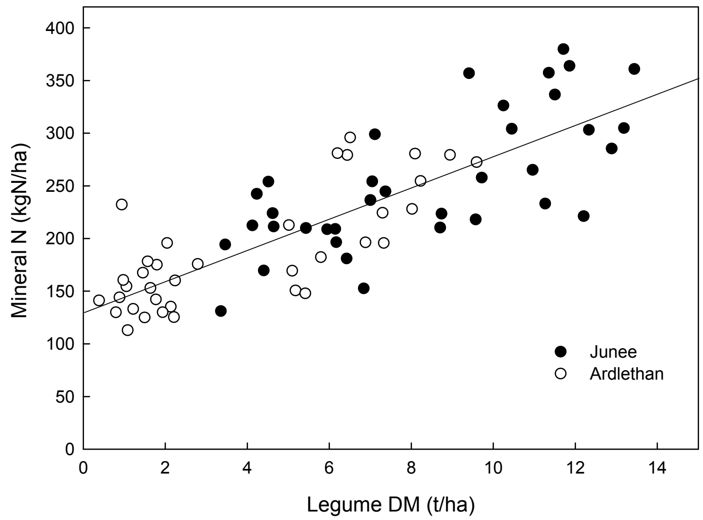

Figure 3. Relationship between concentrations of mineral N in the top 1m of soil just prior to cropping and the total above-ground legume dry matter (DM) accumulated during the previous 3 year pasture phase (regression equation: Mineral N = 130 + 0.0148 x legume DM, r^2 = 0.66). Data are derived from experiments undertaken at two locations in southern NSW (courtesy of Virgona, Dear, Sandral and Swan).

Table 3. Example of the effect of timing of removal of lucerne prior to cropping on concentrations of soil mineral N (top 2m) measured at the time of sowing the first wheat crop, and the subsequent crop uptake of N and grain yield.[A]

Time of lucerne removal (months prior to sowing)	Soil mineral N at sowing (kg N/ha)	Wheat above-ground N at maturity (kg N/ha)	Grain yield (t/ha)
6	206	137	5.9
4	111	109	5.0
2	59	86	3.8

[A] Results from an on-farm trial near Junee in southern NSW (Angus *et al*. 2000 Aust J Agric Res 51: 877-890). Values represent the combined data from both cultivation and herbicide removal treatments.

How much legume N is taken up by following crops and how does this compare to fertiliser?

The fate of N in legume residues is often measured using legumunious materials labelled with the stable (non-radioactive) isotope of N, ^{15}N (discussed by Crews and Peoples 2005 Nutrient Cycling in Agroecosystems 72: 101-120). Such studies generally indicate that <30% of the legume N is taken up by a subsequent crop (Table 4). Such data have led to suggestions that legumes are an inefficient short-term source of N. Certainly there are examples in Table 4 where <10% of the N in a following crop appear to be derived from the prior legume. However, there are also situations where legume sources have provided a significant proportion (around 20% or more) of the next crop's N requirements (Table 4).

Often the ^{15}N-labeled legume inputs utilised in experiments such as those presented in Table 4 represent only shoot material. This ignores the potentially large amounts of below-ground legume N associated with, or derived from, roots and nodules discussed above. Under Australian field conditions wheat has been reported to utilise between 3-10% of the residual below-ground N from a previous lupin crop (McNeill and Fillery 2008), or 8% and 16% of the below-ground N of prior faba bean and chickpea crops, respectively (Khan 2000 PhD thesis Melbourne University). In the case of faba bean and chickpea, this uptake of below-ground N contrasted with an uptake by wheat of just 3% of the residual shoot N (Khan, 2000). Other studies have suggested that below-ground legume N may be the source of between 30-75% of the total mineral N accumulating after legumes (Evans *et al* 2003 Aust J Agric Res 54:

763-776). Thus the below-ground pool of legume N appears to be an important source of N for following crops. Paradoxically, it has often not even been considered.

Table 4. Examples of the extent of uptake of ^{15}N-labelled N from legume residues by a following cereal crop.

Species	Amount of residue N returned (kg N/ha)	Crop uptake of legume N (% residue N)	Proportion of cereal N derived from legume (% crop total N uptake)
Grain legumes			
Chickpea	183	9	19
Lentil	45	6	1
Pea	49-130	6-15	6-13
Faba bean	73-96	11-17	11-19
Lupin	36-86	21-27	6-18
Pasture legumes			
Annual medic	48	24	8
White clover	50-81	25	12-25
Lucerne	40-112	12-21	7-15

Source: Peoples *et al.* (2009) Symbiosis (in press), and Khan (2000 PhD thesis Melbourne University)

Studies that estimate uptake efficiencies of labeled N from legume residues also have a tendency to underestimate the overall N-supplying capacity of a legume-based system. This is likely to be the result of N 'pool substitution' whereby the newly applied ^{15}N-labeled legume N is immobilized in the microbial biomass and unlabeled N is mineralized. The importance of pool substitution was illustrated by Murphy *et al*. (1998 Aust J Agric Res 49: 523-535) in a ^{15}N field experiment in WA. In the second year of a lupin-wheat rotation, they found gross N mineralization in the top 10cm of soil to be 120 kg N/ha, and net N mineralization (i.e. gross mineralization – immobilization) to be only 59 kg N/ha, 69% of which (41 N kg) originated from the soil microbial pool. These data suggest that most of the N initially released from lupin residues was immobilized and thus inaccessible to the wheat crop in the short-term. This was compensated for by mineralization of older (unlabeled) microbial-N that subsequently became available for crop uptake. The net result of such processes is that calculations based on crop recovery of ^{15}N-labeled leguminous material are often lower than determinations of 'agronomic' N benefits derived from including a legume in a rotation.

Comparisons of N use efficiency of legume N with fertilizer

Unfortunately there are only relatively few studies where ^{15}N-labeled inputs have been used to compare legume with fertilizer sources of N under the same experimental conditions. Such comparisons in rainfed farming system indicate that cereal crops, on average, tend to recover more than twice N from fertilizer than from legume residues (mean 36% cf 15% of the legume N applied, Table 5). However, the estimates of N losses from legume sources tend not to be very different from fertilizers (mean 23% cf 33% of the fertilizer N applied), despite a higher proportion of the legume N generally remaining in the soil at harvest as compared to fertilizer (Table 5).

Table 5. Examples of the fate of either ^{15}N enriched fertilizers or legume residues applied to cereal crops, indicating the range of estimates of crop N recovery and the extent of losses of the applied N. Values in parentheses represent the mean.

Source of N applied	Crop uptake (% applied N)	Recovered in soil (% applied N)	Unrecovered [assumed lost] (% applied N)
Fertilizer	17-50 (36)	21-40 (31)	16-62 (33)
Legume	5-27 (15)	37-90 (62)	4-54 (23)

Source: Peoples *et al.* (2009) Symbiosis (in press)

These general conclusions about the relative use and losses of legume and fertilizer N should be qualified by acknowledging that:

(1) The comparative studies summarized in Table 5 have not necessarily always used 'best management practices' when applying either the fertilizer or legume residues.

(2) As discussed above the ^{15}N-labeled legume inputs utilized in most experiments tend to represent only shoot material. This ignores the potentially large amounts of crop and pasture legume N below-ground associated with, or derived from, roots and nodules.

(3) Also as discussed above, studies that estimate uptake efficiencies of labeled N from recently applied legume residues have a tendency to underestimate the overall N-supplying capacity of a legume-based system. This suggestion is also supported by studies that have observed similar grain yield by crops grown on legume or fertilizer sources of N despite lower apparent utilization of the legume N (eg Ladd and Amato 1986 Soil Biol Biochem 18: 417-425).

(4) Often investigations compare N recovery and losses for a single year or just the first crop following a legume phase, and this may be too short in duration to fully demonstrate the consequences of utilizing fertilizer or legume N (see following sections).

Impact of legumes on grain yield by following crops

It is well known that cereal grain yields can be enhanced by including a legume in the rotation. Angus *et al* elsewhere in the 2008 GRDC Updates reported that pulse legumes can enhance wheat yields by 1-1.7 t/ha across a range of environments.

As discussed in detail by Angus and his colleagues, such yield responses should not be attributed only to N. For example, reductions in cereal leaf and root disease have been demonstrated to be major factors contributing to observed yield advantages after legumes and other break crops. One way of estimating the relative value of the N contribution and other rotational benefits of legumes is to compare the quadratic response curves for cereal grain yield with different rates of applied fertilizer N in legume-cereal and cereal-cereal sequences (as discussed by Chalk 1998 Aust J Agric Res 49: 303-316). Where the cereal-cereal response curves converge and intersect the legume-cereal line with increasing rates of fertilizer N, the legume benefit is considered to largely be due to N (such as in Fig. 4a). Converging curves which do not intersect indicate a combination of N and non-N benefits (Fig. 4b). Finally if the yield response curves after the legume and non-legume are parallel, then factors other than N are primarily involved (Fig. 4c). Chalk (1998) compared grain yield responses to increasing rates to applied fertilizer N for a series of wheat-wheat and lupin-wheat rotations undertaken by Rowland *et al* (1988 Aust J Expl Agric 28: 91-97) in WA during the 1980s. He concluded that enhanced N availability derived from the lupin either dominated the rotational effect, or was an important contributing factor in the subsequent yield improvement by wheat in less than half of the experiments (only 9 of the 21 comparisons fell into categories such as those depicted in figs. 4a and 4b). Very few similar studies have been undertaken elsewhere in Australia so it is difficult to say how representative such general conclusions may be in the south-eastern cropping zone at the beginning of the 21st Century.

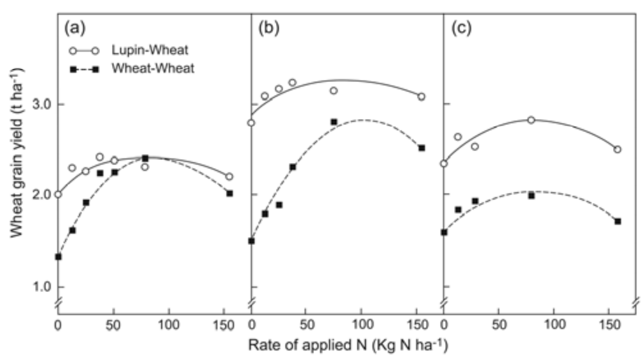

Figure 4. Examples of different grain yield responses of wheat to increasing rates of applied fertilizer N in wheat-wheat sequences (■- -■) or lupin-wheat rotations (○-○). Modified from Chalk (1998) Aust J Agric Res 49: 303-316.

How long might crops benefit from a legume?

Legume effects on grain yield and protein have been observed to occur over several years of cropping (eg Harris *et al* 2002 Aust J Agric Res 53: 1271-1283). The net result of a larger residual pool of legume N combined with a slower pattern of N mineralisation following a perennial pasture legume like lucerne is that crops grown after lucerne can be supplied with N over a much longer period (typically more than 3 years, see Table 2 above), although possibly in lesser amounts in the first year, than following annual pasture legumes or pulses (usually only 1-2 years, eg Table 2). The relative size of the N benefit obtained after lucerne depends upon a combination of the density and productivity of the lucerne and the duration of the pasture phase. However, as mentioned above, there is also a number of other non-N rotational benefits that can be very important in contributing to improvements in subsequent crop productivity.

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