Legume effects on available soil nitrogen and comparisons of estimates of the apparent mineralisation of legume nitrogen

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Abstract
Results from experimentation undertaken in southern NSW indicated that total soil mineral (inorganic) nitrogen (N) measured just prior to sowing wheat in 2012 (0-1.6m) was 42 or 92 kg N/ha greater following lupin grown for either grain or brown manure (BM) respectively, than following wheat or canola in 2011. The apparent net mineralisation of lupin organic N over the 2011/12 summer fallow was equivalent to 0.11-0.18 kg N/ha per mm rainfall and 7-11 kg mineral N per tonne lupin shoot residue dry matter (DM). This represented 22-32% of the total estimated lupin residue N at the end of the 2011 growing season. By the autumn of 2013, there was still 24-40 kg more N/ha after the 2011 lupin treatments than non-legumes. This represented an apparent mineralisation of a further 4-5 kg N per tonne of 2011 lupin's residue biomass and 14% of its N two years after the lupin had been grown. Data collated from four other experiments undertaken in different years and locations in NSW, Vic and SA generated similar increases in soil N availability in the year following legumes, and comparable estimates of N mineralisation. It was concluded that relationships averaged across all eight pulse crops grown for grain in the five separate studies (0.18 kg N/ha per mm; 10 kg N/ha per t shoot residue DM; 26% residue total N) could represent useful 'rules-of-thumb' to predict the likely affects of legumes on the N dynamics of dryland cropping systems.

Key words
Pulses; canola; cereals; on-farm; grower group

Introduction
Even though elevated concentrations of soil mineral nitrogen (N) (i.e. nitrate+ammonium) are frequently observed after legume crops and pastures (Angus *et al* 2015), only a fraction of the N in legume residues remaining at the end of a growing season becomes available immediately for the benefit of subsequent cereal crops (Peoples *et al* 2009). The microbial-mediated decomposition and mineralisation of the N in legume organic residues into plant-available inorganic forms is influenced by three main factors: (i) rainfall to stimulate microbial activity, (ii) the amount of legume residues present, and (iii) the N content (and "quality") of the residues. Field data are utilised to estimate the apparent mineralisation of N from legume stubble, or brown manure (BM; where a legume is killed with "knock-down" herbicide prior to maturity to provide a boost in available soil N and/or to control difficult to manage weeds). The rate of mineralisation is expressed per mm of summer fallow rainfall, per tonne (t) of above-ground legume residue dry matter (DM), and kg total residue N (i.e. above-ground N + N estimated to be associated with the nodulated roots).

Methods
The experiment was located at an on-farm field site at Junee Reefs, NSW, Australia and undertaken in partnership with the FarmLink Research grower group. Soil pH ($CaCl_2$) was 5.50 in the surface 0-10 cm. Soil mineral N prior to the commencment of the experiment in April 2011 (0-1.6m) was 100 kg N/ha. The following crop treatments were replicated four times and were sown in a randomized design in 2.5 x 20m plots in either late-April (lupin and canola) or mid-May (wheat):
(1).Lupin: cv Mandelup - for grain; inoculated at sowing + 75 kg kg/ha MAP (8 kg N/ha);
(2).Lupin: cv Mandelup - for brown manure (BM); inoculated at sowing + 25 kg/ha MAP (3 kg N/ha), with the crop being terminated in September using knock-down herbicides (450 g/L glyphosate (Roundup CT) @ 2 L/ha + 300 g/L clopyralid (Lontrel) @ 150 ml/ha + 240 g/L carfentrazone-ethyl (Hammer) @ 25 ml/ha);
(3).Canola: cv Crusher TT– for grain; (Jockey + Gaucho) + 25 kg/ha MAP (3 kg N/ha) + 100 kg/ha urea (46 kg N/ha) and 80 kg/ha ammonium sulphate (17 kg N/ha) in-crop;
(4).Wheat: cv Lincoln – for grain; Raxil + 25 kg/ha MAP (3 kg N/ha) + 100 kg/ha urea (46 kg N/ha) in-crop.

Above-ground biomass was determined immediately prior to lupin BM termination, or 4 weeks later in the case of the grain crops at around the time of lupin mid-pod fill by removing all plants from 4 × 1m sections of row from each plot. Shoot DM was measured after drying subsamples at 70ºC. Grain yield was determined at maturity by the mechanical harvesting of the central 16m of each plot. Dried plant and grain samples were analysed for % N and ^{15}N abundance using a 20-20 stable isotope mass spectrometer (Europa Scientific, Crewe, UK). At the end of April 2012, each of the replicated plots was sampled for soil mineral N analysis to a depth of 1.6m, and all treatments were sown to Spitfire wheat in mid-May. Further soil samples were again collected for soil mineral N analysis in April 2103. Four additional studies similar to that outlined above at Junee Reefs, have been undertaken in collaboration with the Riverine Plains grower group, Birchip Cropping Group (BCG), Mackillop Farm Management Group (MFMG), NSW DPI, Vic DEPI and SARDI in NSW, Victoria and South Australia. These experiments are not described in detail here; however, summaries of estimates of apparent mineralisation of legume from these studies are included in the current paper for comparative purposes.

Calculations

Estimates of total plant N were derived from the peak biomass shoot N data by assuming ~25% total plant N for lupin, and ~30% for wheat and canola N was associated with roots (Unkovich et al. 2010). The last 1m at each end of the canola and wheat plots received no fertiliser N and plants were collected from these areas at the same time as the lupin sampling and were used as "reference" plants to allow the determination of the proportion of the lupin N derived from atmospheric N_2 (%Ndfa) using the ^{15}N natural abundance technique, and these values were combined with lupin total N data to calculate inputs of fixed N:

Amount of N_2 fixed over the growing season (kg N/ha)

= (total lupin N) x (%Ndfa/100) Equation [1]

The total amounts of N remaining in crop vegetative residues and roots at the end of the 2011 growing season were calculated as:

Total residue N

= (total crop N) – (grain N removed) Equation [2]

The net effect of lupin treatments on available soil N was calculated from the differences in soil mineral N data (0-1.6m) following lupin and wheat in April 2012 and April 2013. The apparent net mineralisation of lupin N was calculated in several different ways from mean treatment data by assuming negligible net N release from the 2011 wheat residues :

Apparent mineralisation of legume residues (kg N/ha per mm fallow rainfall)

= [(mineral N after legume) – (mineral N after wheat)] /(fallow rain) Equation [3]

Apparent mineralisation of legume residues (kg N/ha per tonne shoot residue DM)

= [(mineral N after legume) – (mineral N after wheat)] /(legume shoot residue DM) Equation [4]

Where shoot residue = (peak biomass DM) – (grain yield)

Apparent net mineralisation of legume N (% 2011 total residue N)

= 100x [(mineral N after legume) – (mineral N after wheat)] /(total legume residue N) Equation [5]

Analysis of variance was undertaken on the DM, N and soil mineral N data to provide least significant difference (LSD) determinations. In each case P values were <0.001. However, no such statistical analyses were possible for the derived estimates of apparent mineralisation obtained using Equations [3]-[5], but as DM, N and soil mineral N provide the basis of the estimates, significant differences in these main factors should be sufficient to confer differences in apparent mineralisation.

Results

Crop growth in 2011

The 2011 growing season rainfall (GSR: April-October) was 216 mm which was lower than the 311 mm long-term average, but heavy rainfall in February 2011 (226 mm) resulted in an annual total of 639 mm, around 130 mm wetter than the long-term average (506 mm). The soil moisture profile at the beginning of the growing season was close to full which contributed to good crop establishment and growth, and respectable grain yields (Table 1). The lupin treatments were calculated to have accumulated a total of 290 kg N/ha (lupin BM) and 398 kg N/ha (lupin grain crop) of which 241 kg N/ha (83±3%) and 338 kg N/ha (85±4%) were estimated to have been derived from N2 fixation, respectively (LSD=35; P<0.001). The crop harvest indices (grain as % of above-ground DM) were 35% for lupin, 43% for wheat and 30% for canola. The N content of the stubble remaining after grain harvest was higher for the lupin crop (1.4%N; C:N ratio=28) than either canola (0.7%N; C:N=60) or wheat (0.3%N; C:N=130), but the shoot material in the lupin BM treatment had the highest "quality" (2.6%N; C:N=15). The total amounts of N calculated to be remaining in the vegetative residues and roots of the lupin treatments at the end of the 2011 growing season were between 3- to 5-fold higher than where wheat had been grown (Table 1).

Table 1. Above-ground dry matter (DM), N accumulation, grain yield and the amount of N estimated to be remaining in vegetative and root residues at the end of the growing season where wheat, canola, or lupin was grown for either grain or brown manure (BM) at Junee, NSW in 2011[a]

Crop grown in 2011	Peak biomass (t DM/ha)	Above-ground N (kg N/ha)	Total crop N[b] (kg N/ha)	Grain yield (t/ha)	Grain N harvested (kg N/ha)	N remaining in residues (kg N/ha)
Lupins BM	8.4	218	290	0	0	290
Lupins	9.9	300	398	3.5	210	188
Wheat +N[a]	11.1	106	151	4.8 (10.4% protein)	87	64
Canola +N[a]	10.6	164	207	3.2 (46% oil)	94	113
LSD (P<0.05)	1.3	36	46		11	22

[a] N fertiliser was applied to wheat @ 49 kg N/ha and canola @ 66 kg N/ha.
[b] Above-ground data adjusted to include an estimate of below-ground N (Unkovich et al. 2010).

Trends in available soil mineral N, and estimates of N mineralisation in 2012 and 2013

Soil mineral N measured in April 2012 were similar following the 2011 wheat and canola crops (76-77 kg N/ha), but were 42 or 92 kg N/ha greater than after wheat where lupin had been grown for grain or BM, respectively (Table 2). Apparent net mineralisation over the wet 2011/12 summer fallow (515 mm Sept 2011-April 2012 after BM, or 386 mm Nov 2011-April 2012 for grain crops cf 214 mm long-term average) represented the equivalent of 0.11-0.18 kg N/ha per mm rainfall, 7-11 kg N per tonne residue DM, and 22-32% of the 2011 lupin residue N. Soil mineral N was still 24 or 40 kg N/ha higher in soil in the lupin-wheat sequences than continuous wheat in April 2013 (Table 2), which was equivalent to a further 4-5 kg N per tonne of the 2011 residue DM, with 14% of the residue N subsequently becoming available.

Table 2. Concentrations of soil mineral N (0-1.6m) measured in autumn 2012 and 2013 following either wheat, canola and lupin grown for grain or brown manure (BM) at Junee, NSW in 2011, and calculations of the apparent net mineralisation of lupin N from 2011 expressed per tonne shoot residue dry matter (DM), or as a % of total residue (above+below-ground) N.

Crop grown in 2011	Soil mineral N autumn 2012	Apparent mineralisation of legume N		Soil mineral N autumn 2013	Apparent net mineralisation of legume N	
	(kg N/ha)	(kgN/t DM)	(% residue N)	(kg N/ha)	(kgN/t DM)	(% residue N)
Lupins BM	169	11	32%	167	5	14%
Lupins	119	7	22%	151	4	14%
Wheat	77	-	-	127	-	-
Canola	76	-	-	115	-	-
LSD (P<0.05)	35			20		

Comparisons of legume effects on soil mineral N and N mineralisation at other locations

Each of the four independent experiments undertaken in different locations, years, and soil types indicated improvements in soil mineral N after legumes, and comparable estimates of apparent net mineralisation of legume N (Table 3) were calculated to those obtained for Junee Reefs (Table 2).

Table 3. Examples of the impact of prior legume crops on additional autumn soil mineral N compared to following wheat, and estimates of the apparent net mineralisation of legume N at different locations in NSW, VIC and SA.

Location and year	Legumes grown for grain or BM in previous year	Additional soil mineral N	Apparent net mineralisation of legume N		
		(kg N/ha)	(kg N/ha per mm)	(kgN per t DM)	(% residue N)
Breeza, NSW	Chickpea	38	0.14	12	30
1998	Faba bean	47	0.17	18	36
Hopetoun, Vic	Field pea	47	0.17	6	17
2010	Vetch BM	88	0.24	10	24
Culcairn, NSW	Lupin	61	0.10	11	30
2011	Faba bean	88	0.15	11	27
Naracoorte, SA	Field pea	28	0.23	6	18
2012	Faba bean	42	0.34	10	31
Mean		55	0.19	11	27

Discussion

In common with many previous field experiments where the accumulation of soil mineral N after legumes has been compared with wheat (Angus *et al* 2015), increased concentrations of available soil N were detected following all legume species grown at five different locations across south-eastern Australia (Tables 2 and 3). The estimates of apparent mineralisation of legume N calculated from these data represent the net effect of growing legumes for BM or grain on available soil N regardless of whether the mineral N was derived directly from above- and below-ground legume residues, arose from "spared" nitrate due to a lower efficiency of legume roots in the recovery of soil mineral N, and/or an additional release of N from the soil organic pool (Peoples *et al*. 2009). Although soil mineral N was not determined following grain harvest at the end of the 2011 growing season at Junee Reefs, given that lupin assimilated only 49-60 kg N/ha from the soil (calculated as: total lupin N - N fixed) while 151 kg N/ha was accumulated from the soil and fertiliser by wheat, it is likely that some of the additional available soil N measured after lupin represented unutilised nitrate carried over from the previous season.

The measured improvements in soil mineral N, and the derived estimates of apparent mineralisation of legume N, were similar across all five studies (Tables 2 and 3). As might be expected from the lower C:N ratio of the BM residues and the longer period available for mineralisation to occur (Peoples et al 2009), the calculated estimates of mineralisation were greater, for BM treatments than where pulses were grown for grain (Junee Reefs and Hopetoun). Apparent mineralisation also tended to be higher after lupin or faba bean than following chickpea or field pea (Breeza and Naracoorte average of 14 kg N/ha per t shoot residue DM and 33% residue total N cf 9 kg N/ha per t shoot residue DM and 22% residue total N; Tables 2 and 3).

Conclusions

The relationships between summer fallow rainfall, legume residue DM, or total N, and soil mineral N measured the following autumn, were generally similar across five different experiments and were comparable to estimates previously determined for pasture legumes (Angus and Peoples 2012). This suggests that average estimates of apparent mineralisation might represent useful 'rules-of-thumb' to predict the likely additional mineral N provided by legumes in dryland grain production systems of south-eastern Australia. More experimental data are required to ensure the reliability of such determinations. This is especially important to confirm whether there are consistent differences between legume species and, in the case for legume BM treatments, to quantify the impact of timing of crop termination on the accumulation of mineral N. Of the three different measures of apparent mineralisation examined here, perhaps the estimate of around 10 kg additional soil mineral N/ha per tonne shoot residue DM might be the simplest for farmers and their advisors to apply. Since around one-third of the above-ground biomass is commonly harvested in grain in most pulse crops (i.e. Harvest Index = ~0.33), it should be relatively easy for farmers to calculate residue DM directly from grain yields (i.e. ~ twice the tonne grain harvested/ha). Consequently, 20 x tonne grain yield/ha could be a useful guide to the expected additional mineral N prior to sowing a following crop and provide a basis for modifying decisions on N fertiliser applications. However, it should be recognised that the end result will ultimately be mediated by rainfall over the summer fallow. There are potential negative implications of under-estimating available N using the proposed relationship as supplying too much fertiliser N to wheat in a dry cropping year could increase the risk of yield reductions due to haying-off.

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