Boosting pulse crop performance on acidic soils

Helen Burns, Dr Mark Norton and Peter Tyndall (NSW DPI, Wagga Wagga)

Key findings

- Acidic soil layers below 5 cm adversely affect root growth and architecture, nodulation, plant vigour, N_2 fixation and yield potential of acid-sensitive pulses.
- Moderately (pH_{Ca} 4.6–5.0) and severely (pH_{Ca} <4.5) acidic layers in the 5–20 cm soil profile are not detected using soil samples collected over standard profile depths of 0–10 cm and 10–20 cm.
- Finer sampling at 5 cm intervals is recommended to detect pH stratification.
- The current standard industry practice of spreading lime with no incorporation and sowing with knife point press wheels or disc seeders confines the lime effect to the surface layers.
- Careful paddock selection and forward planning is required to correct pH stratification in the topsoil (0–10 cm).
- Lime application and incorporation with a full cultivation operation at least 6–12 months before sowing acid-sensitive species could be necessary.
- Appropriate lime rates should be used to ensure pH_{Ca} >5.5 in the entire top 10 cm layer.
- The effect of pH stratification on more acid-tolerant species, including canola, lucerne and cereals, should also be monitored.

Introduction

While faba bean, lentil and chickpea, are generally acknowledged as being sensitive to soil acidity, they can be successfully grown on slightly acidic soils (pH_{Ca} >5.0–6.0) in the high rainfall zone (HRZ) and medium rainfall zones of south-eastern Australia, albeit with somewhat inconsistent yields. This paper identifies factors limiting the production and N_2 fixation of pulse crops grown on acidic soils in the south-eastern Australia HRZ.

In NSW these regions are dominated by acidic soils (0–10 cm; pH_{Ca} <6.0). Acid-tolerant lupin species make up 49% of the southern NSW pulse cropping area (Richards & Gaynor 2016), while adoption of more acid-sensitive, but higher value, species, such as faba bean, lentil and chickpea is limited by yield inconsistency, variable prices and perceived high production risk.

Little agronomic research has reported on the response of pulses to soil acidity. Guidelines for pulse tolerance to soil acidity are inconsistent and vague, for example a well-known authority proposes the ideal pH_{Ca} for faba bean is 6.0–8.0, but he has also indicated that pH_{Ca} >5.2 may be suitable (Eric Armstrong pers. com.). The optimal pH_{Ca} range for *Rhizobium* spp. used for faba bean, lentils, chickpea, vetch and field pea is >6.0 with the appropriate rhizobia species sensitive to pH_{Ca} <5.0 (Drew et al. 2012).

The environment to which the rhizobia and host plant are exposed influences the success of the complex nodulation process (Cregan & Scott 1998). Effective nodulation is essential to optimise the early growth, vigour and production potential of pulses sown into (N) nitrogen-depleted soils. Consultation with growers indicates that while the inoculation process and use of the appropriate rhizobia strain are well understood, the management required to avoid biotic and abiotic stresses that compromise the nodulation process, is not.

Numerous studies report acidic layers at 5–15 cm (to 20 cm in sandy soils) in both agricultural and non-agricultural systems (e.g. Conyers & Scott 1989; Paul, Black & Conyers 2003). We have taken that work a step further to investigate the effect of soil acidity below 5 cm depth on nodulation and plant growth. Pulse crop and soil data collected from commercial paddocks in 2015 and 2016 have shown the detrimental effect of moderately to severely acidic layers below 5 cm on root growth, nodulation and crop vigour. We conclude that even at sites where lime application has increased soil pH sufficiently to enable acceptable production from canola and lucerne crops, pH stratification and moderately (pH_{Ca} 4.6–5.0) and severely (pH_{Ca} <4.5) acidic layers below 5 cm depth can still be present and limit pulse crop growth, production and N_2 fixation.

Our findings are likely to be relevant to acid-sensitive pulses grown on acid soils across all rainfall zones. Furthermore, the severity of the acidity below 5 cm depth at a number of sites is sufficient to affect the productivity of the main crop and pasture species, including

Nutrition & soil

cereals, canola and lucerne. The widespread adoption of minimum disturbance systems on acidic soils, with the consequent failure to effectively incorporate surface-applied lime, is contributing to intense pH stratification of the surface soil. The research component of this project (not reported here) addresses the questions of the relative importance of lime rate and lime incorporation on overcoming pH stratification to improve legume nodulation and thus growth, N_2 fixation and yield.

Survey methodology

In 2015 and 2016, a total of 39 commercial legume crops were monitored in NSW, Victoria, SA and Tasmania (Figure 1). The 2015 sites were chosen to achieve geographical spread across acid soil regions of the target zones and included 12 paddocks of faba bean, two of narrow-leaf lupin and one of field pea. Sodosols were the dominant soil type at these sites. In 2016 an additional five growers were engaged in order to investigate a broader range of pulses and soil types – sodosols, chromosol and rudosols (alluvial). Sites monitored in 2016 were sown to faba bean (14), narrow-leaf lupin (2), chickpea (3) and lentil (3).

Figure 1. The acidic soil region of the high rainfall cropping zone of south-eastern Australia showing the location of paddocks monitored in 2015 and 2016.

A uniform, one hectare area of crop was selected at each site. Soils were sampled at depths of 0–10 cm and 10–20 cm, with pH measured using the calcium chloride method through Nutrient Advantage Laboratories.

Each year, crop plants were assessed 2–3 months post-emergence for nodulation effectiveness. Plants with intact root systems were collected at random from the designated areas and scored for nodulation using the Columbia protocol (British Columbia Ministry of Forests 1991). Scores were allocated for:

- plant growth and vigour
- nodule number
- nodule position
- nodule colour
- nodule appearance

with all parameters of equal weighting and 25 (5 × 5) the maximum possible total score.

In 2015, crops with low nodulation scores (<18) were investigated further. Root growth was assessed *in situ* and soil samples were collected at 2.5 cm intervals to a depth of 15 cm and tested for pH using a Manutec® Soil pH Test Kit. In 2016, root growth was assessed *in situ* and soil cores were collected from all sites and divided into increments of 2.5 cm to a depth of 10 cm; and 5 cm increments between 10–20 cm. Soil pH was measured in the NSW DPI Wagga Wagga laboratory.

Results and discussion

Faba bean was the most commonly grown pulse species in this study, enabling us to identify common constraints across the NSW, SA and VIC environments, which are also likely to be relevant to other acid-sensitive legume species. We found that faba bean nodulation was adversely affected by low soil pH in both 2015 and 2016.

Soil acidity and nodulation

The nodulation scores analysis for faba bean crops and pH_{Ca} of 0–10 cm soil samples from the monitored paddocks (Figure 2) showed a strong correlation ($r^2 = 0.88$) between soil acidity and nodulation scores (0 = nil nodules present, to a maximum of 25 = all plants with effective nodules). The form of inoculant used (peat slurry, freeze dried or granular) did not have a significant effect.

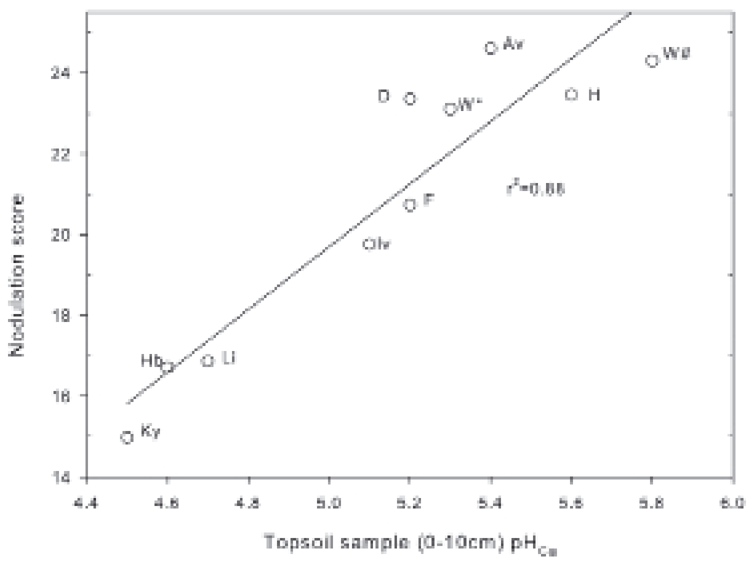

Figure 2. The effect of topsoil pH (0–10 cm) on faba bean nodulation across the south-eastern Australian high rainfall zone in 2015. Sites of sampling include Kybybolite, SA (Ky), Holbrook, NSW (Hb), Lismore, Vic (Li), Inverleigh, Vic (Iv), Frances, SA (F), Darlington, Vic (D), Willaura, Vic (W), Avoca, Tas (Av) and Henty, NSW (H). W* = after wheat, W# = after canola.

The monitored crops fell into two distinct categories:

1. vigorous, well nodulated crops
2. those with a nodulation score below 18, which included extremely variable crops that showed symptoms of nitrogen deficiency within two to three months of emergence, particularly at the Holbrook and Kybybolite sites (both Sodosol soils), recording nodulation scores of 17 and 15, respectively.

Although the percentage of exchangeable aluminium at the Holbrook site was 8% in the 0–10 cm and 35% at 10–20 cm soil depths, the percentage of exchangeable aluminium at both Kybybolite and Lismore was <2%. Therefore, it appears that low pH affected the nodulation process and reduced nodulation, irrespective of aluminium levels.

All 2015 sites, with the exception of Kybybolite, had received applications of lime within the past 5 years. Lime had been applied at the Holbrook site in 2010 and again in 2015 at a rate of 2 t/ha. In 2015, lime and retained stubble from the 2014 wheat crop was mixed in the surface layers using a speedtiller.

The association between nodulation score and soil pH_{Ca} was also evident in crops assessed in 2016. In this paper we will focus on a faba bean crop growing on red chromosol (red-brown earth) at Junee sites J1 and J2 (shown as the squares labelled J1 and J2) in Figure 3; and the chickpea crop growing on dermosol (red-brown earth) at Woodstock, east of Cowra (shown as squares labelled W1 and W2). The nodulation scores for these sites were 20.5 and 16.6 for Junee and 20.7 and 15.5 for Woodstock.

Sites J1 and J2 are within the same paddock at Junee, which received an unincorporated blanket lime application at 1.13 t/ha in 2011.

Nutrition & soil

Sites W1 and W2 are also within the same paddock at Woodstock. Lime had been applied at 2.5 t/ha in 2008 and incorporated using a disc plough. In 2016, the grower established test strips, with and without prilled lime. Using knife points, he drilled the lime to a depth of about 10 cm, through the fertiliser box of his combine, which was set to deliver prilled lime at a rate of 290 kg/ha. GPS guidance allowed him to then sow the chickpea directly over the prilled lime row with a second run.

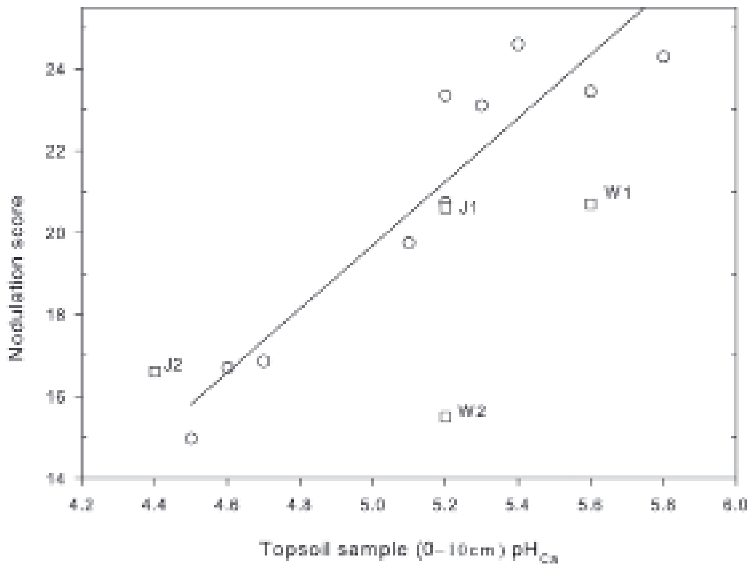

Figure 3. The effect of topsoil pH (0–10 cm) on faba bean nodulation across the south-eastern Australian high rainfall zone in 2015 (open circles) with four additional sites added in 2016 (open squares), marked as J1 and J2 representing sites at Junee growing faba bean crops, with W1 and W2 sites at Woodstock growing chickpea.

Soil pH stratification

The response of the 2015 faba bean crops to soil pH at Holbrook, NSW, Kybybolite, SA, and the 2016 sites at Junee, NSW (J1 and J2) and the chickpea crop at Woodstock, NSW (W1 and W2, Figure 3) are consistent with the observations made on all monitored crops growing in acidic soils, across the range of soil type and seasonal conditions experienced in 2015 and 2016.

As shown in Tables 1 and 2, composite soil samples taken at depths of 0–10 cm and 10–20 cm, which are traditionally used by growers and advisers to guide decisions on acid soil management, failed to detect significant variation in soil pH down the profile at the Holbrook, Junee or Woodstock sites.

The severe pH stratification identified by testing at 2.5 cm layers demonstrated that lime incorporation was ineffective under the no-till systems adopted by the majority of participating growers. The lime was concentrated in the surface layers with little movement of the lime effect below the surface layers (0–5 cm). Clearly, topdressing and no-till systems are ineffective in neutralising acidity below about the 5 cm depth. Failure to incorporate lime limits lime reactivity and potential crop response, which is an opportunity cost to growers.

The effect of acidic layers on faba bean root development and nodulation

Despite the Holbrook site receiving 4 t/ha of lime since 2010, incorporation with a speedtiller was ineffective in mixing the lime below 5 cm. Finer soil sampling of the topsoil indicated that at a sowing depth of about 6 cm the faba bean seedlings and rhizobia were exposed to a hostile environment (pH$_{Ca}$ <4.4), two pH units more acid than the surface soil (pH$_{Ca}$ 6.5). Nodulation was poor and the crop was showing symptoms of severe nitrogen deficiency within three months of emergence. Root growth was restricted to the surface 6 cm and did not penetrate into the severely acidic soil below 5 cm.

The results and observations from the Kybybolite site are included to highlight the impact of low pH on faba bean growth and nodulation. Root hair development was poor and plant roots were stunted, thickened and distorted, all symptoms typical of aluminium toxicity. However, with exchangeable aluminium levels of <2%, it is likely that low pH at this site is primarily responsible for the restricted root growth, reduced rhizobial activity and inefficient nodulation process as reported by Cregan and Scott (1998).

The Junee sites were from lower slope (J1) and mid slope (J2) areas within the same paddock. The soil tests from J1 indicate slight acidity (pH_{Ca} >5.0) from 0–7.5 cm, tending toward moderately acid (pH_{Ca} >4.6) from 7.5–15.0 cm. Plant roots from this area appeared healthy and were well nodulated (nodulation score of 20.6), but root growth was restricted to the top 10 cm. The moderately acidic layers at 7.5–15 cm (pH_{Ca} approx. 4.6) could be responsible for the shallow rooting depth, but the intermittent waterlogging experienced during July to September of 2016 were likely to have compounded the stress caused by the acidic layers.

Table 1. The pH_{Ca} measurements of 0–10 cm and 10–20 cm depths fail to detect the pH stratification in the soil profile at the Holbrook, Kybybolite or Junee sites, compared with tests from finer sampling increments. Soil conditions at each site were reflected in the appearance of faba bean plants.

Soil depth (cm)	Holbrook site 2015		Kybybolite site 2015		Junee 1 site 2016		Junee 2 site 2016	
	Soil pH_{Ca}		Soil pH_{Ca}		Soil pH_{Ca}		Soil pH_{Ca}	
	Nodulation score – 17		Nodulation score – 15		Nodulation score – 20.6		Nodulation score – 16.6	
	Composite sample	Sub samples*	Composite sample	Sub samples*	Composite sample	Sub samples	Composite sample	Sub samples
0–2.5	4.6 (Grower's paddock soil test – 5.2)	6.5	4.5	4.2	5.2	5.5	4.4	4.9
2.5–5.0		5.6		NA		5.4		4.6
5.0–7.5		4.4		NA		5.2		4.2
7.5–10.0		4.2		4.0		4.6		4.1
10.0–15.0	4.1	4.1	5.7	NA	4.8	4.6	4.4	4.2
15.0–20.0		4.1		NA		5.0		4.6
Plant appearance	Plants yellow, stunted. Roots concentrated in top 6 cm; stunted thickened and distorted, typical aluminium toxicity. Roots of <10% of plants extend below 10 cm. Dark coloured roots due to disease – likely due to multiple stresses.		Very poorly nodulated, stunted, yellow plants. Root growth confined to top 10 cm; roots stunted, thickened and distorted. Soil testing <2% aluminium. Minimal root hair development. The site had no history of lime.		Healthy, vigorous plants well nodulated, 35 cm tall at first node stage (Sept.). Healthy dense roots, finer root hairs superior to J2 plants. Roots restricted to top 10 cm.		Most plants yellow, less vigorous, less root hair development than J1 plants. Height 15–25 cm. Most root growth in the top 4 cm, minimal root growth below 4 cm. Root disease evident most plants.	

*Sub samples were not collected from same location as composite samples. pH_{Ca} for Hb and Ky sub samples were estimated using Manutec Soil pH Test Kit; pH_{water} was converted to pH_{Ca} using the relationship: $pH_{Ca} = 1.012pH_W - 0.768$ (Conyers & Davey 1988).

The J2 soil tests indicated moderate acidity in the surface 2.5 cm (pH_{Ca} 4.9), tending to severe acidity from 5.0–15.0 cm, with pH_{Ca} ranging from 4.6 at 2.5 cm, to as low as 4.1 at 7.5–10 cm. In contrast with plants from the J1 site, J2 plants were stunted and showed symptoms of severe nitrogen deficiency two months after sowing. Root growth was restricted to the surface layers (0–4 cm), root hair development was considerably less than J2 plants, and plants were not as well nodulated.

The majority of plants collected from the J2 site showed symptoms of root disease, in contrast with the relatively healthy J1 plants. It is likely the disease infection was a secondary, physiological response to the more hostile soil conditions (i.e. acidity, waterlogging) at J2. The lower incidence of infection observed in plants from J1 suggests that the higher pH in the root zone might have improved the plants health and made them less susceptible to damage and infection. The plants were not screened for specific root diseases, but there are likely to be many different species present, such as Pythium, Rhizoctonia, Fusarium or Phytophthora (K Lindbeck pers. comm.).

The Junee paddock is gently undulating and has a history of lucerne pasture, canola and wheat production. A 2013 soil pH_{Ca} test result from this paddock of 5.4 for the 0–10 cm soil depth failed to detect the variability in soil acidity across the paddock. The blanket lime rate of 1.3 t/ha, applied in 2011, but not incorporated (all subsequent crops being direct drilled with a knife point press wheel seeder), was inadequate to ameliorate the severe acidity to a depth of 10 cm at the J2 site.

The effect of acidic layers on root development and nodulation of chickpea

The test strips of prilled lime established by the grower at the Woodstock sites provided an opportunity to determine the effect of soil acidity on chickpea.

The composite 0–10 cm soil pH readings from samples at the W1 (prilled lime applied at 290 kg/ha) and W2 sites (no prilled lime) were pH_{Ca} of 5.6 and 5.2, respectively (Table 2). Finer sampling of the topsoil layers of W2 indicated that at a recommended sowing depth of 5–7 cm, seed and rhizobia would have been placed in a moderately acidic layer (pH_{Ca} 4.8). The incorporated prilled lime at the W1 site created a more suitable soil environment for the rhizobia and young seedlings, with a pH_{Ca} of 5.5.

Although the nodulation score for the plants growing in the nil lime (W2) indicated poor nodulation (a nodulation score of 15.05 compared with 20.7 at the W1 site), the W2 test strips did not show the obvious associated clinical symptoms of nitrogen deficiency and restricted root growth observed in affected faba bean crops. It was only when plant roots were inspected and scored for nodulation and root growth and then compared with those from the limed strips (W1) that the impact of the more acidic layers below 5.0 cm became clear.

Table 2. The pH_{Ca} measurements of test strips at Woodstock showing the effect of incorporating 290 kg/ha of prilled lime drilled to a depth of 10 cm in the seeding rows. Nodulation scores, plant appearance, nodule number and weight reflect the different soil conditions.

Soil depth (cm)	Woodstock 1 site (+ lime 2016)		Woodstock 2 site (nil lime 2016)	
	Soil pH_{Ca}		Soil pH_{Ca}	
	Composite sample	Sub samples	Composite sample	Sub samples
0–2.5	5.6	5.9	5.2	5.9
2.5–5.0		5.8		5.4
5.0–7.5		5.5		4.8
7.5–10.0		5.2		4.6
10.0–15.0	4.9	4.7	4.8	4.7
15.0–20.0		5.1		4.9
Plant appearance	Plants generally healthy and vigorous, good root development (Aug. and Nov. sampling). Roots more dense, abundance of root hairs compared with W2 plants. In Nov., roots and nodules concentrated in surface 10–12 cm. Minimal evidence of root disease or discolouration.		Aug. and Nov. – shoot growth similar to W1 plants, but root growth relatively poor; shorter, less dense, fewer root hairs. Aug. – root disease evident on most plants. Infection not severe enough to cause plant death, but root pruning and discolouration was evident at Nov. sampling. Nov. – roots and nodules concentrated in surface 6 cm.	
Nodule development (Aug 2016)	Nodulation score – 20.7 Nodule number/20 plants – 172 Nodule weight/20 plants – 1.69 g		Nodulation score – 15.05 Nodule number/20 plants – 140 Nodule weight/20 plants – 1.24 g	

The lime treatment appeared to improve root growth, root hair development and nodulation when the sites were first inspected in August. Nodule number and weight was 23% and 36% greater, respectively, on plants from the W1 strips compared with W2 plants. In addition, plants from W1 strips showed very little evidence of root disease. In contrast, root disease was evident on most plants sampled from W2. The increased susceptibility of chickpea seedlings growing in acidic soils to disease was similar to that observed in faba bean at the J2 site.

By November 2016, chickpeas from W1 and W2 strips were flowering and had reached a height of about 40 cm. Again, there were no obvious differences in shoot growth between the test strips, but differences between the W1 and W2 strips were obvious when the roots were inspected.

The depth and density of roots, root hair abundance and nodulation were superior for plants from the W1 strips, obviously benefiting from a pH_{Ca} ranging from 5.9 at 0–2.5 cm to 5.2 at 7.5–10 cm. Roots and nodules extended to a depth of 10–12 cm. Conditions at the site were extremely wet from July to October, therefore it is not possible to conclude if root development was restricted to the surface 12 cm as a result of intermittent waterlogging or the moderately acid layer at 10–15 cm (pH_{Ca} 4.7). It is probable that the combination of these environmental stresses adversely affected root development.

In contrast, the roots of the W2 plants were restricted to the surface 6 cm; root hair and nodule numbers were considerably less than on W1 plants. The pH_{Ca} of the surface 5 cm (5.9 at 0–2.5 cm and 5.4 at 2.5–5.0 cm) appeared to have been satisfactory for surface roots and nodulation development, but increased acidity from 5–10 cm (4.8 at 5.0–7.5 cm and 4.6 at 7.5–10 cm) restricted root growth and nodule development in these moderately acidic layers. The disease observed on W2 plants in August was still present in November.

Differences in the chickpea root appearance and nodulation suggest a response to the added and incorporated prilled lime within the seeding row, although, using yield maps to compare the test strips this did not translate into a harvest yield response.

Other factors affecting nodulation and early pulse growth

Management practices that caused severe damage to pulse crops monitored in 2015 and 2016 included:

- crop damage caused by sulfonyl urea (SU) herbicide applied in the previous 12 months. Ineffective incorporation of lime produces an elevated pH in the surface soil layers and delays the breakdown of sulfonyl urea herbicides, e.g. triasulfuron.
- adding zinc to inoculant slurries during the inoculation process. Zinc is toxic to rhizobia and when mixed with the inoculant resulted in extremely poor nodulation. If zinc is to be used on pulses, growers should ensure it is not placed in close proximity to the rhizobia at time of sowing, but rather applied in the fertiliser mix, separated from the seed, or sprayed onto the crop as a foliar application.

Conclusion

Effective nodulation underpins productive and profitable pulse crops. When detailed soil pH results were aligned to root growth and pulse crop nodulation, it was concluded that previously undetected, but severely acidic layers were likely to be a major factor in acid-sensitive pulses inconsistent performance on slightly (pH_{Ca} >5.0) and moderately acidic soils (pH_{Ca} 4.6 to 5.0) in the medium and high rainfall zones.

The impact of acidic layers on root hair development was apparent in all monitored crops. As discussed by Drew et al. (2012) the main pathway for rhizobial infection of commonly grown temperate legume species is via root hairs. The exception is lupin.

At all sites recording poor nodulation (Hb, Ky, J2 and W2), the seed and rhizobia encountered an acidic layer (pH_{Ca} 4.4, 4.5, 4.2 and 4.8, respectively) at 5.0–7.5 cm in the profile, which appears to have been sufficient to disrupt the infection process. Optimal nodulation requires pH conditions favourable to both the rhizobia and host plant. These results suggest that although management strategies such as lime pelleting of seed to raise pH in the seed's immediate vicinity could improve rhizobial survival in the short term, pelleting is unlikely to improve soil pH sufficiently to improve root hair development and significantly improve nodulation.

While most growers are effectively managing disease and weeds and are sowing recommended varieties, our findings highlight the need to review basic agronomic principles. Management of pulses sown in acidic soils must focus on promoting the nodulation process and minimising or avoiding environmental stresses. The results from this project, reinforced by grower experience, indicate that well nodulated, vigorous pulse crops have the ability to withstand multiple stresses, including infection by root diseases and transient waterlogging. The 2015 and 2016 experiences indicate that timely sowing, early in the recommended sowing window, allows plants and nodules to establish before cold temperatures slow growth and rhizobial function. Quoting one of the collaborating growers:

'Variety is not as important as agronomy… it's clear from what we are seeing we need to pay more attention to soils and agronomy.'

Faba bean is proving to be 'the canary in the coal mine' for detecting acidic layers. The dramatic clinical symptoms expressed by faba bean plants exposed to acidic layers has helped highlight the extent and severity of pH stratification, even in soils that have had a long history of lime application. From observations at the Woodstock site, shoot growth of other acid-sensitive species such as chickpea (and we suspect lentil, canola and lucerne) do not demonstrate the dramatic response to acidic layers or obvious clinical symptoms exhibited by faba bean. For these crops, we recommend close inspection of the roots in conjunction with finer soil sampling to check for the presence of acidic subsurface layers.

The negative impact on agricultural production of shallow subsurface acidic soil layers is well documented. The presence of these layers effectively places a ceiling on production potential and reduces efficiencies in water and nutrient use. The severity of the acidic layers identified in this study suggests that relatively acid-tolerant species, including barley, canola, lucerne and many wheat varieties, are probably suffering a yield penalty at pH_{Ca} <4.7 in the top 15 cm.

The traditional 0–10 cm soil sampling procedure is not detecting pH stratification. Finer sampling at 5 cm intervals to a depth of 20 cm is needed to verify the presence and depth of acidic layers.

The severe pH stratification identified by testing finer layers demonstrates that lime was concentrated in the surface 0–5 cm layers under the no-till systems adopted by the majority of participating growers. This study indicates that current acidic soil management and liming programs are inefficient in neutralising subsurface acidity or counteracting acidification below the surface layers. Lime rates, frequency and method of lime application need to be reviewed. A rapid solution to severe pH stratification in the 0–10 cm layers requires an aggressive approach, including incorporation with full cultivation and appropriate lime rates to ensure pH_{Ca} >5.5 in the entire surface 10 cm. This will improve lime reactivity, help the lime effect move to deeper in the profile, and increase potential crop response.

References

British Columbia Ministry of Forests (1991). *Field guide to nodulation and nitrogen fixation assessment*.

Conyers MK & Scott BJ (1989). The influence of surface incorporated lime on subsurface acidity. *Australian Journal of Experimental Agriculture* 29, 201–207.

Conyers MK & Davey BG. (1988). Observations on some routine methods for soil pH determination. *Soil Science* 145, 29–36.

Cregan P & Scott B (1998). Soil acidification – an agricultural and environmental problem. In *Agriculture and the environmental imperative*. (Eds JE Pratley & A Robertson). pp. 98–128. (CSIRO Publishing: Melbourne).

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 & Ballard N (2012). *Inoculating legumes: a practical guide*. Grains Research and Development Corporation. Available at: https://grdc.com.au/GRDC-Booklet-InoculatingLegumes

Paul KI, Black S & Conyers MK (2003). Development of acidic subsurface layers of soil under various management systems. *Advances in Agronomy* 78, 187–213.

Richards M & Gaynor L (2016). *Southern NSW pulse survey* 2015–16. NSW Department of Primary Industries, Wagga Wagga.

Robertson M, Kirkegaard J, Peake A, Creelman Z, Bell L, Lilley J, Zhang H, Kleven S, Duff C, Lawes R & Riffkin P (2016). Trends in grain production and yield gaps in the high-rainfall zone of southern Australia. *Crop and Pasture Science* 67, 921–937.

Acknowledgements

These surveys were part of the project 'N fixing break-crops and pastures for high rainfall zone acid soils', DAN00191, 2014–18, with joint investment by GRDC and NSW DPI and in collaboration with CSIRO Food and Agriculture, Holbrook Landcare Network and Mackillop Farm Management Group.

The contribution of the 21 growers participating in this project and their willingness to share their experience is greatly appreciated.