What is the N legacy following pulses for subsequent crops and what management options are important to optimise N fixation?

Tony Swan[1], Mathew Dunn[2], John Kirkegaard[1], Mark Peoples[1], Laura Goward[1], Ewan Leighton[2], Graeme Sandral[2], James Hunt[1,3], Mel Bullock[1], Russell Pumpa[2], Kellie Fiske[2], Aiden Woodford-Smith[1], Daryl Reardon[2], Mehrshad Barry[2] and Helen Burns[2]

[1] CSIRO Agriculture & Food
[2] NSW DPI
[3] University of Melbourne

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Take home messages

- Pulse legumes can improve the profitability and sustainability of your farming system. We found average legume legacy benefits to subsequent canola crops worth **$237/ha** from both higher grain yields and savings in urea costs
- 'Grow what you can and grow it well' to maximise N input. Select the best legume crop, variety and sowing time for your soil and get the agronomy right - ensure effective nodulation, maximise pulse dry matter, remove subsoil constraints, and avoid high soil mineral N and damaging herbicides
- Crop end use (grain, silage/hay or brown manure) affects N legacies in subsequent crops – understand and account for these benefits
- Pulse crops with high grain yield or cut for hay production may not always provide a net input of mineral N, but other benefits include the role as a double break, emergence in heavy stubble and high N residues that assist conversion of cereal stubble to humus to improve soil fertility.

Legume crops - introduction

The benefits of crop rotation are widely recognised in modern farming systems. In Southern NSW, cereal-dominated sequences (wheat and barley) often include canola as a break crop, but rarely include a legume break crop. The uptake of more diverse cropping sequences can provide a range of benefits that may outweigh the challenges and risk associated with growing and marketing legume crops, especially if viewed from a whole-of-system perspective.

System benefits from growing legumes can include soil chemical, structural and biological changes as well as impacts on pests, disease and weed levels that can influence the performance of subsequent crops in the sequence. However, much of the legacy benefit derived from legume crops relates to N supply (Angus *et al.,* 2015; Peoples *et al*., 2017).

In a recent paper on sustainable intensification of cropping systems, Reeves (2020), highlighted several changes to farming systems to ensure our farms remain productive, profitable and sustainable. He concluded that a "new revolution of diversified farming based on the effective integration of crops, pastures, livestock, shrubs and trees together with diverse practices are required to make farms more resilient financially and to the increasing challenges of climate change and climate extremes." To build this resilience, he notes that it is imperative to build soil C and N content and soil health generally (Reeves 2020). Unfortunately, our current intensive cropping systems are reducing both total soil C and N (Sanderman and Baldock 2010), soil organic N is declining over time (Figure 1; Lake 2012) and despite widespread use of lime, current acid soil management programs are not preventing acidification of layers within the 5-15 cm depth layers (Burns and Norton 2018).

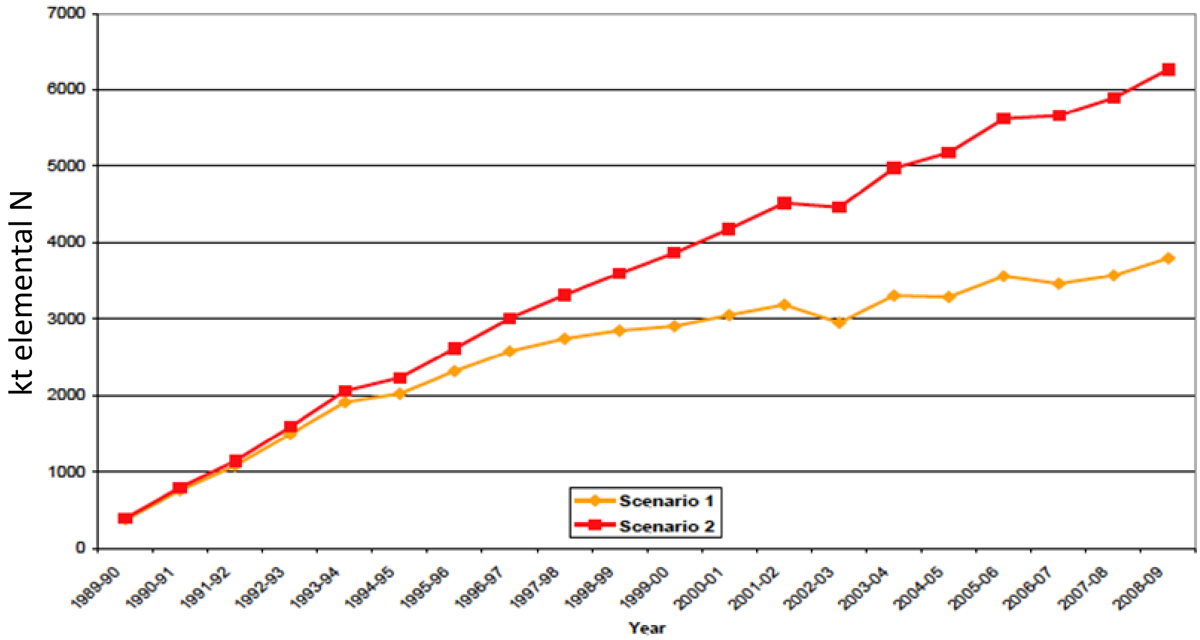

Figure 1. Accumulated deficits expressed as elemental N fertiliser equivalent in Australian temperate crop soils as estimated by two scenarios: Scenario 1 being the best possible case of N fertiliser usage on those crops and Scenario 2 being a more realistic assessment of likely N usage levels. (Lake 2012).

Angus and Peoples (2012) calculated that a fallow typically reduced total soil N by 4.4 % annually and crops by 2.5 % and determined that more frequent inclusion of legumes would be required to offset this decline in soil organic N, or otherwise increased rates of fertiliser N application would be required to maintain yields. If this was to occur it has been predicted that fertiliser N costs would rise as a percentage of gross margin from 9-10 % to around 14.8% by 2037 and 17.5 % by 2067 (Table 1).

Table 1. The increase in fertiliser N calculated to maintain a 4 t/ha and a 2 t/ha wheat crop on a red Mallee soil between 2017 and 2067 (Angus and Peoples 2012).

Year		Soil N (kg N/ha)	Fertiliser N required (kg N/ha)	N cost (% of GM)
2017	Red Soil GSR = 300mm 4t/ha @ 10.5% protein	108	80	9.1
2037		54	134	14.6
2067		27	161	17.7
2017	Mallee Soil GSR = 200mm 2t/ha @ 10.5% protein	45	53	10.5
2037		23	75	15.0
2067		10	88	17.5

In this paper we utilise the findings from recent systems experiments undertaken in southern and central NSW to quantify the contributions of N fixation to legume growth and soil N fertility and to examine the N legacy for following crops. Management options will also be described that can assist in optimizing both the performance of the legume and the flow-on N benefits for subsequent crops.

The GRDC Farming Systems experiments 2018-2021

Experiment outline

Four contrasting locations were selected in 2017 that represented a range of soil types and environmental factors and which encompassed a diverse range of grower and consultant groups. The main core experiment site is located at the Wagga Wagga Agricultural Institute with three regional node sites located at Condobolin Research and Advisory Station, Greenethorpe and Urana. There are six treatment sequences that are common to all sites, with the Wagga Wagga site encompassing all treatments. The crop sequence treatments applied are provided in Table 2. All sites were sown to wheat in 2017 with the treatment sequences starting in 2018. Data from the Wagga Wagga, Greenethorpe and Urana sites are presented in this paper.

Table 2. Farming systems sites with sowing timing, N management and winter grazing strategies applied to different crop sequences.

Crop sequences	**Condobolin & Urana**		**Wagga Wagga**		**Greenethorpe**	
	Sowing	Nitrogen	Sowing + grazing	Nitrogen	Sowing + grazing	Nitrogen
Canola-wheat	E, T	Low, High	E+G, T	Low, High	E+G, T	Low, High
Canola-wheat-barley	T	Low	T	Low, High		
Canola-wheat-wheat					T, L	High
Lentil-canola-wheat	E	Low, High	E, T	Low, High	E	Low, High
Lupin-canola-wheat			T	Low		
Faba bean-canola-wheat	T	Low			T	Low
Chickpea-wheat			T	Low	T	Low
***Legume-canola-wheat**	T	Low	E+G, T	Low, High	E+G, T	Low
Faba bean/canola-wheat			T	Low	T	Low
Wheat-wheat-wheat			T	Low, High	T	Low
Fallow-canola-wheat	E	High	E, T	High		
Flexible one	Flexible	Flexible	Flexible	Flexible	Flexible	Flexible
Flexible two	Flexible	Flexible			Flexible	Flexible

E = Sown early from mid-March to mid-April period
T = Timely sown crops from 3rd week April to mid-May
G = Grazing (always winter grazed and sometimes a 2nd grazing or stubble graze)
Nitrogen = Low (top-dressed nitrogen in June-July for a decile 2-year (N2) grain yield, High (top-dressed nitrogen in June-July for a decile 7-year (N7) grain yield)

Prior to sowing the cereal crop at all sites in 2017, soil samples were taken and analysed for chemical characteristics. It was determined that at Condobolin, Greenethorpe and Wagga lime would need to be applied to ameliorate the soil and increase the soil pH ($CaCl_2$) to > 5.5 in the surface 0-10 cm and > 5.2 between 10-20 cm. A rate of 3 t/ha, 3.5 t/ha and 1 t/ha of lime was applied at the Condobolin, Greenethorpe and Wagga sites, respectively and incorporated to a depth of around 10 cm. The aim was to incorporate the lime deeper (> 15cm) at the Greenethorpe site, however due to the dry conditions, the offset discs were not able to penetrate deeper. To ensure that the early March sown treatments were able to be sown on time with sufficient surface soil moisture to ensure germination and plant emergence at the start of 2018, the Greenethorpe site was not ploughed following a rainfall event in January 2018. We envisaged that the alkalinity from the lime would move lower in the profile to 10-15 cm over the next few years with sufficient rainfall.

Section 1: Nitrogen fixation and legume impacts on soil N dynamics - Results from previous and current farming systems experiments

Many experiments have demonstrated a close relationship between soil mineral N and wheat yield across a range of environments in eastern Australia (Angus *et al.,* 2015). Both soil mineral N and wheat yields are generally lower following wheat crops and highest following legumes. The amount of N mineralised from legume residues that becomes available for a subsequent crop can be influenced by legume species and its end use (i.e., whether it is grown for grain, green or brown manured, grazed or cut for hay), and the amount of rainfall over the summer fallow between crops.

Legume inputs of fixed N

Cost-effective supply of legume N depends on productive and efficient N fixation. Matching species choice to the environment is an important factor that impacts on the total input of N fixed (kg N/ha). Specifically, the amounts of N fixed by legumes are regulated by two factors:

(i) The amount of legume N accumulated over the growing season (as determined by shoot dry matter (DM) production and %N content); and
(ii) The proportion of the legume N derived from atmospheric N_2 (often abbreviated as %Ndfa).

Equation 1: Amount of legume shoot N fixed = (legume shoot DM x %N/100) x (%Ndfa/100)

The greater the amount of biomass that a legume can produce, the higher the potential for more N fixation to occur (Peoples *et al.,* 2009). Where a species is well suited and doesn't have any obvious constraints to N fixation (see section on subsoil constraints), it is likely legumes will derive more than half of their N requirements for growth from atmospheric N_2 via N fixation. Under these conditions it is common for around 15-20 kg of shoot N to be fixed on average per hectare for every tonne of legume shoot DM accumulated during the growing season (Table 3). However, there can be a wide range in %Ndfa and the amounts of N fixed by different legumes across different environments. Analyses of on-farm samples of legumes collected from 61 commercial grower paddocks, indicated an average %Ndfa of 65%, but the range was 8 to 89%. Similarly, the average shoot N fixed per tonne of shoot biomass was 16 kg N/t DM, with a range of between 2 to 25 kg N/t DM (Table 3).

Table 3. Summary of on-farm estimates of N fixation by 61 commercial pulse crops sampled between 2001-2017 (Peoples *et al*. un-published data).

Legume	Number paddocks	%Ndfa	Shoot N fixed (kg N/ha)	Mean shoot N fixed & (range) (kg N/t DM)
Chickpea	8	67%	47	14 (7-25)
Fababean	23	68%	126	17 (10-25)
Fieldpea	8	56%	46	14 (2-20)
Lentil	5	65%	83	18 (4-25)
Lupin	14	63%	83	16 (9-21)
Vetch	3	69%	89	17 (13-22)
Mean		65%	90	16

The estimate of amounts of N fixed per t of DM accumulated can be used to compare N fixation efficiency: 20+ indicating excellent fixation; > 15 is considered OK; but < 10 kg/t DM generally indicates that there is some constraint to root nodulation, the N fixation process or crop growth which will need to be identified and addressed to maximise future inputs of fixed N (see section on constraints to N fixation). In the case of the 61 commercial pulse crops summarized in Table 3, 20 % of the crops sampled (i.e., 12 crops) were deemed to have had sub-optimal N fixation.

Net inputs of fixed N_2

The amount of shoot N fixed by legumes are informative, but what is more important is how much fixed N might be contributed to the soil at the end of the growing season. Since the root systems of legumes can contain between 25 % to 50 % of the total plant N, this below-ground contribution of fixed N can be a substantial component of the potential carry-over N benefit for following crops and should not be ignored (Peoples *et al.,* 2009). Since it is extremely difficult to fully recover root systems of legumes in the field, total N fixed is usually calculated by adjusting the shoot measures of N fixation to include an estimate of how much fixed N might also be associated with the nodulated roots using a 'root factor' (Unkovich *et al.,* 2008*;* Unkovich *et al.,* 2010*,* Peoples *et al.,* 2012). For many pulse legumes around one-third of the plant N is commonly below-ground in roots and nodules; in this case a 'root factor' of 1.5 would be used (Table 4).

Equation 2: Total N fixed = (shoot N fixed) x root factor.

Table 4. A ROUGH RULE OF THUMB for estimating the total amount of N fixed by different legume species to include shoot and root fixed N.

Species	Estimated shoot N fixed (kg N/t DM)	Estimated below ground N (% of total N)	Root factor	Estimated total plant N fixed (kg N/t DM)
Fieldpeas, lupins, fababeans, vetch	20	33%	1.5	30
Chickpeas	20	52%	2.06	41
Lucerne	20	50%	2.0	40
Subclover	20	42%	1.72	34

The net inputs of fixed N (Equation 3) are derived by comparing the total amounts of N fixed to the amounts of N removed in harvested grain, hay, and/or animal products, or lost from the system via ammonia volatilisation from urine patches where the legume-based pastures or legume stubbles are grazed (Peoples *et al.,* 2012).

Equation 3: Net input of fixed N = (total amount of N fixed) – (N removed + N lost)

The total amounts of N remaining in the crop vegetative residues and roots at the end of the 2011 growing season (Table 5) were calculated for pulse crops using Equation 4.

Equation 4: Total residue N = (total crop N) – (grain N removed)

Junee Reefs experiment 2011-2013

Data generated by experimentation at Junee Reefs indicated that brown manured legumes (BM: legume crops killed with knock-down herbicide before weed seed-set as a weed management tool) provided greater net returns of fixed N to soils than grain crops, as large amounts of N were removed in the high-protein legume grain (Table 5). However, it is clear from this dataset and others, that different legume species have very different potential for growth and N fixation, regardless of their eventual end-use (Table 5). In this experiment, legume DM ranged between 5.7 and 9.9 t/ha, with the lupin BM and lupin grain crops having the highest %Ndfa, lentils lower at 59 % and field peas and chickpeas lowest at 50 %. When we examined the net N balance after grain removal compared to brown manuring, there was a range in net N balance between -1kg N/ha in the lentils to an additional 241 kg N/ha following the lupins BM (Table 5).

Table 5. Shoot and grain dry matter (DM) production, N accumulation, grain yield, inputs of N fixed by legume grain or brown manure (BM) crops and estimates of the amount of residual N remaining at the end of the growing season that was derived by fixation and total residual N at Junee Reefs in 2011.

Crop 2011	Biomass (t DM/ha)	Grain yield (t/ha)	Total plant N[A] (kg N/ha)	Ndfa (%)	Inputs of fixed N[A] (kg N/ha)	Grain N (kgN/ha)	Net N balance of fixed N (kgN/ha)	Total residue N (kgN/ha)
Lupin BM	8.4	-	290	83	241	-	+241	290
Field Pea BM	6.3	-	215	52	112	-	+112	215
Lupin	9.9	3.5	398	85	338	210	+128	188
Chickpea	6.4	1.8	247	50	141	77	+64	170
Lentil	5.7	3.2	248	59	137	138	-1	110
Wheat +N[b]	11.1	4.8			49	87		64
Canola +N[b]	10.6	3.2			49	94		111
LSD P<0.05)	1.3	0.5	-	9	-	11	-	22

Source: Legume data from Peoples *et al.,* 2015 GRDC update and Peoples *et al.,* 2017.
[A] The amount of total plant N and shoot N fixed were adjusted to include an estimate of N contributed by the nodulated roots as described by Unkovich *et al.,* (2008), Unkovich *et al.,* (2010).
[b] Urea fertiliser was applied to wheat at 49 kg N/ha and canola at 66 kg N/ha.

The GRDC farming systems experiments 2018-2020

A summary of the average N dynamics from the pulse legume crops for phase 1 (2018-2020) of the current GRDC farming systems experiments located at Greenethorpe, Wagga and Urana are outlined in Table 6. Generally, the high-density legume pastures (HDL) have produced on average, the highest quantities of shoot N fixation with estimates of shoot N fixed ranging between 16-20 kg N/t DM (Table 6). The faba bean at Urana, faba bean-canola inter-crop treatments at both Wagga and Greenethorpe in 2018 and 2019, lupins at Wagga and lentils (N2) at Urana also all had reasonable fixation rates that were > 17 kg N/t DM. Generally, the chickpeas and lentils at both the Wagga and Greenethorpe sites and the chickpeas at Urana had the lowest rates of N fixed with < 12 kg N/t DM (Table 6).

In the GRDC project experimental sites, no legume crop was managed as a brown manure (BM) crop. Rather the early sown HDL legume crops were grazed in June before cutting for hay in October, whilst the mid-April to early-May sown HDL crops were cut for hay in October of each year, with the aim to increase gross margin from the sale of the hay and the grazing if applicable. When we calculated the average net inputs of fixed N remaining in crop residues following grain or hay removal, we found that across the two decile 1 and one decile 9 year treatments at each site, the faba beans at Urana had the highest net return of fixed N of 116 kg N/ha, the HDL averaged across all sites was 75 kg N/ha, and generally all other crops produced less than 40 kg fixed N/ha in remaining residues (Table 6). In the cropping sequences where the wheat and canola preceding the pulse crop were fertilised at a higher nitrogen level (Decile 7 strategy), the fixation rate and the quantity of fixed N remaining after grain harvest was generally reduced (lentils at Urana - 9 *cf* 33, lentils at Wagga = 6 *cf* 40). However, at the Greenethorpe site, less than 25 kg N/ha remained following the harvest of the faba bean or lentil crops.

Table 6. Average N dynamics of the legume crops at each field site in the 'Southern Farming Systems' project. Values presented are averages across three seasons (2018, 2019 & 2020).

Field Site	Crops 2018, 2019, 2020	Legume biomass (t/ha)	Shoot N fixed (kg N/t DM)	Total fixed N from root & shoot[A] (kg N/ha)	N removed from grain or hay (kg N/ha)	Fixed N remaining in crop resides (kg N/ha)	Total Residue N in crop (kg N/ha)
Greenethorpe	HDL[C] un-grazed, T	4.7	20	166	78	89	167
	HDL grazed, E	4.5	19	136	63	73	153
	Chickpea	5.5	10	133	88	45	169
	Fababean/canola[B]	4.4	17	112	88	24	94
	Fababean[D]	5.9	14	128	144	24	91
	Lentil (N7) [E]	4.5	12	84	82	1	65
	Lentil (N2) [E]	4.2	10	66	81	-15	66
Wagga	HDL grazed, E (N2)	4.6	21	148	69	79	116
	HDL grazed, E (N7)	4.9	18	135	63	72	120
	HDL un-grazed, T (N7)	4.4	18	116	54	62	117
	HDL un-grazed, T (N2)	4.8	16	115	54	61	137
	Lupin	4.4	25	144	131	47	85
	Lentil (N2)	4.9	16	114	74	40	105
	Chickpea	4.1	11	101	63	38	126
	Lentil (N7)	5.0	11	83	77	6	111
Urana	Fababean	9.6	17	235	119	116	218
	HDL un-grazed, T	6.1	17	168	79	38	182
	Chickpea	4.7	12	118	79	38	107
	Lentil (N2)	4.6	18	130	97	33	109
	Lentil (N7)	3.7	16	91	82	9	86

[A] The amounts of shoot N fixed were adjusted to include an estimate of N contributed by the nodulated roots as describe by Unkovich et al. (2010)
[B] Sown mixture of fababean and canola – Intercrop in 2018 and 2019 only
[C] HDL – Pasture mix consisting of vetch, Arrowleaf and Balansa clover
[D] Average results from fababean at Greenthorpe in 2018 and 2019 only
[E] The N7 and N2 relate to the nitrogen requirement in the crop sequence, not the legume crop.

To better examine the year-to-year interaction across the three sites, a complete dataset for each year is provided in Tables 7 to 9.

2018

In 2018, the %Ndfa of the chickpea crops at Greenethorpe and Wagga were very low (26-31%) and shoot N fixed were 5-7 kg N/t DM. The %Ndfa of the lentil crop at Greenethorpe was also low (30-40%), with shoot N fixed representing 6-7 kg N/t DM (Table 7). By comparison, the lentil and faba bean crops performed very well on the alkaline soils at Urana with high shoot N fixed values (17-23 kg N/t DM). The HDL crops across all sites performed the best with high %Ndfa (58-79%), and high shoot N fixed (16-27 kg N/t DM). However, more N was removed in grain and hay than was estimated to be fixed for the chickpeas and lentils at Urana and Greenethorpe (Table 7).

2019

In the extremely dry 2019 year, the total amount of total legume biomass produced was low and this ultimately reduced the quantity of fixed N remaining in the crop residues. Nonetheless, the faba bean/canola intercrop, faba bean, lupin and HDL treatments had good %Ndfa (67-81 %) and generally had the highest amounts of fixed N in the crop residues following harvest or hay cut (Table 8). The higher soil mineral N concentration at the start of 2019 at both Wagga and Urana probably resulted in the poorer N fixation and lower net inputs of fixed N (Table 8).

2020

In 2020, all sites received substantial rainfall and this impacted different pulse crops in different ways. The Greenethorpe site received 767 mm of rainfall and the combination of the high rainfall, the persistent subsoil acidity layer (7-15 cm) with a high aluminium concentration resulted in the death of the rhizobia in the faba bean crops. To ensure a successful faba bean harvest and to not damage the long-term treatment, 170 kg/ha of urea was applied to ensure a 4-5 t/ha faba bean grain yield. As such no analysis of N fixation could occur. The HDL and chickpea crops at Greenethorpe had a high legume biomass, high Ndfa% (70-92 %) and high rates of shoot N fixed (17-34 kg N/t DM), which resulted in significant net inputs of fixed N remaining in the residues after grain or hay was harvested (Table 9). By comparison, there was little or no fixed N remaining in the lentil residues.

At the Wagga site in 2020, all legume crops produced between 5 and 8t/ha of legume biomass and all crops except the lentil (N7) had > 50 % Ndfa. The HDL and chickpea crops generated the highest net inputs of fixed N following harvest (74-106 kgN/ha). The lupin crop had a high %Ndfa (75 %) and high rates of shoot N fixed (24 kg N/t DM), but after removing the 4.7 t/ha of grain, only 32 kg fixed N/ha was calculated to remain in that treatment's residues (Table 9).

The Samira faba beans at the Urana site in 2020 produced a massive 18.2 t/ha of legume biomass with a high %Ndfa and good shoot N fixed (17 kg N/t DM). So, after subtracting the N removed from the 5.3 t/ha of grain yield, there was potentially a net input of 256 kg fixed N/ha in the crop residues (Table 9). All crops performed very well in the alkaline soils of Urana in 2020, with high grain yields; however, the lower legume biomass from the lentil (N7 treatment) and the chickpea resulted in considerably less fixed N remaining in crop residues following harvest (Table 9).

Apparent mineralisation (calculated soil mineral N benefit)

Even though elevated concentrations of soil mineral N are frequently observed after legume crops (Angus *et al*. ,2015), only a fraction of the N in legume residues remaining at the end of the 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 legumes 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 (Peoples *et al.,* 2015: Peoples *et al.,* 2017).

We calculated the apparent mineralisation at Junee Reefs (Tables 10 and 11) in the year following the pulse crops (2012) using three different equations (Equations 5 to 7).

Equation 5: Apparent mineralisation of legume residues (kgN/ha <u>per tonne of grain yield</u>)
= 100 x [(mineral N after legume) – (mineral N after wheat)] / (grain yield 2011).

Equation 6: Apparent mineralisation of legume residues (kgN/ha <u>per tonne of shoot residue N</u>)
= 100 x [(mineral N after legume) – (mineral N after wheat)] / (legume shoot residue N). Where shoot residue = (peak biomass DM) – grain yield.

Equation 7: Apparent mineralisation of legume N (as a <u>% 2011 total residue N</u>) = 100 x [(mineral N after legume) – (mineral N after wheat)] / (total legume residue N).

Results suggest that the net mineralisation over the wet 2011/12 summer fallow period represented the equivalent of 11- 46 kg N/ha per tonne of grain yield, 16 -18 kg N/ha per tonne of shoot residue DM, and 22-56 % of the pulse crop residues (Table 10). Interestingly, the apparent net

Table 7. Soil mineral N at sowing, legume biomass (DM), shoot N content (%N), reliance upon N fixation for growth (%Ndfa), shoot N accumulation and estimated quantity of shoot N and total plant N (shoot+root) fixed, grain and hay DM yields, N removed in grain or hay at harvest and the calculated net inputs of fixed N at Greenethorpe, Wagga and Urana in 2018 for a range of legume crops and treatments.

Field Site	Crops	Starting soil Mineral N* 0-2m (kgN/ha)	Total Biomass ( ) & Legume Biomass[#] (t/ha)	Legume (%N)	Ndfa (%)	ShootN (kgN/ha)	Shoot Nfixed (kgN/ha)	Shoot NFixed (kgN/tDM)	Total N fixed by shoot & roots[A] (kgN/tDM)	Total Hay () & Legume Hay Yield[B] (t/ha)	Grain Yield (t/ha)	Grain[EF] (%N)	Total Fixed N from root & shoot (kgN/ha)	N removed from grain or hay (kgN/ha)	Fixed N remaining in crop resides (kgN/ha)
Greene-Thorpe	HDL[C] Grazed, E	145	(4.2) 4.0	3.5	78	140	108	27	41	(3.0) 2.8			163	76	87
	HDL Un-Grazed, T	144	(5.0) 3.7	3.3	68	124	82	22	33	(3.5) 2.6			123	58	66
	Fababean	139	6.1	2.3	58	141	83	13	20		2.1	4.4	124	94	30
	Fababean/Canola[D]	133	4.4	2.2	78	96	75	17	26		2.1	4.4	113	91	21
	Chickpea	153	5.0	2.1	26	106	27	5	11		1.9	3.9	55	74	-19
	Lentil (N2)	141	5.4	2.0	30	108	31	6	9		1.7	4.2	47	72	-25
	Lentil (N7)	158	5.4	1.8	40	98	39	7	11		1.7	4.3	58	73	-15
Wagga	HDL Grazed, E	64	3.8	2.7	65	102	68	18	27	2.6			102	47	54
	HDL Un-Grazed, T	64	4.1	2.2	79	87	67	17	25	2.8			100	47	54
	Lentil (N2)	64	3.3	2.6	70	85	59	18	27		1.4	4.0	88	57	31
	Lentil (N7)	69	3.1	2.3	74	72	52	17	26		1.3	4.0	79	54	24
	Chickpea	64	2.5	2.4	31	59	18	7	15		1.3	3.7	38	47	-9
Urana	HDL Un-Grazed, T	73	3.0	2.8	58	82	47	16	24	2.1			71	33	38
	Fababean	73	3.0	2.9	78	88	68	23	35		1.8	3.9	103	72	31
	lentil (N2)	73	2.3	2.6	64	59	38	17	25		2.6	4.0	57	104	-47
	lentil (N7)	73	2.2	2.7	68	58	39	18	27		1.9	4.0	58	76	-18

* Soil mineral nitrogen determined from 0-2m at Greenethorpe and Urana.

Total plant biomass is indicated in brackets if it is different than the total legume biomass.

[A] The amounts of shoot N fixed were adjusted to include an estimate of N contributed by the nodulated roots as described by Unkovich et al. (2010)

[B] Hay calculated as 70% of the total plant dry matter

[C] HDL - Pasture mix consisting of Vetch, Arrowleaf and Balansa clover

[D] Sown mixture of fababean and canola - Intercrop

[E] Lentil grain %N at Urana and Wagga were derived from average grain nitrogen concentrations at Greenethorpe, Urana and Wagga (2018-2020).

[F] The chickpea grain %N for Wagga was derived from the Greenethorpe analysed chickpeas (2018-2021)

Note: Legume crops had <8kgN/ha of added fertiliser at sowing. N2 or N7 refer to the other crops in the sequence fertilised at a low (N2) or high (N7) rate. If no rate indicated, other crops fertilised at low rate.

Table 8. Soil mineral N at sowing, legume biomass (DM), shoot N content (%N), reliance upon N fixation for growth (%Ndfa), shoot N accumulation and estimated quantity of shoot N and total plant N (shoot+root) fixed, grain and hay DM yields, N removed in grain or hay at harvest and the calculated net inputs of fixed N at Greenethorpe, Wagga and Urana in 2019 for a range of legume crops and treatments.

Field Site	Crops	Starting soil Mineral N* 0-2m (kgN/ha)	Total Biomass ( ) & Legume Biomass[#] (t/ha)	Legume (%N)	Ndfa[E] (%)	ShootN (kgN/ha)	Shoot Nfixed (kgN/ha)	Shoot NFixed (kgN/tDM)	Total N fixed by shoot & roots[A] (kgN/tDM)	Total Hay () & Legume Hay Yield[B] (t/ha)	Grain Yield (t/ha)	Grain[FG] (%N)	Total Fixed N from root & shoot (kgN/ha)	N removed from grain or hay (kgN/ha)	Fixed N remaining in crop resides (kgN/ha)
Greene-thorpe	Fababean/Canola[D]	177	4.5	2.5	67	109	75	16	25		1.8	4.7	112	85	27
	Fababean	220	5.7	2.3	69	128	88	16	23		2.4	4.7	132	114	18
	HDL Grazed, E	193	(3.8) 3.7	3.3	13	119	15	4	6	(2.6) 3.7			22	10	12
	HDL Un-Grazed, T	229	(5.2) 3.4	3.5	12	117	14	4	6	(3.7) 2.4			21	10	11
	Lentil (N7)	236	2.7	2.5	49	68	33	12	19		0.8	4.6	50	39	11
	Chickpea	217	2.9	2.3	39	68	27	9	19		1.2	4.1	55	52	4
	Lentil (N2)	252	2.4	2.5	27	61	17	7	10		0.9	4.7	25	40	-15
Wagga	HDL Grazed, E (N2)	93	4.4	2.7	80	120	96	22	33	3.1			144	67	77
	HDL Grazed, E, (N7)	112	4.4	2.4	72	106	76	17	26	3.0			114	53	61
	HDL Un-Grazed, T (N7)	113	4.0	3.1	75	97	73	18	27	2.8			109	51	58
	Lupin	82	3.9	2.8	70	111	78	20	30		1.3	4.5	117	59	58
	Lentil (N2)	82	4.0	2.1	62	86	54	13	20		0.6	4.0	81	26	55
	Chickpea	82	3.2	1.9	50	61	31	10	20		0.5	3.7	63	20	44
	HDL Un-Grazed, T (N2)	82	3.7	2.9	46	108	50	14	20	2.6			75	35	40
	Lentil (N7)	113	4.2	2.2	22	90	17	4	7		0.7	4.0	26	30	-5
Urana	Fababean	73	7.7	2.4	51	183	92	12	18		2.0	3.9	138	78	60
	lentil (N2)	73	4.6	2.3	63	105	67	14	22		1.1	4.0	101	46	55
	HDL Un-Grazed, T	73	4.6	2.5	57	114	64	14	21	3.2			96	45	51
	lentil (N7)	159	4.2	2.5	43	103	45	11	16		1.3	4.0	68	51	16

* Soil mineral nitrogen determined from 0-2m at Greenethorpe and Urana.

Total plant biomass is indicated in brackets if it is different than the total legume biomass.

[A] The amounts of shoot N fixed were adjusted to include an estimate of N contributed by the nodulated roots as described by Unkovich et al. (2010)

[B] Hay calculated as 70% of the total plant dry matter

[C] HDL - Pasture mix consisting of Vetch, Arrowleaf and Balansa clover

[D] Sown mixture of fababean and canola - Intercrop

[E] The non-refernce plant delta's that were used to dermine the percentage of nitrogen fixed by the legume at Urana was from 2018 and 2020 non-legume weed species.

As such, all of the Nitrogen fixation values and estimates of nitrogen remaining after grain or hay removal are to be used as a guide only and not to be used for journal publisable data.

[F] Lentil grain %N for 2019 were derived from average grain nitrogen concentrations at Greenethorpe, Urana and Wagga (2018-2020).

[G] The chickpea grain %N for Wagga and Urana is derived from the Greenethorpe analysed chickpeas (2018-2021)

Note: Legume crops had <8kgN/ha of added fertiliser at sowing. N2 or N7 refer to the other crops in the sequence fertilised at a low (N2) or high (N7) rate. If no rate indicated, other crops fertilised at low rate.

Table 9. Soil mineral N at sowing, legume biomass (DM), shoot N content (%N), reliance upon N fixation for growth (%Ndfa), shoot N accumulation and estimated quantity of shoot N and total plant N (shoot+root) fixed, grain and hay DM yields, N removed in grain or hay at harvest and the calculated net inputs of fixed N at Greenethorpe, Wagga and Urana in 2020 for a range of legume crops and treatments.

Field Site	Crop 2020	Starting soil Mineral N* 0-2m (kgN/ha)	Total Biomass ( ) & Legume Biomass[#] (t/ha)	Legume (%N)	Ndfa (%)	ShootN (kgN/ha)	Shoot Nfixed (kgN/ha)	Shoot NFixed (kgN/tDM)	Total N fixed by shoot & roots[A] (kgN/tDM)	Total Hay () & Legume Hay Yield[B] (t/ha)	Grain Yield (t/ha)	Grain[E] (%N)	Total Fixed N from root & shoot (kgN/ha)	N removed from grain or hay (kgN/ha)	Fixed N remaining in crop resides (kgN/ha)
Greene-thorpe	HDL Un-Grazed, T	139	(7.0) 6.9	3.3	92	247	236	34	51	(4.9) 4.9			355	165	189
	Chickpea	184	8.4	2.4	70	200	140	17	35		4.1	3.4	289	139	149
	HDL Grazed, E	167	(6.2) 5.8	3.7	86	174	149	26	39	(4.3) 4.1			224	104	119
	Chickpea/Linseed[D]	225	5.0	2.2	85	109	93	19	39		2.3	3.1	192	73	119
	Lentil (N7)	230	5.4	2.4	74	129	96	18	27		3.1	4.4	143	135	8
	Lentil (N2)	174	4.8	2.6	68	125	84	17	26		3.0	4.3	127	131	-4
	Fababean[F]	235	7.9	2.6	NA	201	NA	NA	NA		5.2	4.3	NA	225	NA
Wagga	HDL Grazed, E (N2)	106	5.5	2.7	83	148	132	23	35	3.9			199	93	106
	HDL Grazed, E (N7)	81	6.7	2.4	79	158	127	19	29	4.7			191	89	102
	HDL Un-Grazed, T (N2)	107	6.7	2.9	59	186	113	17	25	4.7			169	79	90
	Chickpea	101	6.6	2.4	64	155	99	15	31		3.4	3.7	203	124	79
	HDL Un-Grazed, T (N7)	121	5.0	3.1	60	157	92	18	28	3.5			138	65	74
	Chickpea/Linseed[D]	81	5.6	2.3	53	130	68	12	26		2.7	3.7	140	100	40
	Lentil (N2)	79	7.4	2.5	62	186	116	16	23		4.0	3.5	174	138	35
	Lupin	87	6.7	3.3	75	219	163	24	37		4.7	4.5	245	213	32
	Lentil (N7)	148	7.8	2.7	45	214	96	12	19		4.2	3.5	144	147	-3
Urana	Fababean	102	18.2	2.2	77	403	309	17	25		5.3	4.0	464	208	256
	HDL Un-Grazed, T	101	10.6	3.1	70	326	226	21	32	7.4			339	158	181
	lentil (N2)	120	6.8	2.6	87	178	154	23	34		4.0	3.5	232	140	91
	lentil (N7)	137	4.7	2.6	79	124	98	21	31		3.3	3.6	146	117	29
	Chickpea	121	6.2	2.1	66	129	87	14	27		4.3	3.7	169	158	11

* Soil mineral nitrogen determined from 0-2m at Greenethorpe and Urana.

Total plant biomass is indicated in brackets if it is different than the total legume biomass.

[A] The amounts of shoot N fixed were adjusted to include an estimate of N contributed by the nodulated roots as described by Unkovich et al. (2010)

[B] Hay calculated as 70% of the total plant dry matter

[C] HDL - Pasture mix consisting of Vetch, Arrowleaf and Balansa clover

[D] Sown mixture of chickpeas and linseed - Intercrop

[E] The chickpea grain %N for Wagga and Urana is derived from the Greenethorpe analysed chickpeas (2018-2021)

[F] Fababean: The interaction between subsoil acidity and a wet season resulted in the rhizobia being killed. An additional 170kg/ha of urea was applied to ensure sufficient N for fababean grain yield.

Note: Legume crops had <8kgN/ha of added fertiliserN at sowing. N2 or N7 refer to the crops in the sequence fertilised at a low (N2) or high (N7) rate. If no rate indicated, other crops fertilised at low rate.

Table 10. Concentrations of total residue N from legume crops in 2011, soil mineral N (0-1.2m) measured in autumn 2012 following either wheat, canola, lupins or field peas from brown manure (BM), and lupins, chickpeas or lentils for grain at Junee Reefs, NSW in 2011, and calculations of the apparent net mineralisation of N (soil mineral N net benefit) from legume residues.

	Total residue N from legume & non-legume crops by end 2011	Peak Biomass 2011 minus grain/hay yield	Additional soil mineral N from legumes	Calculated soil mineral N benefits (kg N/ha)		
				Per tonne of grain yield	Apparent mineralisation of 2011 legume N (kg N/t DM)	Apparent mineralisation of 2011 legume N (% residue N)
Crop 2011	(kg N/ha)	(t/ha)	(kg N/ha)			
Lupins BM	290	8.4	86	-	10	30%
Field Pea BM	215	6.3	43	-	7	20%
Lupin	188	6.4	40	11	6	21%
Chickpea	170	4.6	82	46	18	48%
Lentil	110	2.5	41	13	16	37%
Wheat	64		-			-
Canola	111		-			-
Average after BM crops			65	-	8.5	25%
Average after grain crops			54	23	13	35%

Source: Peoples *et al.,* 2015 GRDC update, Peoples *et al.,* 2017 and un-published results.

mineralisation of the crop residues from the legume BM and lupin grain crop in the 2011 year represented around 10 % of the soils mineral N prior to sowing the second cereal crop (Table 11). It is evident that in those crops (chickpea and lentil 2011) that mineralised more N from their residues prior to sowing the first cereal crop, they provided no detectable N benefit for the second cereal crop in 2013 (Table 11). Peoples *et al.,* (2017) also calculated that the soil mineral N benefit from the legume crops was 0.13 kg N/ha per millimetre of summer rainfall.

Table 11. Concentrations of total residue N from legume crops in 2011, soil mineral N (0-1.6m) measured in autumn 2013 following either wheat, canola, lupins or field peas from brown manure (BM), lupins, chickpeas or lentils for grain at Junee reefs, NSW in 2011, and calculations of the apparent net mineralisation of N from legume residues. (Chickpea and lentil were not included as they did not provide benefits through to the second cereal crop)

Crop 2011[a]	Total residue N from legume & non-legume crops by end 2011 (kg N/ha)	Soil mineral N autumn 2013 (kg N/ha)	Additional soil mineral N from legumes in autumn 2013 (kg N/ha)	Apparent mineralisation of legume N (% 2011 residues)
Lupins BM	290	167	34	12%
Field Pea BM	215	151	18	9%
Lupin	188	151	18	10%
Wheat	64	133	-	-
Canola	111	115	-	-
Average BM crops			26	11%
Average of grain crops			18	10%

Source: Peoples *et al.,* 2015 GRDC update, Peoples *et al.,* 2017 and un-published results.
[a] measures of soil mineral N in 2013 following the 2011 chickpea and lentil treatments were not significantly different from the soil mineral N detected after the 2011 wheat treatment so were not included in the analysis.

How to optimise N fixation

Where a legume species is well suited and doesn't have any obvious constraints to N fixation, it is likely to derive more than half of its N requirements for growth from N_2 fixation. To achieve the desired outcome of increased inputs of fixed N by legumes, the interaction between the best legume and rhizobial genotypes tailored to the local environment and grown with the best agronomic management is required. As outlined in equation 1, to maximise the amounts of N_2 fixed by legumes for the subsequent crop, the grower needs to produce the highest amount of legume N by growing the maximum quantity of legume DM with the highest %N content and ensure that there is a very high proportion of the legume N derived from atmospheric N_2 (%Ndfa).

Given the close relationships that have frequently been observed between legume productivity and the amounts of N_2 fixed by many different crop and forage legumes growing across a diverse range of locations in Australia (e.g., see Peoples *et al.,* 2009; Unkovich *et al*., 2010; Peoples *et al*., 2012), management options specifically aimed at supporting greater legume growth will generally have the desired effect of improving inputs of fixed N.

Constraints to N_2 fixation and pulse growth

A. Restricted legume growth:

- Drought
- Poor in-crop weed control
- Carry-over of herbicide residues or in-crop residues
- Nutritional constraints associated with acid soils and P or Mo deficiency.

B. Low % Ndfa resulting from:

- Failure of legume to nodulate due low rhizobia numbers in the soil or poor inoculation
- Acidic subsurface layers
- High soil mineral N (60kgN/ha in Chickpeas, >100 kg N/ha in faba beans and other pulses).

Sub-surface acidity

Many growers are trying to diversify their cropping programs to include higher value pulse legumes to increase the profitability and sustainability of their properties. Most growers have been implementing a liming program since the late 1980's, however in a recent survey of paddocks sown to pulse crops across SE Australia between 2015-17, 83 % of these sites had acid sub-surface layers between 5-15 cm or 5-20 cm (Burns and Norton 2018) (Figure 2). Of the 55 sites, only 9 (17 %) of those soils were in the low-risk category and had a soil type suitable for growing acid-sensitive pulse crops.

The authors point out that the mean soil pH_{Ca} in the moderate and high-risk category soils at depths between 5 and 15 cm were (4.8-5.2, and 4.6-4.8) respectively, indicating that root development, nodulation and therefore production could be compromised. The severity and depth of the acid layer in the extreme risk category soils make these unsuitable for acid-sensitive pulse crops. To obtain maximum growth and maximum nitrogen fixation, correct paddock selection for each species with optimal soil pH are critical factors.

The optimal soil pH_{ca} for a range of pulse legumes is outlined in Table 12. Burns indicates that any potential paddocks where pulse crops are to be sown should be identified and checked for acidic

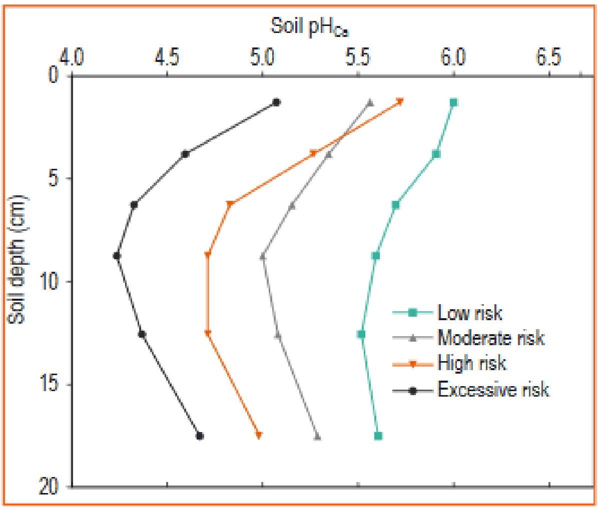

Figure 2. Mean soil pH_{Ca} in surface and subsurface layers of the 55 acidic sites surveyed, categorised (Low, Moderate, High or Excessive) for potential risk of poor nodulation and reduced seedling vigour of acid sensitive pulse species (Burns and Norton page 16).
pulses (Burns and Norton 2018).

sub-surface layers well in advance of sowing acid-sensitive pulses. A liming program to rectify the surface and sub-surface layers then needs be implemented which may require more specialised machines to ensure the lime is moved into the sub-surface layer and enough time allowed for the pH to sufficiently increase to sow acid-sensitive pulses. Depending on the environment, rainfall, soil type, mixing and quality of lime used, this may require up to 24 months in low rainfall zones.

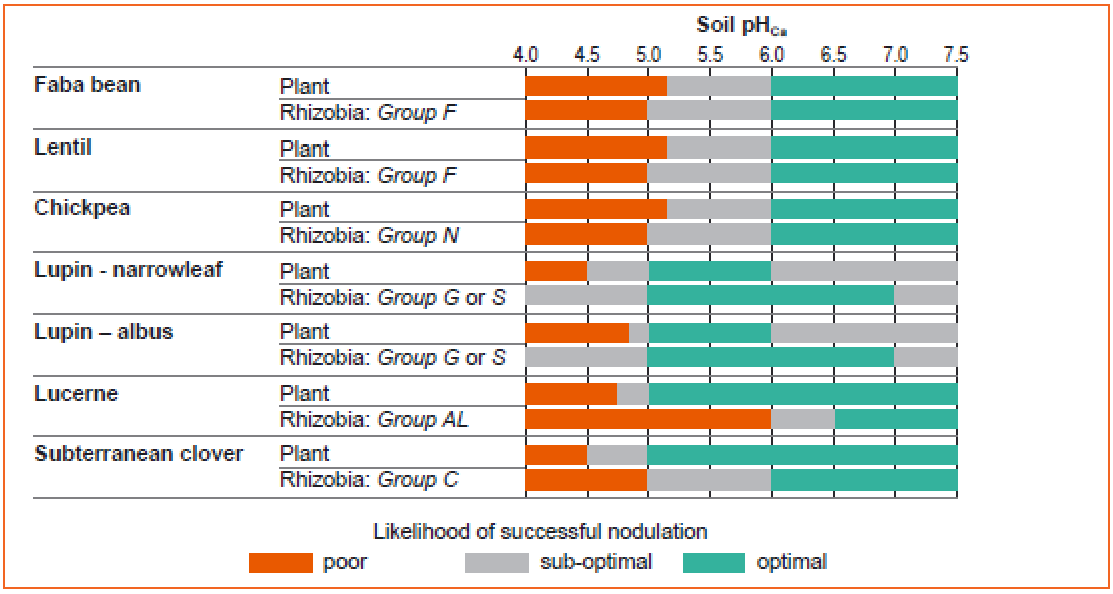

Figure 3. The tolerance of legume species and their associated rhizobia to a range of soil pH_{ca} and the likelihood of successful nodulation (poor, sub-optimal or optimal). (Extracted from Burns and Norton 2018).

The GRDC/NSW DPI publication 'Legumes in acidic soils' (Burns and Norton 2018) and GRDC Update paper (Burns and Norton 2020) offer some practical information to assist growers to better understand the agronomic management required to grow pulses and ensure maximum biomass potential and N fixation is achieved. There are a range of publications that can assist growers better understand the requirements for paddock selection, constraints, crop and variety selection, time of sowing, fertiliser/herbicide and fungicide applications. A few of these publications include:

- Pulses: putting life into the farming system (2015). Armstrong E and Holding Di;
- GRDC Inoculating legumes: A practical guide (2011) Drew et al.
- GRDC Legumes in acidic soils – maximising production potential. (2018) Burns and Norton;
- GRDC Grow Notes for Lentil, Chickpea, Fababean, Lupins (all available at https://grdc.com.au/resources-and-publications/grownotes/crop-agronomy/lentil-southern-region-grownotes).

Sodicity and salinity

Unfavourable and hostile soils that limit legume root exploration (e.g. soil compaction, sodicity, salinity), inhibit nodulation or restrict shoot growth (e.g. soil acidity, nutrient deficiencies) should also be ameliorated (Peoples *et al.* 2009; Santachiara *et al.,* 2019; Vanlauwe *et al.,* 2019). Lentils and chickpeas are also very sensitive to saline soils. Where the electrical conductivity (EC_{se}) of the saturated soil extract is 2 dS/m and 3 dS/m, a yield reduction of 20 % and 90 % has been found.

Soil mineral N

To achieve high %Ndfa, concentrations of available soil mineral N would also need to be low at sowing (<55-85 kg N ha^{-1}; Voisin *et al*. 2002; Salvagiotti *et al.* 2008), and > 60 kgN/a in the soil at depths of 0-1.2m prior to sowing chickpeas (Doughtan *et al.,* 1993; Drew *et al.,* 2012). Higher concentrations of soil N would inhibit nodule initiation and the N fixation process (Peoples *et al.,* 2009; Guinet *et al.,* 2018). High N and ensuing suppression of N fixation is less likely to occur under reduced tillage practices where the retention of stubble from a previous cereal crop is more likely to immobilize soil mineral N resulting in higher rates of N fixation (Torabian *et al.,* 2019).

Effective inoculation

Prospective agronomic practices to achieve this would include the use of high quality rhizobial inoculants at sowing, efficient inoculation practices, and the ameliorating of any soil conditions that are either hostile to rhizobia's survival and persistence or results in erratic nodulation (e.g. soil pH or nutrient deficiencies).

Crop species

In terms of genetic factors, the choice of legume species (and maturity group) most adapted for the local soil type, season or climate is likely to play a crucial role (Peoples *et al.,* 2009; Tagliapietra *et al.,* 2021), as will plant improvement for enhanced disease resistance (Peoples *et al.* 2019).

Greenethorpe farming system trial results in 2021

In January 2020, 3.3/ha of lime was applied and incorporated using a Horsch-Tiger to a depth of 26 cm at the Greenethorpe Farming system site. The 2021 year was extremely wet (952 mm) which resulted in some significant challenges such as higher disease levels in the pulse crops than experienced in 2020 (767 mm rainfall year). The ameliorated lime improved the %Ndfa and shoot N fixation (12-24 kg N/t DM) in all pulse crops at Greenethorpe compared to 2020 even in such a wet year with high disease pressure (Table 12). A new northern type of faba beans was grown in 2021 that produced excellent grain yields (7.7 t/ha), but potentially produced less biomass compared to the longer maturing Samira faba bean that was sown in 2020. The high grain yield and reduced faba bean biomass DM has resulted in lower net inputs of fixed N remaining in the crop residues compared to what may have been remaining if a southern later maturing variety such as Samira had been sown (Table 13).

Table 12. Soil mineral N at sowing, legume shoot biomass, %N content, and estimates of the proportion (%Ndfa), and amounts of shoot and total plant (shoot+root) N fixed at Greenethorpe in 2021 for a range of legume crops.

Crop 2021	Starting soil Mineral N 0-2m (kgN/ha)	Legume Biomass (t/ha)	Legume (%N)	Ndfa (%)	ShootN (kgN/ha)	ShootN fixed (kgN/ha)	ShootDM (kgN/tDM)	Total N fixed shoot & root (kgN/tDM)
Vetch Un-Grazed (T)	110	7.1	2.9	82	207	171	24	36
Faba bean	146	11.2	2.8	79	310	244	22	33
Chickpea (N2) (ChP-W)	106	9.4	1.9	63	176	111	12	24
Chickpea (N7) (C-W-ChP)	92	9.5	2.0	67	188	127	13	28
Chickpea (N2) (C-W-ChP)	91	8.9	2.5	57	226	128	14	29
Chickpea intercrop	150	6.2	2.1	78	127	99	16	33

Total plant biomass is indicated in brackets if it is different than the total legume biomass.

The cool September/October resulted in delayed flowering of the chickpea variety Captain when compared to previous years. The site did not reach the average daily temperature of 15 degrees Celsius until late October, with the daily temperature between mid-August and the end of October generally staying below 15 degrees Celsius (Figure 4). The longer growing season assisted chickpea to produce more biomass and reasonable grain yields despite the continued impact of fungal diseases that included Ascochyta blight, sclerotinia and botrytis grey mould. This higher biomass resulted in high net inputs of fixed N (Table 13). The same chickpea population (35 plants/m^2) was sown and established in the chickpea/linseed intercrop treatment, but the chickpeas were sown in alternate rows, 50 cm wide. The linseed did not emerge in high numbers and this treatment became a predominately chickpea crop sown on 50 cm wide rows. Interestingly, there was considerably less biomass and grain yield compared to the chickpea monoculture sown on 25 cm row spacing.

Table 13. Grain and hay yields, grain %N, N removed in grain or hay and the estimated residual fixed N remaining after grain or hay removal from a range of legume crops at the Greenethorpe site in 2021.

Crop 2021	Total Hay () & Legume Hay Yield (t/ha)	Grain Yield (t/ha)	Grain (%N)	Total Fixed N from root & shoot (kgN/ha)	N removed from grain or hay (kgN/ha)	Fixed N remaining in crop resides (kgN/ha)
Vetch Un-Grazed (T)	(5.0) 5.0			257	120	137
Faba bean		7.7	4.3	366	331	36
Chickpea (N2) (ChP-W)		3.1	3.2	229	101	128
Chickpea (N7) (C-W-ChP)		2.6	3.2	262	84	177
Chickpea (N2) (C-W-ChP)		2.9	3.2	263	94	169
Chickpea intercrop		2.0	3.2	203	64	139

Total plant biomass is indicated in brackets if it is different than the total legume biomass.

* Hay calculated as 70% of the total plant dry matter

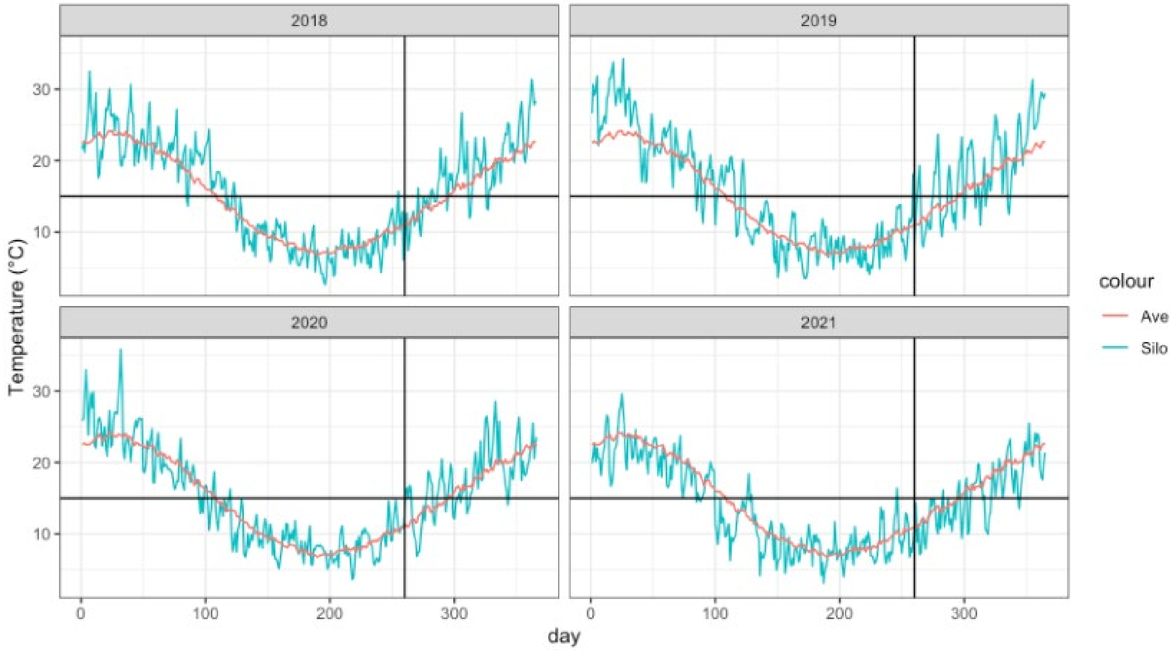

Figure 4. The daily and average daily temperature at the Greenethorpe trial site in 2018-2021 from interpreted data (Silo). Data courtesy of Dr Jeremy Whish.

Section 2: Legume crop legacy

Soil N

The main route for biologically fixed N to enter the soil N pool is through the decomposition of legume crop residues. The magnitude and timing of the release of legume N as plant-available forms represents a balance been the microbial-mediated mineralisation and immobilisation processes in the soil, which in turn are affected by the efficiency of use of the legume organic C by the decomposer population, and the microbial demand for C and N for growth (Kumar and Goh, 2000; Fillery, 2001). Inorganic N tends to be released from plant residues once excess C has been consumed by microbial growth. As compared to cereal crop residue, legume crop residue contains both a higher N content as well as a lower C to N ratio. These characteristics favour net N mineralisation and therefore lead to higher soil mineral N concentrations as legume crop residue breaks down. While legume crop residue breakdown is the primary source of soil N availability improvements after legume crops, this is not the only source. Other sources include: the carry-over of un-utilised mineral N after the legume crops and reduced N immobilisation by the soil biology compared to cereal stubbles.

Junee Reefs experiment 2011-2013

The large differences in soil mineral N observed following pulses grown for grain or BM in 2011 at the Junee Reefs experiment compared to wheat or canola top-dressed with fertiliser N at stem elongation, resulted in increases in wheat N uptake and higher wheat grain protein percentage in 2012 (Table 14). However, the impact of the additional N supply was not fully reflected in grain yields, with only a 0.6-0.7 t/ha increase in wheat grain yield. The drier growing season of 2012 reduced the maximum grain yield to 4.1 t/ha. The subsequent calculations indicate that the 2012 wheat crop recovered the equivalent of 29-39 % (mean 32 %) of pulse residue N (Table 14). This compared to 49-61 % (average 55 %) of the top-dressed fertiliser N. When Peoples *et al.* (2017) examined a range of crops between 1990 and 2016 across New South Wales and South Australia,

Table 14. Grain yield and crop N uptake by wheat in 2012 following either wheat, canola, and lupin or field pea grown for brown manure (BM) or lupin, chickpea or lentil grown for grain at Junee, NSW in 2011, and calculations of the apparent recoveries by wheat of either N from pulse crop residues, or top-dressed fertiliser N.

	Soil mineral N autumn 2012 (kg N/ha)	N fertiliser applied 2012 (kg N/ha)	Wheat grain yield (t/ha)	Wheat grain protein %)	Wheat total N uptake (kg N/ha)	Apparent recovery of legume or fertiliser N (%)
Lupins BM	152	49	4.0	13.6	198	29%
Field Pea BM	113	49	4.1	12.3	177	29%
Lupin	110	49	3.9	12.4	170	30%
Chickpea	152	49	4.0	12.4	181	39%
Lentil	111	49	4.0	11.2	152	35%
Wheat	70	49	3.4	9.9	114	-
Wheat	70	100	3.8	11.7	145	61%
Canola	72	49	3.4	9.8	118	-
Canola	72	100	3.8	11.8	143	49%
Mean legume						32%
Mean fertiliser						55%

Source: Peoples *et al.,* 2015 GRDC update, Peoples *et al.,* 2017 and un-published results.

they found that the average apparent recovery of legume N was 30% from grain legume crops and 29% from BM crops.

The CSIRO/NSW DPI farming system teams will examine the current farming systems and determine if the apparent recovery legume N by the following crop is within the range that Peoples *et al.* (2017) reported.

Southern Farming Systems project results (2018-2021)

The inclusion of fully phased crop sequences with and without legumes across a range of locations (Wagga Wagga, Greenethorpe, Urana & Condobolin) and seasons (2018, 2019, 2020 & 2021) in this project has allowed the investigation of a number of key questions:

(i) To what degree do legume crops boost the soil mineral N available to subsequent crops?
(ii) To what degree do legume crops boost the grain yield of subsequent crops, and
(iii) What is the approximate dollar value of these legume legacy benefits?

The legume crops at all four sites often resulted in more mineral N being available at sowing of the subsequent crops (Figure 5 and Table 15). Averaged across legume crop types, seasons and sites, an extra 50 kg/ha of extra mineral N was available at sowing in the subsequent season as compared to a cereal crop in the same season. Much of this N wasn't available directly after the legume harvest, but became available over the summer fallow period.

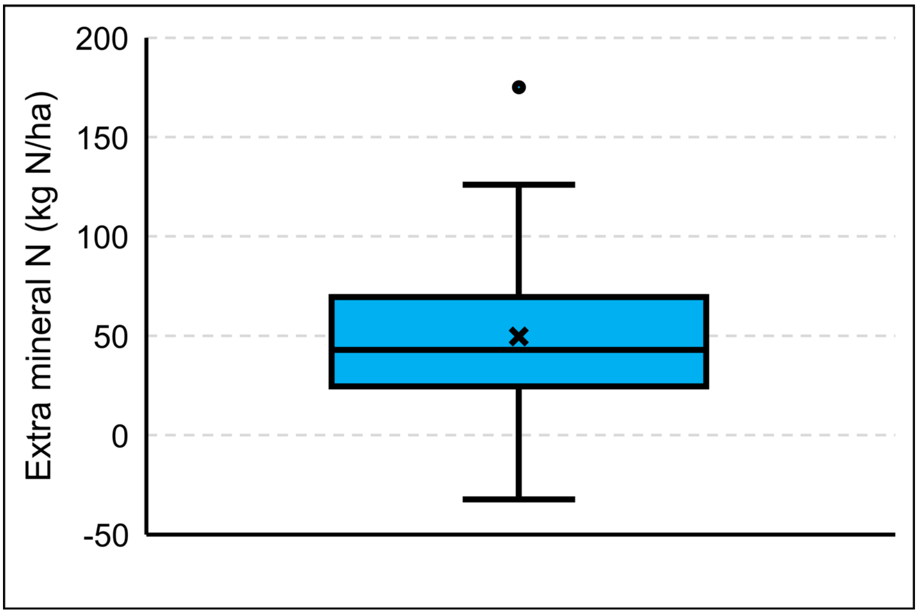

Figure 5. Extra soil mineral N (0-2 m) available at sowing following a legume crop compared to a cereal crop; averaged across four legume crops (lentil, lupin, faba bean & vetch), four sites (Wagga Wagga, Greenethorpe, Urana & Condobolin) and three seasons (2018, 2019 & 2020). Comparisons made between equivalent timely sown, decile 2 N strategy crop sequences. n=33, average=50 kg N/ha. The blue area represents the middle 50 % of data points, the two outside lines represents the maximum and minimum data point and the dot represents an outlying data point.

As evident in Figure 5, a significant amount of variability exists in the amount of extra soil mineral N that was available to the subsequent crops following a legume crop. Some trends exist between field site and season, however few clear trends are evident between preceding crop type (Table 15). This highlights that legume crop choice is better governed by performance and profitability potential for a given farm enterprise rather than potential soil mineral N benefits, which is a secondary consideration.

Table 15. Extra soil mineral N (0-2 m) available at sowing following a range of legume crops compared to a cereal crop at each site; averaged across three seasons (2018, 2019 & 2020). Comparisons made between equivalent timely sown, decile 2 N strategy sequences.

Preceding crop type	Field site			
	Wagga Wagga	Greenethorpe	Urana	Condobolin
	Extra mineral N (kg N/ha)			
Lentil	34	-	70	42
Lupin	15	-	-	60
Fababean	-	67	50	-
Vetch	37	63	77	37

With synthetic fertiliser prices at current all-time highs, more people are looking to legumes as a potential N source. One way to compare synthetic N sources to legume N sources is to value the short-term N benefit that legume crops can provide at the equivalent cost of urea. This comparison is presented in Table 16. At high urea prices as are currently being experienced ($1,200/t in early

2022), the value of legume N benefits can be significant at over $200/ha. It is important to note that this valuing of the soil N legacy left by legume crop only considers the extra mineral N accumulation over the summer period and does not consider any further in-crop mineralisation that can occur during the following growing season.

Table 16. Average extra soil mineral N (0-2 m) available at sowing following a legume crop compared to a cereal crop at each field site, with the value of this extra mineral N displayed at a range of urea prices. An assumption of 30 % N loss from applied urea has been applied.

	Field site			
	Wagga Wagga	Greenethorpe	Urana	Condobolin
	Average extra mineral N (kg N/ha)			
	29	64	66	47
Urea price ($/t)	Value of extra mineral N as Urea ($/ha)			
600	54	119	123	88
800	72	159	164	117
1,000	90	199	205	146
1,200	108	239	246	175
1,400	126	278	287	204

Using the crop sequences implemented in the southern farming systems project, not only are we able to examine the soil N legacy effects following legume crops, but we are also able to examine the urea savings and grain yield benefits provided to subsequent crops.

The N management strategies compared across some crop sequences in this project were based on either a conservative seasonal outlook (decile 2), or a more optimistic (decile 7) seasonal outlook. For each non-legume crop in each year of the sequences, soil mineral N was measured pre-sowing and a potential yield estimate was made based on starting soil water, N level and seasonal conditions up to that time. N was then applied as urea assuming either a decile 2 or a decile 7 finish to the season. Assuming an average season is decile 5, this means that often the decile 2 N strategy would be too low, and the decile 7 treatment too high to maximise yield potential in any year. Using this approach, the legacy benefits of carry-over N from either legumes or unused fertiliser N would be accounted for in the pre-sowing tests and less N applied accordingly. This approach (compared to set N rates) better mimics farmer practice.

For a given N management strategy, the extra soil mineral N often available following legume crops results in a reduction in the rate of top-dressed urea needing to be applied to the subsequent canola crops. This saving is urea cost combined with any grain yield benefit can be used to provide an indication of the legume legacy benefit in $/ha. Averaged across the three field sites, four legume crop types and three seasons, the average urea saving and grain yield benefit to the following canola crop was 78 kg/ha and 0.22 t/ha respectively (Table 17). When these benefits are valued at $1,200/t for urea and $650/t for canola, the total value of the legume value ranges from $171 to $330/ha depending on the field site, with an average of $237/ha (Table 17).

The above comparisons are made under a decile 2 N strategy. However, at the Wagga Wagga field site we can also make comparisons with decile 7 N strategy cereal sequences. This allows the comparison of legume legacy benefits to non-legume sequences where N is less limiting due to higher rates of urea applied.

Table 17. Urea saving, extra canola grain yield and the dollar value of these benefits following a legume crop compared to a cereal crop at each field site; averaged across a range of legume crops (lentil, lupin, faba bean & vetch) and three seasons (2018, 2019 & 2020). Comparisons made between equivalent timely sown, decile 2 N strategy crop sequences.

Field site	Wagga Wagga	Greenethorpe*	Urana	Condobolin	Average
Average urea saving (kg/ha)	29	120	69	94	78
Average extra canola yield (t/ha)	0.21	0.18	0.38	0.11	0.22
Value of urea saving: Urea=$1,200/t ($/ha)	35	144	83	113	94
Value of extra canola yield: Canola=$650/t ($/ha)	137	117	247	72	143
Total value of legume legacy ($/ha)	171	261	330	184	237

*Only legacy effects from the 2019 legume crops included for the Greenethorpe site.

The implementation of the higher decile 7 nitrogen strategy instead of the decile 2 strategy on the non-legume sequence resulted in an increased canola grain yield. However, this increase in grain yield was not high enough to offset the significant extra urea cost. As a result, the $/ha value of the legume legacy benefits are even higher when compared to the decile 7 non-legume sequence (Table 18).

Table 18. Urea saving, extra canola grain yield and the dollar value of these benefits following a legume crop compared to a cereal crop across two N management strategies (decile 2 & decile 7) at the Wagga Wagga field site; averaged across a range of legume crops (Lentil, lupin, faba bean & vetch) and three seasons (2018, 2019 & 2020). Comparisons made between equivalent timely sown, decile 2 & 7 N strategy crop sequences.

Nitrogen strategy of non-legume crop sequence	Decile 2	Decile 7
Average urea saving (kg/ha)	29	204
Average extra canola grain yield (t/ha)	0.21	0.02
Value of urea saving: Urea=$1,200/t ($/ha)	35	245
Value of extra canola yield: Canola=$650/t ($/ha)	137	13
Total value of legume legacy ($/ha)	171	258

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References

Angus JF and Peoples MB (2012). Nitrogen from Australian dryland pastures. Crop and Pasture Science, 2012, 63, 746-758. http://dx.doi.org/10.1071/CP12161

Angus JF, Kirkegaard JA, Hunt JR, Ryan MH, Ohlander L and Peoples MB (2015). Break crops and rotations for wheat. Crop and Pasture Science, 2015, 66, 523-552. http://dx.doi.org/10.1071/CP14252

Subsurface acidity threatens central and southern NSW cropping areas. In: National Soil Science Conference, Canberra 2018. Available at: https://www.researchgate.net/publication/330305076_Subsurface_acidity_threatens_central_and_southern_NSW_cropping_areas

Burns H and Norton M (2018). Legumes in acidic soils. Maximising production potential in south eastern Australia. Grains Research and Development Corporation. Available at: https://grdc.com.au/legumes-in-acidic-soils

Burns H, Norton M and Condon J (2020). It's not all about lime – management strategies to improve nodulation and N_2 fixation on acidic soils. 2020 Wagga Wagga GRDC update paper.

Drew E, Herridge D, Ballard R, O'Hara G, Deaker R, Denton M, Yates R, Gemell G, Hartley E, Phillips L, Seymour N, Howieson J and Ballard N (2012). Inoculating legumes: A practical guide. Grains Research and Development Corporation. Available at: https://grdc.com.au/GRDC-Booklet-InoculatingLegumes

Doughtan JA, Vallis I and Saffigna PG (1993). Nitrogen fixation in chickpea. Influence of prior cropping or fallow, nitrogen fertiliser and tillage. Aust. J.Agric.Res., 1993, 44, 1403-13.

Fillery IRP (2001). The fate of biologically fixed nitrogen in legume-based dryland farming systems: a review. Aust. J. Exp. Agric. **41**, 277-463.

Guinet M, Nicolardot B., Revellin C, Durey V, Carlsson G, Voisin AS (2018). Comparative effects of inorganic N on plant growth and N_2 fixation of ten legume crops: towards a better understanding of the differential response among species. Plant Soil **432**, 207–227.

Kirkegaard JA, Peoples MB, Angus JF and Unkovich MJ (2011). Diversity and evolution of rainfed farming systems in southern Australia. In "rainfed farming systems". (Eds P Tow, I Cooper, I Partridge, C Birch) pp.715-754. (Springer: Dordrecht, The Netherlands).

Kirkegaard J, Hunt J, Peoples M, Llewellyn R, Angus J, Swan T, Kirkby C, Pratt T and Jones K (2017a). Opportunities and challenges for continuous cropping systems. GRDC update (2017) Adelaide, Wagga Wagga, Ballarat.

Kirkegaard J (2017). A review of factors constraining farming systems efficiency in southern NSW (Milestone 106 – Project CFF00011.

Kumar K, Goh KM (2000). Crop residues and management practices: effects of soil quality, soil nitrogen dynamics, crop yield, and nitrogen recovery. Adv. Agron. **68**, 197-319.

Lake AHW (2012). Australia's declining crop yield trends II: The role of nitrogen nutrition. The Regional Institute Australia. http://www.regional.org.au/au/asa/2012/nutrition/8166_lakea.htm

People MB, Brockwell J, Herridge DF, Rochester IJ, Alves BJR, Urquiaga S, Boddey RM, Dakora FD, Bhattarai S, Maskey SL, Sampet C, Rerkasem B, Khan DF, Hauggaard-Nielsen H, Jensen ES (2009). The contributions of nitrogen-fixing crop legumes to the productivity of agricultural systems. Symbiosis 48, 759-786. https://doi.10.1071/CP12123

Peoples MB, Brockwell J, Hunt JR, Swan AD, Watson L, Hayes RC, Li GD, Hackney B, Nuttall JG, Davies SL (2012). Factors affecting the potential contributions of N_2 fixation by legumes in Australian pasture systems. Crop Pasture Sci. **63**, 759-786.

Peoples M, Swan T, Goward L, Hunt J, Li G, Harris R, Ferrier D, Browne C, Craig S, Van Rees H, Mwendwa J, Pratt T, Turner F, Potter T, Glover A and Midwood J (2015). Legume effects on soil N dynamics. Comparison of crop responses to legume and fertiliser N. In: GRDC Grower Update 2015, Corowa and Finely, NSW.

Peoples M, Swan T, Goward L, Hunt J, Hart R, Hart B (2015). Legume effects on available soil nitrogen and comparisons of estimates of the apparent mineralisation of legume nitrogen. Proceedings of the 17th ASA Conference, 20-24 September 2015, Hobart, Australia. Web site: www.agronomy2015.com.au

Peoples *et al*. (2016). Profitable Break Crop Management Guide. Available at: www.farmlink.com.au/project/crop-sequencing "Profitable Break Crop Management Guide".

People M, Swan T, Goward L, Hunt J, Li G, Schwenke G, Herridge D, Moodie M, Wilhelm N, Potter T, Denton M, Browne C, Phillips L, Khan D (2017). Soil mineral nitrogen benefits derived from legumes and comparisons of the apparent recovery of legume or fertiliser nitrogen by wheat. Soil Research. 2017; 55:600-615. https://doi.org/10.1071/SR16330

Peoples MB, Hauggaard-Nielsen H, Huguenin-Elie O, Jensen ES, Justes E, Williams M (2019). The contributions of legumes to reducing the environmental risks of agricultural production, in: Lemaire, G., De Faccio Carvalho, P.C., Kronberg, S., Recous, S. (Eds.), Agroecosystem diversity- Reconciling contemporary agriculture and environmental quality. Academic Press, Elsevier, London, U.K., pp. 123-143.

Reeves TG (2020). Is sustainable intensification of cropping systems achievable? 2020 Wagga Wagga GRDC Update.

Sanderman J and Baldock JA (2010). Accounting for soil carbon sequestration in national inventories: a soil scientist's perspective. IOP Publishing Ltd. Environmental Research Letters, Volumn 5, Number 3.

Santachiara G, Salvagiotti F, Rotundo JL (2019). Nutritional and environmental effects on biological nitrogen fixation in soybean: A meta-analysis. Field Crops Res. **240**, 106–115

Salvagiotti F, Cassman KG, Specht JE, Walters DT, Weiss A, Dobermann A (2008). Nitrogen uptake, fixation and response to fertilizer N in soybeans: A review. Field Crops Res. **108**, 1-13.

Tagliapietra EL, Zanon AJ, Streck NA, Balest DS, da Rosa SL, Bexaira KP, Richter GL, Ribas GG, da Silva MR (2021). Biophysical and management factors causing yield gap in soybean in the subtropics of Brazil. Agron. J. **113**, 1882-1894.

Torabian S, Farhangi-Abriz S, Denton MD (2019). Do tillage systems influence nitrogen fixation in legumes? A review. Soil Till. Res. **185**, 113-121.

Unkovich M, Herridge D, Peoples M, Boddey R, Cadisch G, Giller K, Alves B, Chalk P (2008). Measuring plant-associated nitrogen fixation in agricultural systems. ACIAR Monograph No. 136; Australian Centre for International Agricultural Research, Canberra. 1-258.

Unkovich MJ, Baldock J, Peoples MB (2010). Prospects and problems of simple linear models for estimating symbiotic N_2 fixation by crop and pasture legumes. *Plant & Soil* **329**, 75-89.

Vanlauwe B, Hungria M, Kanampiu F, Giller KE (2019). The role of legumes in the sustainable intensification of African smallholder agriculture: Lessons learnt and challenges for the future. Agric. Ecosyst. Environ. **284**. 106583. https://doi.org/10.1016/j.agee.2019.106583.

Voisin AS, Salon C, Munier-Jolain NG, Ney B (2002). Quantitative effects of soil nitrate, growth potential and phenology on symbiotic nitrogen fixation of pea (*Pisum sativum* L.). Plant Soil **243**, 31–42.

Contact details

Tony Swan
CSIRO Agriculture and Food
Clunies Ross St, Acton, Canberra ACT 2601
Ph: 0428 145 085
Email: tony.swan@csiro.au
Twitter: @tony_swan64

Mathew Dunn
NSW Department of Primary industries
Wagga Wagga Agricultural Institute
Ph: 0447 164 776
Email: mathew.dunn@dpi.nsw.gov.au

Dr Mark Peoples
CSIRO Agriculture and Food
Clunies Ross St, Acton, Canberra ACT 2601
Email: mark.peoples@csiro.au