LEGUMES IN ACIDIC SOILS

MAXIMISING PRODUCTION POTENTIAL

IN SOUTH EASTERN AUSTRALIA

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GRDC
GRAINS RESEARCH & DEVELOPMENT CORPORATION

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1. INTRODUCTION

Effective nodulation and vigorous early growth sets the production and nitrogen fixation potential of pulse crops.

Pulse crops and legume pastures offer growers the option to diversify cropping programs that are currently dominated by cereals and canola. The Grains Research and Development Corporation (GRDC) have co-invested in research with New South Wales Department of Primary Industries (NSW DPI), in collaboration with grower groups and consultants to identify opportunities to improve the profitability, reliability and nitrogen contribution of these crops and pastures on acidic soils of south eastern Australia, through the project *N fixing break crops and pastures for HRZ acid soils*.

A major component of this project involved a survey of commercial pulse crops in the high rainfall zone (HRZ) grain production regions with a long-term average annual rainfall:

- >450 mm in Victoria, South Australia and Tasmania; and
- >550 mm in north east Victoria, and the central and southern slopes of New South Wales.

Crops monitored were located on soils typical of the region with pH_{Ca} <6.0 in the soil surface 0–10 cm (Figure 1.1 and Figure 1.2).

Although most of the surveyed crops were sown into paddocks with a history of lime application, detailed soil testing identified extreme pH stratification at 83% of sites, with an 'acid throttle' at depths of 5 to 15 or 20 cm. These were not detected using soil samples collected at standard depths of 0–10 and 10–20 cm.

Consultation with growers and advisors indicates that acceptable canola yield is commonly used as an indicator of effective management of soil acidity and to guide paddock selection for acid-sensitive pulses. However, canola is more tolerant of soil acidity than the majority of legume species and their associated rhizobia. As shown in Figure 1.3, the soil pH must be favourable to both the rhizobia and the host plant for nodules to form and effectively fix atmospheric nitrogen. The soil pH of layers within the surface soil at 95% of the commercial sites surveyed was below the optimal range for both the pulse and associated rhizobia.

Figure 1.1 Areas within the high rainfall zone grain growing regions of south eastern Australia that are dominated by acidic soils, with stars marking the approximate location of commercial pulse crops monitored in 2015, 2016 and 2017.

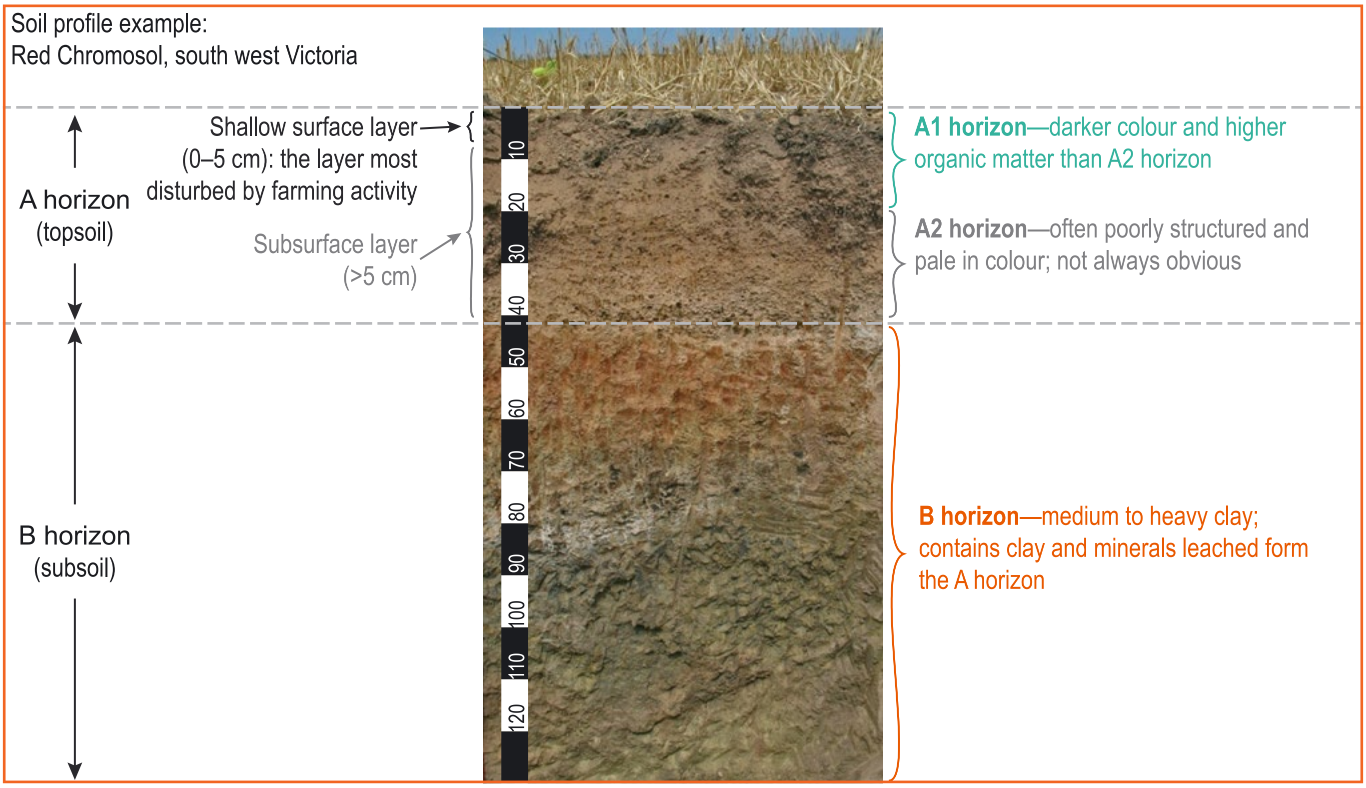

Figure 1.2 The duplex soils that dominate the HRZ have a light-textured, acidic topsoil (A horizon) overlying a dense subsoil (B horizon).
Photo: M Imhof

Most growers are effectively managing disease and weeds in pulse crops and sow recommended varieties. However, our study indicates that failure to detect and manage acidic subsurface layers within the surface 0–20 cm of soil is a major reason for lower-than-expected yield from pulse crops in the HRZ. Production potential of pulse crops is influenced by soil pH stratification within the surface layers and the depth of the acidic layers (i.e. the soil 'pH profile'): the lower the pH of the acidic layers, the greater the risk of ineffective nodulation, reduced root growth and poor plant vigour.

There is a need to review basic agronomic principles and management of pulses sown in acidic soils. Fundamental to improving production potential of pulses is proactive management of soil acidity and effective nodulation. The results from this project, reinforced by grower experience, indicate that well nodulated, vigorous pulse crops are more tolerant of multiple stresses than poorly nodulated pulses.

The guidelines presented in this report focus on agronomic management aimed at minimising the negative impact of low pH and other stress factors on nodulation and early growth of pulses. Achieving production potential (yield and nitrogen fixation) of acid-sensitive pulse crops (i.e. faba bean, lentil and chickpea) in acidic soils in the HRZ, requires forward planning and attention to detail.

- Choose the species best adapted to the soil and climatic conditions of your location.
- Select and prepare paddocks based on crop and pasture requirements, with attention to soil pH and internal drainage.
- Sow early in the recommended sowing window for your location.
- Optimise nodulation: follow manufacturer guidelines regarding storage and application of inoculant to ensure rhizobia survival in storage, during application, at sowing and during the nodulation process.
- Get basic agronomy right and avoid stresses that will compromise plant vigour, including poor nutrition, disease and pest damage and herbicide injury.

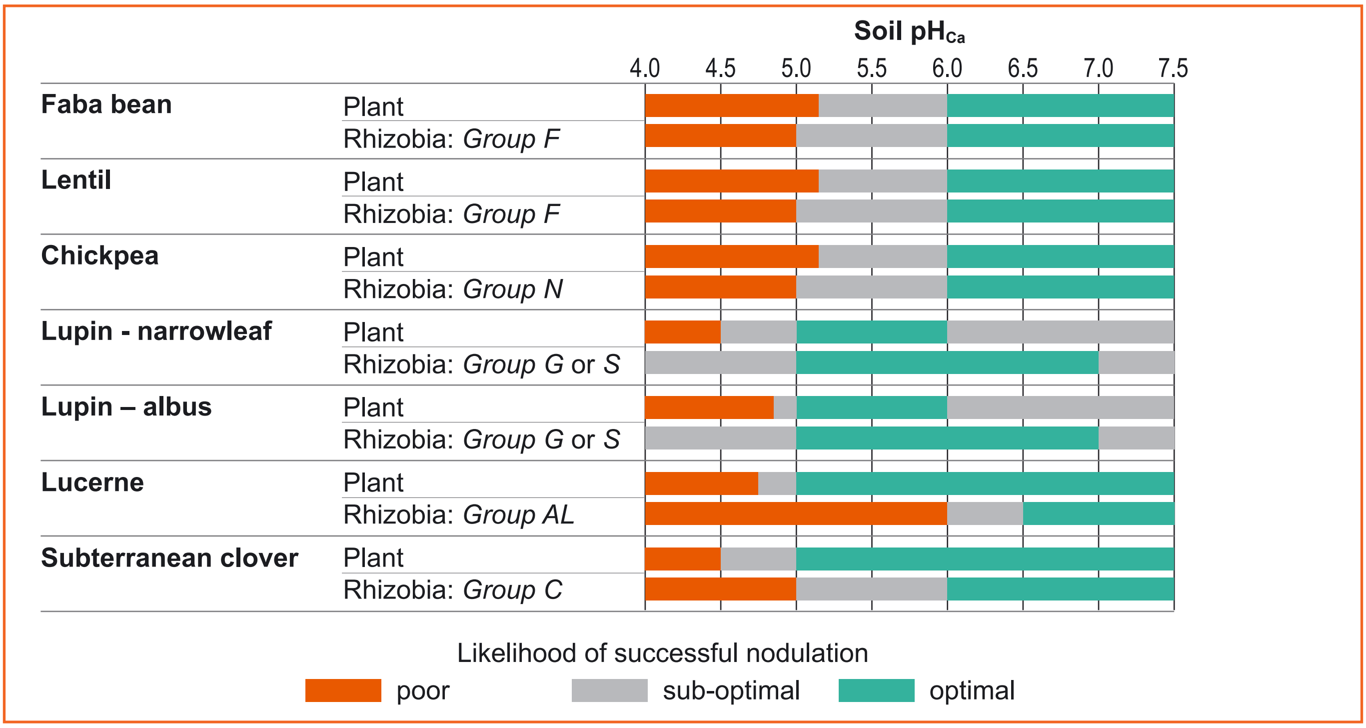

FIGURE 1.3 The tolerance of legume species and their associated rhizobia to a range of soil pH$_{Ca}$ and the likelihood of successful nodulation (poor, sub-optimal or optimal).
Adapted from: Drew *et al* 2012, Hackney *et al* 2017; various NSW DPI publications.

The information presented is based on soil data, assessment of nodulation and early growth of pulse crops in the 2015 to 2017 growing seasons in New South Wales, Victoria, South Australia and Tasmania, and draws on the experience of researchers, advisors and growers working in these regions. Variability at the landscape and paddock level in the HRZ, particularly the soil type and management history, makes it difficult to provide generic recommendations. Therefore the information in this report should be used in conjunction with local experience and data, as it becomes available.

Industry feedback and additional investigation (Burns and Norton 2018) suggests that pH stratification and subsurface acidity at depths of 5 to 20 cm is likely to be an issue across all rainfall zones of south eastern Australia and has potential to reduce production potential of pulses and other species grown in acidic soils, including canola, barley and wheat varieties.

The pH measure used throughout this publication refers to pH measured in calcium chloride (pH$_{Ca}$). Most soil kits measure soil pH in water (pH$_{W}$). The pH$_{Ca}$ values are about 0.8 to 1.0 units less than the pH$_{W}$ values.

NOTE: *There are numerous comprehensive publications that provide agronomic information for legume pastures and pulse crops, including variety selection and disease, weed and nutrient management. Such information is not included in this publication.*

2. SOIL ACIDITY

KEY POINTS

- Soil sampling at 5 cm intervals is recommended to detect acidic layers; pH stratification is not detected using soil samples collected at the standard sampling depths of 0–10 cm and 10–20 cm.
- Root growth, nodulation, plant vigour and nitrogen fixing potential of acid-sensitive pulses is reduced in soils with acidic layers (pH_{Ca} <5.0) within the top 0–20 cm of the soil profile.
- The pH of layers within the surface 0–20 cm and the depth of the 'acid throttle' should guide species choice and liming programs.
- The severely acidic subsurface layers identified in this study are likely to be affecting the yield potential of species with some acid-tolerance, including canola, lucerne, barley, wheat and lupin.

Effective nodulation is essential for optimum early growth, vigour and production potential of pulses sown into nitrogen depleted soils. However, the soil conditions to which the rhizobia and host plant are exposed influence the success of the complex nodulation process.

The presence of an 'acidic throttle' in subsurface layers at depths of 5 to 15 cm (up to 20 cm in sandy soils) in both agricultural and non-agricultural systems has been previously reported (e.g. Paul *et al* 2003). In this project the plant response to acidic layers within the 5–20 cm subsurface layer (Figure 1.2) was also considered.

Crop and soil data collected from commercial pulse paddocks showed that acidic layers below 5 cm had a detrimental effect on root growth, nodulation and crop vigour. Moderately (pH_{Ca} 4.6–5.0) and severely (pH_{Ca} <4.5) acidic layers below 5 cm depth were sufficient to limit growth and N fixation potential of acid-sensitive pulse crops, even at sites where lime application had increased soil pH sufficiently to achieve acceptable production from canola and lucerne crops.

2.1 NODULATION OF PULSE CROPS IN ACIDIC SOILS

From 2015 to 2017 NSW DPI investigated the impact of soil pH on nodulation of pulses in 45 commercial paddocks in New South Wales, Victoria, South Australia and Tasmania – 30 were sown to faba bean, five to lupin, five to lentil, four to chickpea and one to field pea (Figure 1.1). The crop locations provided geographical spread across acid soil regions of south eastern Australia and included the main soil types (see Section 3.2) and main temperate pulse species. Growing season rainfall ranged from drought conditions in south west Victoria and South Australia in 2015 (decile range 1–2) to above average rainfall and waterlogging at most locations in 2016 (decile range 9–10).

Plant and soil samples were collected from a representative one hectare area within each paddock. Soil was sampled from traditional sampling depths of 0–10 and 10–20 cm in 2015, and tested for pH, using the calcium chloride method (pH_{Ca}). The stratified pH_{Ca} within the subsurface detected at a number of the 2015 sites prompted sampling at finer intervals in 2016 and 2017: sampling increments of 2.5 cm, to a depth of 10 cm, and 5 cm increments from 10 to 20 cm.

In 2016 and 2017 soil and plant samples were collected from two sites within paddocks that displayed visual differences in crop growth (‘good’ and ‘poor’ areas). Over the course of the project, a total of 59 soil and plant samples were collected from 45 paddocks sown to pulses, each made up of 20 individual plant samples and soil cores. Four sites did not fit the project guidelines (pH_{Ca} >6.0 throughout the surface soil layers), so were not included in the following analyses or discussion.

Plant samples were collected at random within four months of crop emergence to assess nodulation[1]. Plants with no nodules were assigned a score of ‘0’, with a maximum of ‘25’ for sites if all 20 plants were vigorous and had numerous effective nodules. In our experience, the nodulation and vigour of crops scoring below ‘18’ was unsatisfactory. A score of 18 aligns with a score of ‘2’ from a possible ‘5’ used in the nodulation assessment method described by Drew et al (2012).

Low pH reduces nodulation

The sampled areas fell into two distinct categories:

1. vigorous, well nodulated plants with nodulation score >18 at sites with pH_{Ca} >5.0 in the 0–10 cm soil sample; and
2. stunted, yellow plants with an unsatisfactory nodulation score <18, which in most cases coincided with pH_{Ca} <5.0 in the 0–10 cm soil sample.

There was no evidence that form of inoculant (peat slurry, freeze dried or granular) used in the commercial crops affected the nodulation score.

As shown in Figure 2.1, the analysis of the pH_{Ca} of 0–10 cm soil samples and the nodulation scores for the acid-sensitive pulses in this study (faba bean, lentil and chickpea) indicated that satisfactory nodulation was achieved at most sites when 0–10 cm pH_{Ca} >5.0, with nodulation adversely affected by low pH (R^2=0.429). Note the increased scatter of points at pH_{Ca} <5.0 in Figure 2.1. While nodulation was ‘satisfactory’ at a number of sites with soil pH_{Ca} <5.0, the risk of poor nodulation increased as pH declined. Satisfactory nodulation at sites with low pH coincided with favourable conditions during sowing and establishment, for example warm soil temperatures and adequate moisture.

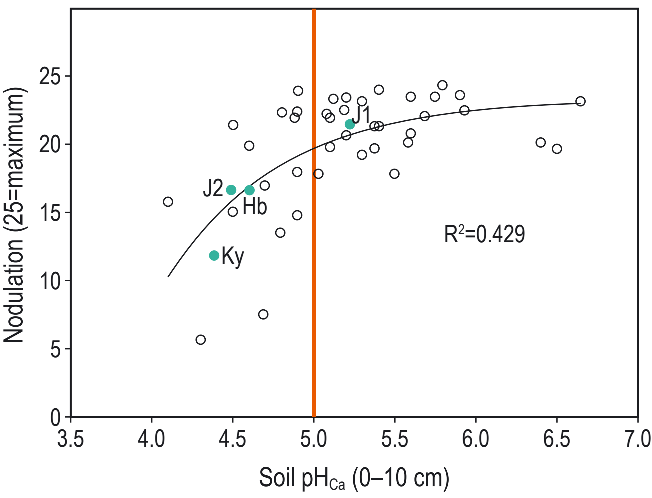

FIGURE 2.1 The effect of surface soil pH (0–10 cm) on nodulation of commercial faba bean, lentil and chickpea crops at 45 sites in the HRZ of south eastern Australia in 2015–2017. The solid circles represent sites at Holbrook (Hb) and Junee (JI and J2) in New South Wales and Kybybolite (Ky), South Australia. Details of these are discussed in Section 2.2.

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[1] Nodulation was assessed using the Columbia protocol (Anon, 1991), with scores allocated for (1) plant growth and vigour, (2) nodule number, (3) nodule position, (4) nodule colour, (5) nodule appearance. All parameters were of equal value, with ‘25’ the maximum possible score.

One of the most dramatic examples of the impact of low pH on nodulation and early vigour was in a faba bean crop at Holbrook (Hb in Figure 2.1) in 2015. Although sown with 60 kg/ha of MAP fertiliser, most plants developed severe nitrogen deficiency symptoms by late August 2015, four months after sowing, probably when fertiliser, seed and soil nitrogen reserves had been exhausted (Figure 2.2). Nodulation at this site was obviously ineffective, scoring 17, with most plants having nil to very few small nodules.

Faba bean has earned the reputation as ‘the canary in the coal mine’ because it is an excellent indicator of subsurface acidity. However, the severely acidic subsurface layers detected at 24% of the surveyed sites are likely to be also limiting productivity of more acid-tolerant species, including cereals, canola and lucerne.

Figure 2.2 The poorly nodulated faba bean crop at Holbrook, New South Wales, was stunted and yellow four months after emergence. The canola crop in the background had been topdressed with 90 kg of urea.
Photo: T Geddes

Poor nodulation in acidic soils. Don't blame the rhizobia!

Key points

- Most pulse crops and their associated rhizobia are sensitive to low pH.
- If low pH is not corrected, poor nodulation may result, even where good inoculation practices have been followed.

The negative effect of low pH on rhizobia survival is well publicised. However, the direct influence of low soil pH on the development of pulse roots and nodule formation, and its indirect influence on host plant vigour and N fixation potential is often overlooked. Maximum N fixation will only occur if conditions favour rapid development of functional nodules and vigorous plant growth. **The plant is the source of carbon for the rhizobia, and the rhizobia is the source of N for the plant.**

The diagram in Figure 2.3 highlights the complexity and interdependence of the processes involved in the development of functional nodules. Root infection, nodule formation and N fixation are closely linked to growth and function of both the plant and the rhizobia. Each component is influenced by soil condition: temperature, moisture and soil pH.

The development of nodules in legumes follows a sequence of steps involving chemical signalling between the host plant and the rhizobia, accumulation of large numbers of rhizobia at the growing tip of the host root, the production of chemicals by the rhizobia (Nod factors) and the growth and infection of root hairs. All these processes are sensitive to low pH.

If suitable rhizobia are not already present in the soil, they need to be added via inoculation. Good inoculation practices ensure that rhizobia are present in sufficient number, close to the emerging seedling roots. Under ideal soil conditions the rhizobia multiply and colonise the root rhizosphere. Exudates (flavonoids) from the developing root, released in greatest amounts near root tips, act as 'chemo-attractants' and concentrate compatible, host-specific rhizobia adjacent to the growing root tip, near emerging root hairs. The flavonoids activate nodulation genes in the rhizobia, which trigger the rhizobia to attach to and infect root hairs and form nodules (Richardson *et al* 1988, Abdel-Lateif *et al* 2012).

Note: Rhizobia infect most legumes via root hairs, but in some species, including lupin, the site of infection is between cells near emerging lateral roots.

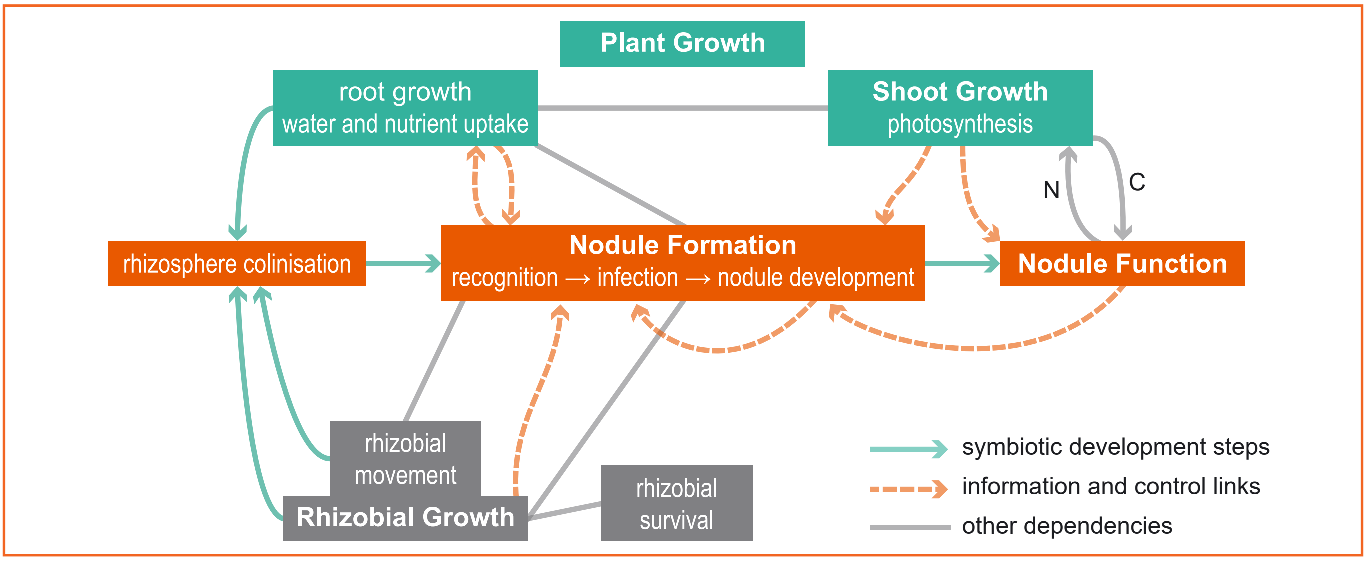


FIGURE 2.3 Soil acidity can reduce nodulation due to the detrimental impacts on rhizobial survival, root growth and each of the steps in the interrelated sequence of events that result in the formation of functional nodules.
Adapted from: Munns (1986)

Once nodules have formed, the amount of N fixed is driven by plant growth rate and demand for N. Therefore, any factor that limits plant growth will limit N fixation potential.

Maximising the N fixation potential in acidic soils depends on minimising or avoiding stresses that:

- compromise plant growth;
- compromise growth and function of the rhizobial population; or
- disrupt the nodulation process.

Stress factors identified as being likely to disrupt the development of effective nodules in pulse crops growing in acidic soils and management guidelines to avoid or minimise their impact are presented in Table 2.1.

Although it is possible to improve nodulation in acidic soils by increasing the rate of inoculant applied or by introducing acid-tolerant rhizobia (Ballard *et al* 2018), neither address the detrimental effect of low pH on root growth and vigour of the host plant. In the longer term, the combination of an effective liming program that increases pH and neutralises acidification, and the use of acid-tolerant rhizobia currently being evaluated, may provide a sustainable solution to improving nodulation and N fixation, and increasing the production potential of pulses grown in acidic soils.

Management practices focusing on minimising the impact of soil acidity on plant function are discussed in more detail in Section 2.2.

FIGURE 2.4 The faba bean crop on the right failed to nodulate when zinc was mixed with the rhizobia during the inoculation process. Rhizobia are sensitive to toxic chemicals and therefore contact with pesticides, fungicides, trace elements or fertilisers should be avoided or minimised. Check product labels before treating legume seed with pesticides or mixing products with the inoculant.

Photo: R Hamilton

TABLE 2.1 Soil acidity and other stress factors that may reduce nodulation in legumes by disrupting key steps in the pulse-rhizobia symbiosis shown in Figure 2.3: rhizobial growth, plant growth, and nodule formation and function.

Component	Stress factor	Impact on nodulation
Rhizobial growth	Poor inoculant storage, handling and application method – *follow label guidelines*	Fewer nodules
	Pesticides, fungicides, trace elements and fertiliser compounds in direct contact with rhizobia. ▪ Check pesticide and fungicide labels for compatibility with rhizobia before treating seed – follow label recommendations ▪ Trace elements such as zinc and copper are toxic to rhizobia (Figure 2.4) ▪ If molybdenum* is to be mixed with the seed during inoculation use molybdenum trioxide or ammonium molybdate. **Do not** mix sodium molybdate with inoculant ▪ Avoid direct contact of rhizobia or inoculated seed with fertiliser	Prolonged exposure of rhizobia to incompatible chemicals and pesticides can result in nodulation failure
	Low pH	Reduces rhizobia survival, which delays and reduces nodulation
	Low temperature e.g. delayed sowing	Slows rhizobia colonisation and nodule activity (N fixation rate)
	Dry conditions at sowing	Rhizobia numbers applied to seed will decline in extended dry conditions
Plant growth	Low pH	▪ Reduces signalling between host plant and rhizobia ▪ Restricts root growth and limits opportunity for rhizobia infection ▪ Reduces plant vigour and limits N fixation potential
	Low temperature	▪ Delayed rate of nodule formation ▪ Plant growth and N fixation slows as temperature declines
	Herbicide injury caused by: ▪ carryover of residue from herbicide applied to previous crop(s) ▪ physiological stress caused by in-crop herbicide application	▪ Root damage limits rhizobial infection sites ▪ Phytotoxic effect reduces plant vigour and photosynthetic capacity, and nodule activity and N fixation
Nodule formation and function	Low pH	Disruption of several steps in the nodule formation pathway reduces nodule number
	Herbicide injury	Root damage limits the number of rhizobial infection sites
	High soil nitrogen	Moderate levels of soil N reduce N fixation. High levels (>50 kg/ha in the root zone) will reduce nodulation
	Low temperature	Rhizobial activity and N fixation declines as soil temperature drops – negligible at below 10°C

**Note*: Molybdenum (Mo) is a micronutrient that is essential for production of enzymes needed for N fixation. Mo availability declines as pH decreases and is most likely to be deficient in soils of pH_{Ca} <5.0

2.2 PLANT RESPONSE TO SUBSURFACE ACIDITY

Management practices that optimise nodulation, seedling vigour and biomass accumulation before the onset of cold and wet winter conditions, are fundamental for pulses to achieve their production potential.

It is a mistake to presume that paddocks with a soil pH profile capable of producing 'acceptable' production from canola, barley and/or lucerne would be suitable for pulses. Although these species are generally considered to be acid-sensitive, our study suggests that the production potential of pulse crops (i.e. faba bean, lentil and chickpea) is even more constrained by acidic subsurface layers.

A rapid and effective way to confirm or discount subsurface acidity as the primary cause of poor crop vigour is to inspect the roots of affected plants for the presence of nodules and test pH of the surface soil layers from the affected area (see Section 2.5). Fine sampling at intervals of <5 cm aids detection of pH stratification, which is masked by traditional sampling depths of 0–10 cm and 10–20 cm.

Figure 2.5 shows that roots and nodules of the Holbrook faba bean crop (Figure 2.2) were concentrated in the shallow surface layers with pH_{Ca} of 6.5 at 0–2.5 cm and 5.6 at 2.5–5.0 cm. The roots were stunted, had low root hair density, very few nodules and did not grow into the toxic subsurface layers below 5 cm, with pH_{Ca} <4.4 and 21% aluminium (Al).

Figure 2.5 The pH_{Ca} of soil samples collected at 2.5 cm intervals show intense stratification at the 2015 Holbrook site (Figure 2.2). Stunted roots, with few root hairs and low nodule numbers are typical symptoms of pulse crops collected from sites with severely acidic subsurface layers.
Photo: H Burns

In the case of the Holbrook crop, the grower was confident the paddock was suitable for faba bean. He based his decision to sow faba bean on a paddock with a history of above district-average canola and wheat yields and soil test results. Samples collected in 2015 from a depth of 0–10 cm showed pH_{Ca} 5.2 and <2% exchangeable Al. However, soil pH results from this traditional sampling depth did not reflect the toxic soil conditions experienced by rhizobia-inoculated seed placed at a sowing depth of about 7 cm. The germinating seed was in a severely acidic layer that was harmful for early root development and colonisation and nodulation by rhizobia.

The Holbrook site had 2 t/ha of fine grade lime topdressed in 2010 and another 2 t/ha applied in March, 2015, which was incorporated prior to sowing using a Speedtiller® set to a depth of 8–10 cm. The elevated pH in the shallow surface layers (0–5 cm) indicates that incorporation was ineffective and that the effect of four tonnes per hectare of lime applied in the previous five years was confined to the shallow surface soil.

The pH profile of the Holbrook site, with elevated pH in the shallow surface layers and acidic layers in the subsurface, is typical of surveyed sites with a recent history of lime application, irrespective of soil type.

The high percentage of exchangeable Al at the Holbrook site (21% Al in the 5–10 cm and 35% Al at 10–20 cm) is likely to be a major cause of poor root hair development and ineffective nodulation. However, faba bean crops at acidic sites in Victoria and South Australia had similar poor root development and were poorly nodulated despite low exchangeable Al (<2%). This suggests that low pH (pH_{Ca} <4.5) will reduce nodulation, even in soil with low Al levels, for example at Kybybolite, South Australia (Figure 2.6) where the soil pH_{Ca} 0–15 cm was <4.5 and Al was <2%. Nodulation at this site was very poor, with a nodulation score of 15.

Figure 2.6 Roots of the faba bean crop growing on the unlimed site at Kybybolite, South Australia in 2015 were stunted, distorted and very poorly nodulated (nodulation score of 15). The site was severely acidic throughout the surface 0–15 cm layer (pH_{Ca} <4.5) but <2% Al.
Photo: H Burns

Variable crop growth and areas of stunted, pale plants were the most common visual indication that low soil pH was a likely factor affecting nodulation in the pulse crops we surveyed. Growers reported patchy areas of 'yellow' crops, and 'going backwards' about three to four months after emergence. Early growth often appeared to be satisfactory while plants were able to draw on seed and soil nitrogen reserves, but once these were depleted the poorly nodulated plants quickly developed nitrogen deficiency symptoms (Figure 2.7). Affected areas, ranging in size from a few square metres to large zones of a paddock, were often related to landscape and a change in soil type or uneven lime application.

A revision of soil sampling protocols and improved understanding of soil type and spatial variability is necessary for paddocks targeted for acid-sensitive pulses. The following case at Junee, NSW, highlights soil pH variability revealed in a paddock sown to faba bean for the first time, in 2016.

Figure 2.7 A patchy crop with areas of stunted, pale green plants is an indication that soil acidity may be an issue. Check for acidic layers to 0–20 cm depth by testing soil pH from samples collected at 5 cm intervals and inspecting plant roots for effective nodulation.
Photo: H Burns

A soil test collected in 2013 bulking multiple 0–10 cm samples from the entire Junee paddock, indicated pH_{Ca} 5.4. Based on this apparently satisfactory pH result and a history of relatively uniform and acceptable yields from canola and wheat crops, the grower was confident the paddock was suitable for faba bean.

Although the 2016 faba bean crop emerged evenly, by late August the lower areas of the paddock were obviously more vigorous and dark green compared with stunted and yellow areas in the balance of the paddock.

Soil and plant samples collected in 2016 from the lower slope (J1) and mid slope (J2) areas indicated that low pH was the likely cause of stunted root and top growth, and poor nodulation observed in J2 samples (Figure 2.1, Figure 2.8). The J1 plants were vigorous, well nodulated (score 20.6), which coincided with slightly acidic layers (pH_{Ca} >5.0) from 0–7.5 cm, tending toward moderately acidic layers (pH_{Ca} >4.6) from 7.5–20.0 cm (Table 2.2).

Table 2.2 Soil test results for Junee sites J1 and J2 using revised soil sampling protocols identified an acidic layer from 5 to 15 cm with high levels of aluminium.

Soil depth (cm)	pH_{Ca}		Al%
Site J1 lower slope Nodulation score 20.6 CEC (0–10 cm) = 9.0			
0–2.5	5.2	5.5	<2
2.5–5.0		5.4	<2
5.0–7.5		5.2	<2
7.5–10		4.6	4
10–15	4.8	4.6	3
15–20		5.0	<2
Site J2 upper slope Nodulation score 16.6 CEC (0–10 cm) = 5.3			
0–2.5	4.4	4.9	<2
2.5–5.0		4.6	5
5.0–7.5		4.2	13
7.5–10		4.1	17
10–15	4.4	4.2	10
15–20		4.6	2

In contrast, the J2 plants showed symptoms of severe nitrogen deficiency three months after sowing and soil tests indicated the presence of severely acidic subsurface layers (pH_{Ca} 4.1 and 4.2) at depths of 5–15 cm (Table 2.2).

Root growth was restricted to the shallow surface soil by the severe acidity below 5 cm; root development and root hair density was poor, and plants were poorly nodulated (score 16.6).

Figure 2.8 Vigorous, well nodulated plant from J1 site (left) compared with stunted, poorly nodulated plant from J2 (ight) where severely acidic layers at depths of 5–15 cm appear to have reduced nodulation and root growth.
Photo: H Burns

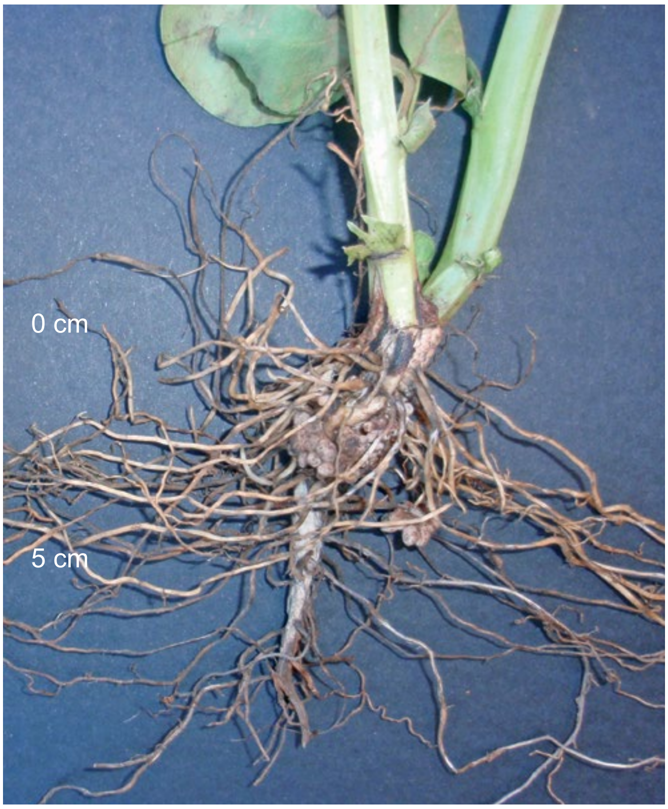


Figure 2.9 Disease infection in J2 plants compromised by multiple stresses, including low soil pH and waterlogged conditions.
Photo: H Burns

Yield from the two areas, estimated from yield map data, reflected the visual differences in crop vigour, with the J1 lower slope area producing about 50% higher grain yield (3.5 t/ha) compared with the J2 mid slope area (<2.0 t/ha).

Clearly, the single 2013 soil sampling procedure produced misleading results and failed to detect pH variability across the paddock and the pH stratification within the subsurface layers. In hindsight, the paddock should have been sampled in two zones and in 5 cm increments.

Soil acidity may reduce the tolerance of pulses to other stress factors

Optimising seedling vigour and biomass accumulation before the onset of cold and wet winter conditions is fundamental for pulses to achieve their production potential in the HRZ. Our study indicates that the negative impacts of environmental stresses or poor management practices (e.g. late sowing) are amplified in pulse crops growing in acidic soils.

Experienced growers and advisors report that vigorous, well nodulated plants were 'healthier' and are more tolerant of stresses, such as waterlogging, than poorly nodulated plants. This supports our field observations and conclusions that at pH_{Ca} <5.2 plant vigour is compromised and the weakened plant is more susceptible to potential stress factors. Some of these factors (soil acidity, disease infection, nutrition and herbicide injury) can be managed by the grower, while others associated with environmental conditions (soil depth and waterlogging) are less easily addressed.

We noted a potential link between plant vigour, low pH and disease infection at several paired sites across a range of growing seasons. For example, the majority of plants collected from the most acidic J2 site at Junee showed more severe root disease infection (*Fusarium*, *Rhizoctonia*, *Pythium* and *Phytophthora*) than plants from the less acidic J1 site. Although waterlogging affected the entire Junee crop, it is likely that the combination of unfavourable conditions at J2 (i.e. severe acidity, high aluminium levels and waterlogging) compromised the plants' tolerance to disease infection (Figure 2.9); i.e. the plants lacked vigour and disease infection was a secondary, physiological response to the plants' weakened condition. These observations align with sub clover research by O'Rourke *et al* (2012) that highlighted the role of adequate nutrition (including N or effective nodulation) in promoting plant growth and sufficient compensatory roots to decrease the severity of root disease, including *Pythium* and *Fusarium*.

While we detected disease infection by close examination of roots, clinical symptoms of other stresses, such as herbicide injury, were less obvious. Root pruning, poor nodulation and suppressed growth was noted in faba bean and lentil seedlings exposed to high rates of residual herbicide, and in an extreme case total establishment failure of lupin was attributed to persistence of sulfonylurea residue where lime had been topdressed and resulted in elevated pH_{Ca} (>6.5) of the surface soil. Drew *et al* (2007) reported reduced yield in drought-stressed field pea treated with registered rates of various in-crop herbicides. They attributed the herbicide-induced yield effect to reduced herbicide tolerance under exceptionally dry conditions, which either:

1. reduced root hair development and disrupted the nodulation process; or
2. reduced growth rate, and slowed metabolism of the herbicide by the plant and delayed recovery.

We do not have data to conclude that soil acidity causes herbicide-induced yield loss in pulses. However, we observed reduced vigour in pulses growing in acidic soils, and suggest that plants in a weakened state are at greater risk of herbicide injury, as reported by Drew *et al* (2007). It is important to understand the impact of environmental conditions and soil type on herbicide breakdown and to adhere to herbicide label recommendations regarding variation in application rates with soil type.

Our observations indicate that direct and indirect influences of soil acidity on the tolerance of acid-sensitive pulses to multiple stresses encountered in most seasons in the HRZ are under-estimated. We suggest that production potential of pulses in these sub-optimal environments is reduced by interacting stresses, with soil acidity a major, underlying factor influencing the ability of pulses to tolerate and recover from stress 'hits', including low temperatures, nitrogen deficiency (poor nodulation), waterlogging, disease infection and/or herbicide injury.

Our experiences indicate that increased effort and attention to detail is required to achieve water-limited yield potential from pulses growing in acidic soils.

Forward planning and management is absolutely critical to minimising or avoiding stress factors and achieving production potential of pulses in all environments.

2.3 IDENTIFICATION AND MANAGEMENT OF STRATIFIED SOIL pH

Check for acidic layers within the 5–20 cm soil subsurface two years before sowing acid-sensitive pulses to identify (and prepare) paddocks suitable for pulses and to rule out those paddocks that are not suitable.

Early detection of acidic layers in the subsurface is absolutely essential to:

1. **avoid sowing acid-sensitive species into soils with severely acidic pH to depth;**
2. **guide acidic soil management strategies; and**
3. **allow time for applied lime to react and increase pH.**

Key points

- Check for presence of acidic layers by sampling soils at intervals of 5 cm to a depth of 20 cm. A field soil test kit provides a quick and cheap indicator of acidic layers. Follow-up with an analysis from an accredited laboratory.
- The industry practice of topdressing lime with no incorporation and sowing with minimum soil disturbance confines the lime effect to the shallow surface layers (0–5 cm) and does not address subsurface acidification.
- A rapid solution to acidic layers in the surface layers (0–20 cm) requires an aggressive approach including appropriate lime rates and strategic cultivation to a depth of 10 cm, at least 12 months (greater than 18 months in dry environments) prior to sowing sensitive species.
- Effective incorporation of adequate rates of fine-grade lime hastens the lime reaction and increases the depth of the lime effect.

Our investigations indicate that soil pH is an underlying influence that sets the yield and N fixation potential of acid-sensitive pulses: the lower the pH in the subsurface layers, the greater the risk of poor nodulation and compromised yield, and the greater the susceptibility of the acid-sensitive plants to other stresses. Soil test results from the commercial paddocks surveyed suggest that severe to moderate subsurface acidity may compromise pulse production potential at 83% of the 54 acidic sites we surveyed (21 in Victoria and the South Australia border region, 33 in New South Wales).

Acid-sensitive pulses favour free-draining soils with no subsoil constraints and pH_{Ca} >5.5 throughout the root zone, but particularly in the 0–20 or 0–25 cm surface layers, where, under ideal conditions, up to 80% of the roots of most pulse species are concentrated. Roots growing in these soils access deep moisture to achieve their production potential. Comparable production may be achieved from well nodulated pulses growing in soils with minor chemical or physical constraints that restrict rooting depth, provided crops receive adequate rainfall throughout the growing season and mild spring temperatures during flowering and grain fill to achieve their water-limited yield potential.

Based on industry guidelines for optimal soil pH for acid-sensitive pulse species (Section 3.2) and using soil pH data in the 5–20 cm layers and the depth of the acidic layers of the acidic sites, we grouped surveyed sites into four categories for potential risk of poor nodulation and reduced seedling vigour—Low, Moderate, High and Excessive. Based on soil pH alone, 32 of the 55 acidic sites surveyed (59%) are not suitable for growing acid-sensitive pulses without first amending subsurface acidity:

- Low risk: pH_{Ca} >5.2 within the surface 0–20 cm layers; 17% of sites
- Moderate risk: pH_{Ca} 4.8–5.2 within the surface 0–20 cm layers; 24% of sites
- High risk: pH_{Ca} 4.5–4.8 at 5–15 cm; 35% of sites
- Excessive risk: pH_{Ca} <4.5 at 5–20 cm; 24% of sites.

Figure 2.10 shows the mean soil pH_{Ca} at each layer (at 2.5 cm intervals from 0–10 cm and at 5 cm intervals from 10-20 cm) within each category.

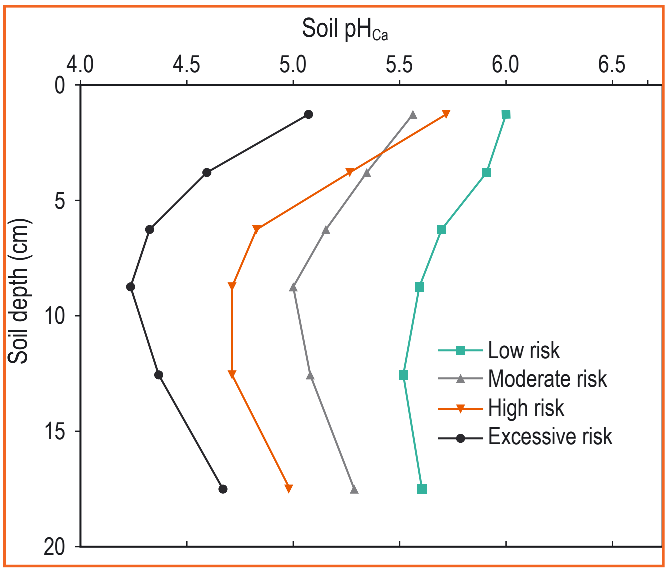


Figure 2.10 Mean soil pH_{Ca} in the surface and subsurface layers of the 55 acidic sites surveyed, categorised (Low, Moderate, High and Excessive) for potential risk of poor nodulation and reduced seedling vigour of acid-sensitive pulse species.

Although 51 of the 55 acidic sites had a history of lime application, only 9 sites (17%) were in the 'Low risk' category and had soil characteristics suitable for acid-sensitive pulses, including satisfactory internal drainage and pH_{Ca} >5.2 to a depth of at least 0–20 cm. The soil pH within the 0–20 cm surface layers at these sites was in the optimal to sub-optimal range for both plant and rhizobia (Figure 1.3). Presuming there are no physical subsoil constraints, crops growing in these soils should access deep moisture (below 60 cm), and so have some tolerance to moisture stress and rising temperatures during flowering and grain fill as the crop matures. These crops are more likely to achieve their water-limited yield potential across a range of seasons than crops growing in lower pH soils. (Desirable soil characteristics for pulses are discussed in more detail in Section 3.1).

Mean pH_{Ca} of sites in the 'Moderate risk' category were acidic (pH_{Ca} 4.8–5.2) at the pulse sowing depth (usually 5–8 cm), which may compromise root development, nodulation and yield potential, particularly in soils with additional constraints such as poor internal drainage and shallow topsoil. Production potential of pulses growing in these soils is likely to be more variable than for sites in the higher pH, 'Low risk' category. Early seedling vigour and effective nodulation is important for acid-sensitive pulses sown into such sub-optimal soil conditions. Timely sowing, early in the recommended sowing window, will promote vigorous seedling growth before the onset of low winter temperatures, typical of the HRZ, when plant growth rate and rhizobial function will slow.

Sites in the 'High risk' category had moderately acidic layers with mean soil pH_{Ca} 4.6–4.8 in the 5–15 cm layers. This is likely to limit root development, nodulation and therefore production potential. A liming program implemented 12–24 months prior to sowing, using adequate rates of effectively incorporated fine-grade lime, with high neutralising value, will increase pH to the depth of incorporation. Even so, it is likely that rooting depth of pulses sown into these amended soils will be restricted to the depth of lime incorporation. In these cases production potential and N fixation would be highly dependent on favourable seasonal conditions during establishment, with grain yield particularly reliant on mild temperatures and adequate moisture in the root zone during flowering and pod fill.

The severity and depth of the acidic layers of the severely acidic sites (pH_{Ca} <4.5) in the 'Excessive risk' category, such as the Holbrook site (Figure 2.5) make these unsuitable for acid-sensitive pulses. The severity and depth of the acidic subsurface layers are likely to limit production potential of most crop species, including canola, barley, narrow-leaf lupin and wheat. Acceptable production from pulses in such paddocks would require a long-term approach to increase pH.

Are current liming programs addressing subsurface acidification?

The extreme pH stratification detected in recently limed paddocks with a history of minimum tillage systems highlights an opportunity cost to growers. The lime is not reaching the acidic layers where it is needed.

Soil data collected from the commercial paddocks (and from other surveys not reported here) indicate that pH stratification and subsurface acidity within the 0–20 cm surface layers is common in the high and medium rainfall zones of the grain growing regions of south eastern Australia. It is important to note that the sites surveyed are a biased sample selected by growers for their presumed suitability for pulses, and represent some of the most productive cropping soils of the HRZ.

Samples collected from the 55 acidic sites were grouped on the basis of recent liming history: sites that were limed more than five years before sampling (Group 1); and those limed within the last two years (Group 2). Fifty-one (51) of the sites have a history of lime application, typically two to three applications in the previous 25 years, while four sites had no previous lime applications.

The mean soil pH of surface layers for each group is shown in Figure 2.11. The pH of the shallow surface layers (0–5 cm) of both groups was elevated, declined in the subsurface and then increased with depth. The exaggerated higher pH in the layers within the 0–5 cm depth of the recently limed sites (Group 2) demonstrates that lime remains concentrated in the shallow surface layers and has had limited effect on increasing pH or neutralising acidity below 5 cm under the no-till systems adopted by the majority of participating growers.

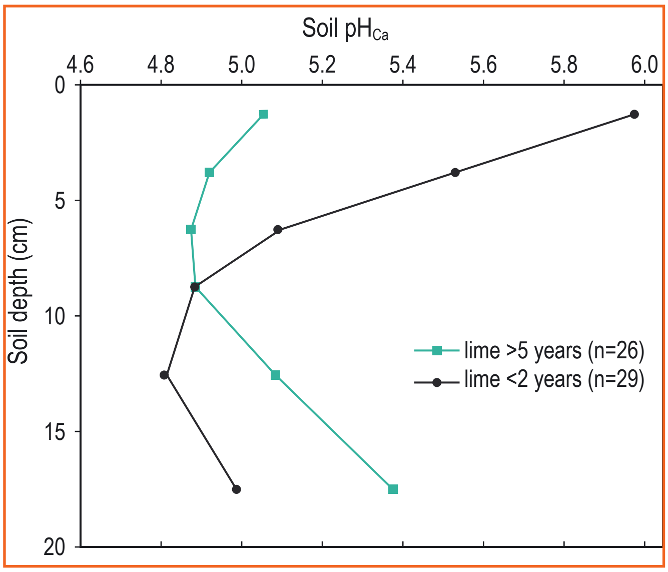


Figure 2.11 The mean soil pH_{Ca} in the surface layers of 55 sites: Group 1–limed greater than five years before sampling; or Group 2–limed within the last two years. Soil samples were collected from depths of 0–2.5, 2.5–5.0, 5.0–7.5, 7.5–10.0, 10–15 and 15–20 cm at each site.

Sampling at fine increments highlights the potential inaccuracy of tests from standard depths of 0–10 and 10–20 cm and the risk of underestimating the intensity of soil acidity in the subsurface layers. Concentration of lime in the shallow surface layer under no-till systems makes 0–10 cm soil testing even less useful. Sampling at <5 cm intervals is particularly important for sites with a recent and regular history of lime applications, as shown in the Group 2 example (Figure 2.11). Using the calculated means of soil pH_{Ca} the 0–10 and 10–20 cm layers, based on 5 cm intervals, the values would be 5.4 and 4.9, respectively. This masks the exaggerated pH stratification, with pH_{Ca} declining from the 0–2.5 cm to the 7.5–10 cm layer by 1.1 pH units.

The proportion of surveyed sites with pH_{Ca} <4.5 in the 5–15 cm increments (32%) was unexpected and is concerning, particularly given the lime history and chemical properties of soils in this biased sample of commercial sites. With the lowest pH at the 10–15 cm depth of the recently limed sites (Group 2), this suggests that the liming programs for many of the sites surveyed are not preventing acidification below 10 cm.

Unfortunately there is no baseline soil pH data for the surveyed sites to monitor changes in soil pH that would enable us to assess the effectiveness of efforts to ameliorate acidity or prevent re-acidification. However, our data suggests that contemporary acidic soil management and liming programs are ineffective in neutralising subsurface acidity or counteracting acidification below the shallow surface layers. In fact, the depth of the most acidic layer at 10–15 cm suggests that current lime rates, and frequency and method of lime application need to be revised. This conclusion is supported by previous studies (Scott *et al* 2017) and additional soil data (Burns and Norton 2018).

One of the risks of pH stratification in the surface soil is carryover of sulfonylurea (SU) herbicide residues. Elevated pH in the surface soil layers delays the breakdown of SU herbicides, e.g. triasulfuron, which may extend the plant-back interval to 22 months when surface (0–5 cm) soil pH_{Ca} >5.8. Check herbicide labels for guidelines on soil type, soil pH and plant-back intervals.

2.4 HOW DO WE AMEND SUBSURFACE ACIDITY?

Thorough research undertaken from the 1980s to early 2000s is the basis of many of the recommendations currently used to manage soil acidity in Australian farming systems. While this rigorous research provided a broad understanding of the soil processes associated with acidification and amelioration, the recommendations arising from that work through the NSW Government Acid Soil Action (ASA) program (1997–2003) are based on outdated farming systems. The rates recommended to ameliorate soil acidity targeted pH in the surface 0–10 cm layer and presumed effective incorporation of lime to a traditional cultivation depth of 10 cm.

Despite considerable changes in farming systems, including widespread adoption of zero or no-till systems, increased crop yield and nitrogen fertiliser inputs, the acidic soil management programs have not changed. A 2017 survey of advisors indicated a pH_{Ca} 4.8–5.0 in the 0–10 cm soil sample is commonly used to trigger lime application. Lime application rates commonly aim to achieve a pH_{Ca} target of about 5.2, as this eliminates most 'problems' associated with acidic soils, i.e. aluminium toxicity. This approach is satisfactory if the lime is incorporated and if pH_{Ca} of the 5–20 cm subsurface layers is >5.0. However, as shown in Figure 2.11, under minimum disturbance tillage systems, the lime effect (i.e. the alkali from the dissolution of the applied limestone) does not penetrate below about 5 cm.

Our work has highlighted opportunities to increase the return on lime investments for growers. Simple adjustments could be made to current approaches to amelioration of soil acidity that would improve the effectiveness of liming programs. These include:

1. Identification of stratified pH using sampling intervals of 5 cm or less to a depth of 20 cm to inform liming programs.
2. Allow time for the lime to react and raise pH. Acid-sensitive species should not be sown for at least 12 months after lime application and >18 months in low rainfall zones.

   Although lime begins to react and raise pH as soon as the soil is moist, the reaction is slow and will not be fully effective for 12 to 18 months after application, depending on several factors including rainfall and effectiveness of incorporation. The 'lime effect' is very slow to move and it will take years for the alkali to move and raise pH below the depth of incorporation.
3. Our results indicate that: (i) 0–10 cm soil tests are being used to maintain pH_{Ca} around 5.0, i.e. 'Maintenance applications'; (ii) under no-till systems, this liming strategy may raise pH to depths of 5–7.5 cm, but it is ineffective in preventing acidification deeper in the profile.

If pH_{Ca} of the 10–20 cm layer is <5.0, and the objective is to increase subsurface pH, a ‘capital application’ of lime is necessary to raise the 0–10 cm soil surface pH_{Ca} >5.5.

Maintaining pH_{Ca} >5.5 will ensure net movement of alkali down the profile. To achieve this it is necessary to apply the amount of lime needed for maintenance, plus an extra amount to achieve the desired increase in pH. We propose an upfront, larger ‘capital’ rate, effectively incorporated, to boost pH of the surface 0–10 cm layer to pH_{Ca} >5.5, followed by maintenance rates to maintain the surface 0–10 cm layer at pH_{Ca} >5.5 (Li et al 2019).

4. Current liming programs where lime is not incorporated and remains concentrated in the shallow surface layers are inefficient. This is an opportunity cost to growers as lime reactivity is slowed by the elevated pH of the shallow surface soil.

   Effective incorporation of adequate rates of lime to a depth of 10 cm with a strategic, full cultivation is a rapid solution to subsurface acidity. This will hasten the lime reaction and increase the lime effect to the depth of incorporation. ‘Tillage with care’ is the catch cry: take into account erosion risk and potential trafficability issues in the subsequent crop. Recent research by Dr Mark Conyers indicates that occasional, strategic cultivation has a minimal short-term effect on soil structure. GRDC project *Strategic tillage* (GRDC research code: DAN00152) Link: https://grdc.com.au/GRDC-FS-StrategicTillage

5. Absence of baseline data from the surveyed sites makes it impossible to measure changes in pH or to assess the effectiveness of current acidic soil management programs. Such data, in conjunction with periodic monitoring will inform rate and depth of acidification, and provide growers and advisors with the confidence to adjust lime rates, re-liming intervals and implement more aggressive programs, such as strategic cultivation.

   Sampling at 5 cm increments every 3–5 years to monitor changes in pH is the only way to assess acidic soil management programs. Baseline data and trends from periodic testing provide growers and advisors with the confidence to adjust rates and guide re-liming intervals and the need for strategic cultivations, which may be required every 10 years or so.

Soil sampling to monitor pH change over time

The point sampling method is recommended as it allows re-sampling specific locations and monitoring changes in soil chemical properties over time. Samples are collected from a small area that is representative of the larger area or zone of interest, with similar soil type, depth, aspect, elevation, etc. It is important that the person sampling is confident in selecting a representative point. It is also important to collect samples at the same time of year to minimise variation in measured values caused by seasonal fluctuations.

Baseline sampling

1. Select a representative point and record GPS coordinate (this is the Original Reference Point).
2. Collect 0–20 cm soil cores from 20 locations within a 10 m radius of the recorded point, avoiding fertiliser bands if at all possible.
3. Segment each core into four increments: 0–5 cm, 5–10 cm, 10–15 cm and 15–20 cm. Store samples in a cool, dry location until they are dispatched for testing.
4. Soil tests: pH_{Ca} ($CaCl_2$ method).
5. Additional soil tests that would be useful include: Cation exchange capacity (CEC), Colwell phosphorus (P) and aluminium percentage.
6. Archive soil test results for future reference.

Subsequent sampling

1. Select a reference point offset approximately two metres* from the Original Reference Point and record the GPS coordinates. Use the GPS coordinates to avoid previous sampling locations in future sampling rounds.
2. Follow steps 2 to 5 above.

*Note that the two metre offset distance is appropriate if hand-held corers are used, but should be increased to five metres when machine-driven cores are used.

It is beyond the scope of this project to provide more specific guidelines on acidification rates, re-liming intervals or rates of lime required to ameliorate acidity in the 10–20 cm layer. The lime rates required to increase pH in the 0–10 cm layer are shown in Table 2.3, which are based on fine grade agricultural lime with a neutralising value (NV) >95. We refer readers to NSW DPI Agfact from the ASA program *Soil acidity and liming*
Link: https://www.dpi.nsw.gov.au/__data/assets/pdf_file/0007/167209/soil-acidity-liming.pdf

Finely crushed limestone is the product most commonly used in broadacre agriculture to raise soil pH, although alternative products have been evaluated through a joint GRDC-NSW DPI project: *Novel approaches for amelioration of subsoil acidity*. (GRDC research code: DAN00206)
Link: https://www.dpi.nsw.gov.au/__data/assets/pdf_file/0016/1261033/subsoil-factsheet-no.25-recommendation.pdf

TABLE 2.3 The quantity of lime required to increase pH in the 0–10 cm surface layer. Rates have been calculated for fine-grade lime of neutralising value (NV) >95.
Source: Upjohn *et al* (2005).

Soil test ECEC (meq/100 g)	Lime required (t/ha) to lift pH of the top 10 cm:			
	from 4.0 to 5.2	from 4.3 to 5.2	from 4.7 to 5.2	from 5.2 to 5.5
1	1.6	0.8*	0.3*	0.2*
2	2.4	1.2	0.5*	0.4*
3	3.5	1.7	0.7	0.5*
4	3.9	2.1	0.9	0.6
5	4.7	2.5	1.1	0.7
6	5.5	3.0	1.2	0.8
7	6.3	3.3	1.4	1.0
8	7.1	3.8	1.6	1.1
9	7.9	4.2	1.8	1.2
10	8.7	4.6	1.9	1.3
15	12.5	6.7	2.8	1.9

* It is recognised that low rates of lime are impractical to apply, but over-liming can cause nutrient imbalances, particularly in these light soils

Key: limestone rate

0.5 t/a	1.0 t/ha	1.5 t/ha	2.0 t/ha	2.5 t/ha	3 to 4 t/ha	Split applications may be necessary

Don’t forget to check the accuracy of lime spreaders

Uneven lime distribution from spreaders appears to be the reason for patterns of variable growth in pulse crops (Figure 2.12, Figure 2.13). A quick test with a soil pH kit provides an on-the-spot check if crop variability is the result of spatial differences in soil pH.

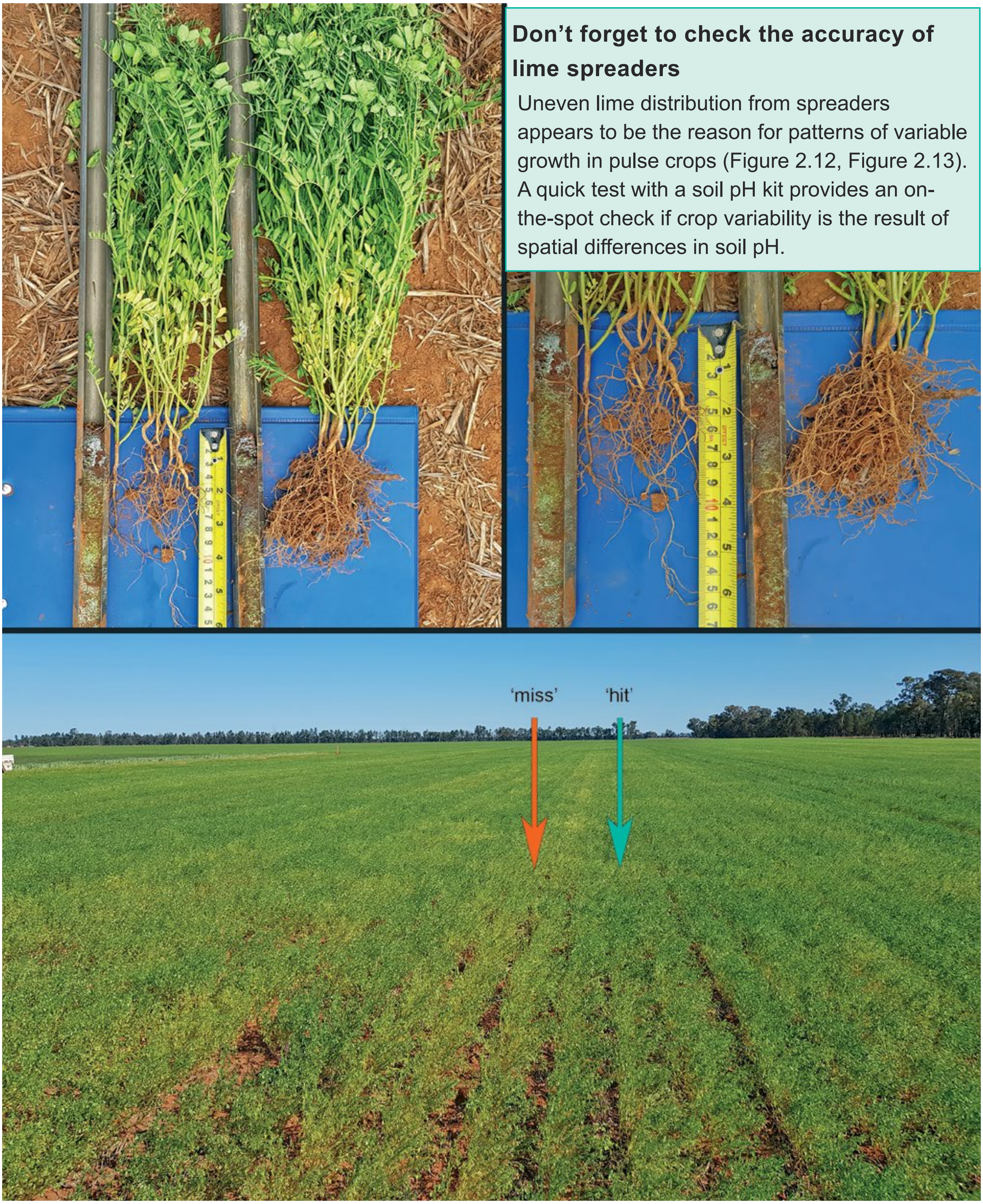
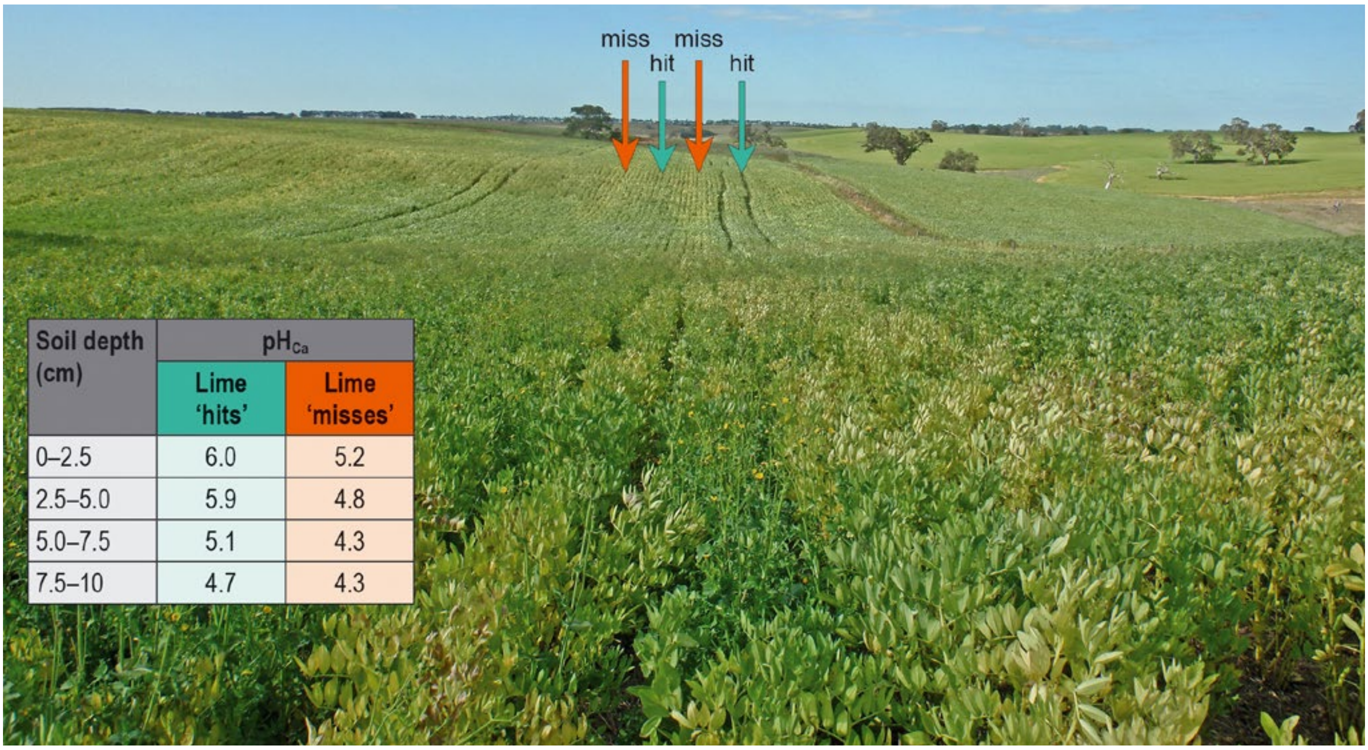


Figure 2.12 Definite strips of stunted and yellow crops indicate uneven lime distribution from the spreader. An on-the-spot check with a field pH kit indicates that low pH is the major reason for reduced root development and biomass production in the lentils growing on the low pH ‘miss’ strips (estimated $\mathrm{pH_{Ca}}$ >6.0 at 0–4 cm and <4.5 at 4–10 cm) at Methul, New South Wales, compared with more vigorous plants in the ‘hit’ strips with estimated $\mathrm{pH_{Ca}}$ >6.0 at 0–9 cm. The plants in the top photos were dug from ‘miss’ (left) and ‘hit’ (right) strips as indicated by arrows in main photo.
Photos: K Moore



Soil depth (cm)	pH_{Ca}	
	Lime 'hits'	Lime 'misses'
0–2.5	6.0	5.2
2.5–5.0	5.9	4.8
5.0–7.5	5.1	4.3
7.5–10	4.7	4.3

Figure 2.13 Soil tests from this paddock in south west Victoria reveal the stripping in these faba beans is due to uneven lime spreading with lime 'misses' and lime 'hits'.
Photo: H Burns

2.5 CHECKING FOR pH STRATIFICATION AND ACIDIC LAYERS IN VARIABLE CROPS

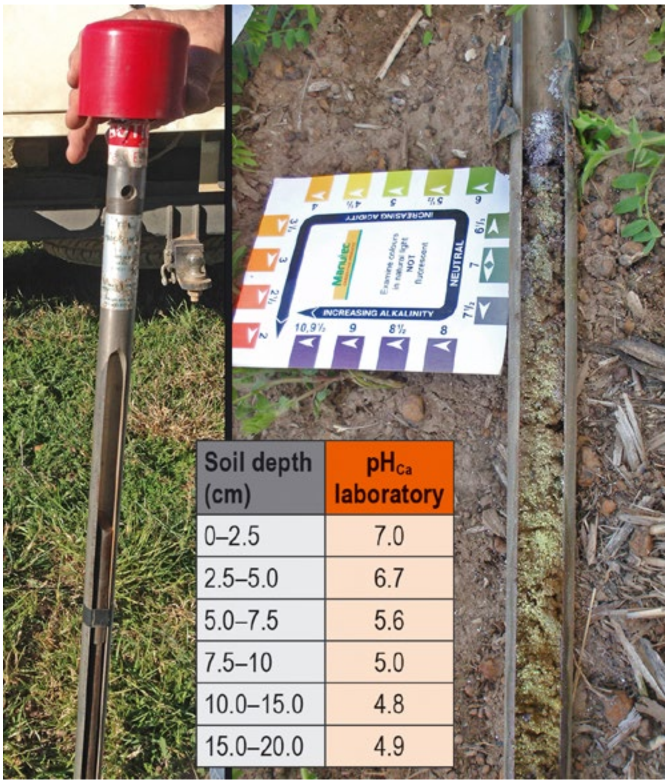
A shovel or soil probe and a soil pH kit (available from most rural or garden/hardware suppliers) provide a quick and convenient option to check for the presence of acidic subsurface layers (Figure 2.14).

There are three different types of soil pH testers: electronic meters; indicator test strips; and colour dyes. Prices start at about $20. For the purpose of a quick and simple field check to detect acidic layers, a tester that is sensitive enough to distinguish pH variability is adequate.

In the following examples samples were collected from areas of 'good' and 'poor' crop growth.

Ideally, soil and plants samples should be collected when the soil is moist and while the crop is actively growing. This makes it easier to collect intact soil cores and plant samples and to also align plant root growth and/or nodulation with acidic layers, if present.

Step 1. Collect intact soil samples to a depth of at least 20 cm (Figure 2.13).



Soil depth (cm)	pH_{Ca} laboratory
0–2.5	7.0
2.5–5.0	6.7
5.0–7.5	5.6
7.5–10	5.0
10.0–15.0	4.8
15.0–20.0	4.9

Figure 2.14 The Spurr Soil Probe or 'Dig Stick' (left) is a useful tool to collect soil cores. The chemical dye and indicator powder from the Manutec® kit can be placed directly onto the undisturbed soil core (right). Laboratory pH values are presented in the table.

Step 2. Dig up plants typical of the 'good' and 'poor' area, taking care to leave roots intact. A garden fork is less aggressive than a shovel on plants with large root systems. Observe differences in root systems and nodules (Figure 2.12, Figure 2.15).

Figure 2.15 Faba bean plants carefully dug from 'good' (left) and 'poor' (right) areas of a crop. Field soil pH test identified an acidic layer at 5–7 cm (Figure 2.17).
Photo: W Holding

Step 3. Follow the directions on the Soil pH Test Kit (such as the Manutec® kit, Figure 2.14, Figure 2.17).

Figure 2.16 The 'dig stick' and a field pH test kit give a quick and convenient measure of soil acidity.
Photo: M McClure

Step 4: Any soil acidity issues observed should be followed-up with more detailed sampling and analysis through an accredited laboratory to guide management decisions.

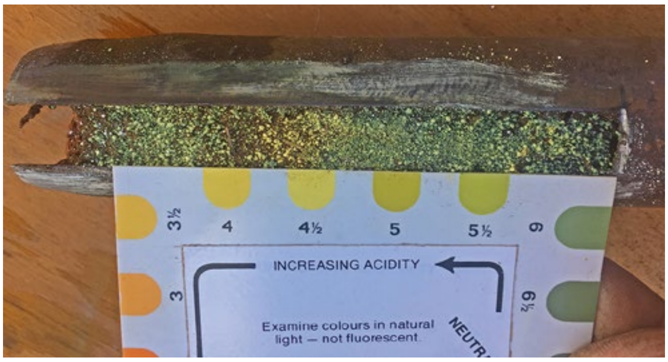


Figure 2.17 A quick Manutec field soil pH test identified an acidic layer at 5–7 cm in the 'poor' areas of a faba bean crop (Figure 2.15).
Photo: W Holding

3. LEGUME OPTIONS AND PADDOCK SELECTION FOR ACIDIC SOILS

3.1 LEGUME OPTIONS FOR ACIDIC SOILS

Key messages

- Select paddocks at least 2 years before sowing acid-sensitive crops based on soil characteristics, especially soil type, pH and absence of physical or chemical constraints that may limit rooting depth or increase the risk of waterlogging; ameliorate constraints where appropriate.
- Implement liming programs well in advance of sowing acid-sensitive species. Yield potential of most legume species is compromised on soils with acidic layers (pH_{Ca} <5.2) within the 0–20 cm soil surface.

Selecting the legume species that are best adapted to local conditions is central to maximising profitability and productivity. When estimating probable financial returns from pulse crops it is essential that the target or break even yield used is based on results from locations with comparable soil and environmental conditions.

Table 3.1 summarises the key soil and climatic considerations for the legumes currently grown in the HRZ. The guidelines are very broad, so should be used in conjunction with local information from advisors familiar with local soils and experience with legume crops and/or pastures in your region.

FIGURE 3.1 Lentil crops growing in free-draining soils with pH_{Ca} >5.2 such as this crop near Morven, southern New South Wales, have potential to achieve reliable yields across a range of seasons.
Photo: H Burns

TABLE 3.1 Soil and climatic guidelines for legume species suited to Temperate and/or Mediterranean HRZ regions of south-eastern Australia.

Species	Soil type	Ideal pH_{Ca} range*	Climatic conditions	Comments
Pulse crops				
Lupin: Narrow-leaf (*Lupinus angustifolius*) Albus (*L. albus*)	▪ Free-draining sandy to sandy loam soils	▪ Narrow-leaf lupin: Optimal pH_{Ca} 5.0–6.0; tolerant of pH_{Ca} 4.5–5.0 ▪ Albus lupin: Optimal pH_{Ca} 5.0–7.0 ▪ Avoid sowing into calcareous soils, containing free lime		▪ Very susceptible to waterlogging - avoid soils with subsurface constraints; Albus lupin is more susceptible than narrow-leaf lupin ▪ Rhizobia function (and nodulation) may be reduced at pH_{Ca} <5.0, particularly in paddocks with no recent lupin history ▪ Albus lupin averages 5–15% higher yield than narrow-leaf lupins on well-drained soil, under high rainfall conditions
Faba bean (*Vicia faba minor*) Broad bean (*Vicia faba major*)	▪ Deep, well-drained loams to clays with good water holding capacity	▪ Optimal pH_{Ca} 6.0–8.0; tolerant of pH_{Ca} >5.2–6.0	▪ Maximum yield will be achieved in long-season, high rainfall environments ▪ Broad beans have longer growing season, so suited to higher rainfall areas ▪ Relatively frost tolerant	▪ More tolerant of waterlogging than other pulses; early vigour improves tolerance ▪ Relatively shallow root system (60–70 cm) ▪ High dry matter production: poorly adapted to periods of high temperature, particularly sensitive to moisture stress from flowering to pod filling ▪ Not recommended for shallow soils or sandy soils with low water holding capacity. Satisfactory yield in such soils is dependent on reliable spring rainfall and mild temperatures during pod fill
Lentil (*Lens culinaris*)	▪ Free-draining soil, with good water holding capacity	▪ Optimal pH_{Ca} 6.0–8.0; tolerant of pH_{Ca} >5.2–6.0	▪ Cold growing conditions can result in short plants and difficulties with harvest ▪ Frost sensitive	▪ Not suitable for soils prone to waterlogging ▪ Stony or cloddy seedbeds cause harvesting difficulties; may be managed by rolling soon after sowing ▪ Select paddocks with even soil type to ensure uniform growth and maturity
Chickpea (*Cicer arietinum*)	▪ Deep loams to self-mulching clay soils ▪ Not recommended for sandy or shallow soils with low water holding capacity	▪ Optimal pH_{Ca} 6.0–9.0; tolerant of pH_{Ca} >5.2–6.0	▪ Not suitable for cold regions; pod set is temperature dependent – no varieties available that set pods below 15 ˚C ▪ Frost sensitive	▪ Deep root system compared with other pulses (up to 120 cm), high yield potential if rooting depth is not restricted ▪ Benefit from stored subsoil moisture and/or spring rainfall to extend flowering and grain filling period ▪ Tolerance to dry conditions and high temperatures during grain fill if deep root system can access subsoil moisture ▪ No tolerance to waterlogging
Field pea (*Pisum sativum*)	Suited to a wide range of soil types from sandy loams to heavy clays	Optimal pH_{Ca} 5.2–8.0	▪ High risk of disease in high rainfall environments ▪ Frost sensitive	▪ Stony or cloddy seedbeds cause harvesting difficulties ▪ Recommended for later sowing than other pulses (late May and June) ▪ Will not tolerate extended periods of waterlogging

TABLE 3.1 Soil and climatic guidelines for legume species suited to Temperate and/or Mediterranean HRZ regions of south-eastern Australia.

Species	Soil type	Ideal pH_{Ca} range*	Climatic conditions	Comments
Pasture legumes – perennial species				
Lucerne (*Medicago sativa)*	▪ Deep, well-drained soils ensure persistence; but adapted to range of soils with good internal drainage	▪ pH_{Ca} 6.0–7.0; lime application is necessary to ensure establishment if pH_{Ca} <5.2 ▪ Avoid shallow soils or those with pH_{Ca} <5.2 to depth	▪ Deep-rooted perennial species adapted to a range of climatic conditions ▪ Maximum production in areas with high summer rainfall	▪ Once established, lucerne can persist on deep soils (e.g. Red and Brown Chromosols) with moderately acidic (pH_{Ca} 4.6–5.0) subsurface layers at 5–15 cm, *provided* roots can access nutrients and moisture in the deeper layers (pH_{Ca} >5.2) ▪ Range of varieties to choose from depending on environmental conditions and intended use ▪ Does not tolerate waterlogging
Pasture legumes - annual species				
Sub clovers (*Trifolium subterraneum*) subspecies: ▪ *Subterraneum* ▪ *Yanninicum* ▪ *Brachycalycinum*	▪ Suited to a wide range of soil types from sandy to clay loams; not suited to hard setting soils that prevent seed burial ▪ *Yanninicum* subspecies suited to poorly drained soils, prone to waterlogging	▪ pH_{Ca} 4.8–7.0; (*Brachycalycinum* subspecies pH_{Ca} 7.0–8.0)	▪ Ideally suited to Temperate and Mediterranean climates ▪ >30 varieties available with range of maturities and disease tolerance	▪ Range of varieties available to suit specific environmental conditions ▪ Select mid to late season varieties to maximise forage production and N fixation potential ▪ Select varieties with tolerance to Phytophthora root rot and clover scorch, particularly on poorly drained soils ▪ Check the maturity ratings and 'days to flower'; ensure the proposed sowing date allows sufficient time for seed to mature before moisture stress in late spring stops seed development
Balansa clover (*Trifolium michelianum*)	▪ Tolerant of waterlogging and extended periods of inundation	▪ pH_{Ca} 4.5–7.0		▪ Annual, hard-seeded legume ▪ Tolerant to Phytophthora root rot and clover scorch ▪ Very small, weak seedling ▪ Very slow growth rate in autumn and winter with maximum growth in spring ▪ Often included in pasture mixes on soils prone to waterlogging
Arrowleaf clover (*Trifolium vesiculosum*)	▪ Suited to a wide range of soil types from sandy to clay loams	▪ pH_{Ca} 4.5–6.5; not suited to pH_{Ca} >7.5	▪ Suited to Temperate climates with March to November rainfall >200 mm	▪ Susceptible to waterlogging, especially during establishment ▪ Very slow growth rate in autumn and winter ▪ Taproot can grow to >1.5 m in free-draining deep soils, so able to access deep soil moisture out of reach of sub clover ▪ Role in one-year high density forage legume mixes in cropping program, mixed with other clovers to extend grazing into summer

*The pH range refers to the pH of the main root zone, i.e. to a depth of at least 20–25 cm

Adapted from: Mullen C (2004) *The right pulse in the right paddock in the right time*. NSW Department of Primary Industries, Orange, NSW. Link: https://www.dpi.nsw.gov.au/__data/assets/pdf_file/0011/151112/the-right-pulse-in-the-right-paddock-at-the-right-time.pdf

3.2 PADDOCK SELECTION FOR LEGUMES IN ACIDIC SOILS

Know the soil to manage the constraints

The key to achieving consistent and profitable productivity from legumes growing in acidic soils is effective nodulation and seedling vigour. Fundamental to this is paddock selection based on an understanding of soil types, specifically pH of the soil profile, potential rooting depth and internal drainage.

KEY POINTS

- Sample and test soil to understand potential chemical and physical limitations up to two years in advance and amend where appropriate.
- Low pH within the soil surface and subsurface layers will reduce root growth, nodulation and early vigour.
- Avoid soils with shallow topsoil and impermeable subsoil. Hardpans and impermeable subsoils limit rooting depth and restrict drainage.
- Implement liming program at least 12 months before sowing for reliable and consistent production from acid-sensitive legumes. Extend to 24 months in low rainfall regions.

Consistent and profitable yield from legumes, across a range of seasons, depends on the chemical and physical properties of the topsoil and the ability of the plant roots to penetrate the subsoil and access deep, stored moisture. Preparation for sowing acid-sensitive legumes should begin with an assessment of the soil and landscape, to gain an understanding of potential soil constraints and variability at the paddock level. This enables:

- Avoidance of soil types with severe chemical and/or physical constraints,
- Selection of appropriate species, and
- Amelioration and/or management of soil constraints.

Most legumes have specific requirements for soil properties and climate if they are to achieve their production potential (Table 3.1).

The high rainfall cropping zone of south eastern Australia is dominated by acidic, duplex soils. There are only small areas of the deep, free-draining, high pH soils favoured by most pulses and lucerne.

Duplex soils have a pronounced textural change with a relatively light textured, sandy loam to loam topsoil (the A horizon) overlaying a dense, clay subsoil (the B horizon) (Figure 1.2),. **The pH and depth of the A horizon, and the permeability of the B horizon are the main soil characteristics to consider when selecting paddocks for acid-sensitive legumes**.

The pH of the A horizon is often acidic (pH_{Ca} <6.0), with the most acidic layers (pH_{Ca} <5.0) usually at 5–15 cm, or 5–20 cm on lighter sandy loam soils. Depth of the A horizon can vary from 10 to 50 cm, sometimes within a very small area (Figure 3.2).

Our study indicated that low pH within the surface soil is likely to be one of the main reasons for poor productivity of acid-sensitive pulses in the HRZ, limiting root development and reducing efficiency of the nodulation and nitrogen fixation processes. Plants growing in such hostile soils lack vigour and are less tolerant of additional stresses (e.g. disease infection and waterlogging) and poor management decisions (e.g. late sowing and herbicide injury).

If root growth and rooting depth is limited by physical or chemical constraints, plants will only access nutrients and moisture within the restricted root zone. As many of the duplex soils have a light-textured A horizon with low water holding capacity, shallow-rooted plants are very susceptible to moisture stress, particularly during the critical flowering and grain filling periods. Acceptable yield on these soils is dependent on mild temperatures and substantial rainfall in spring.

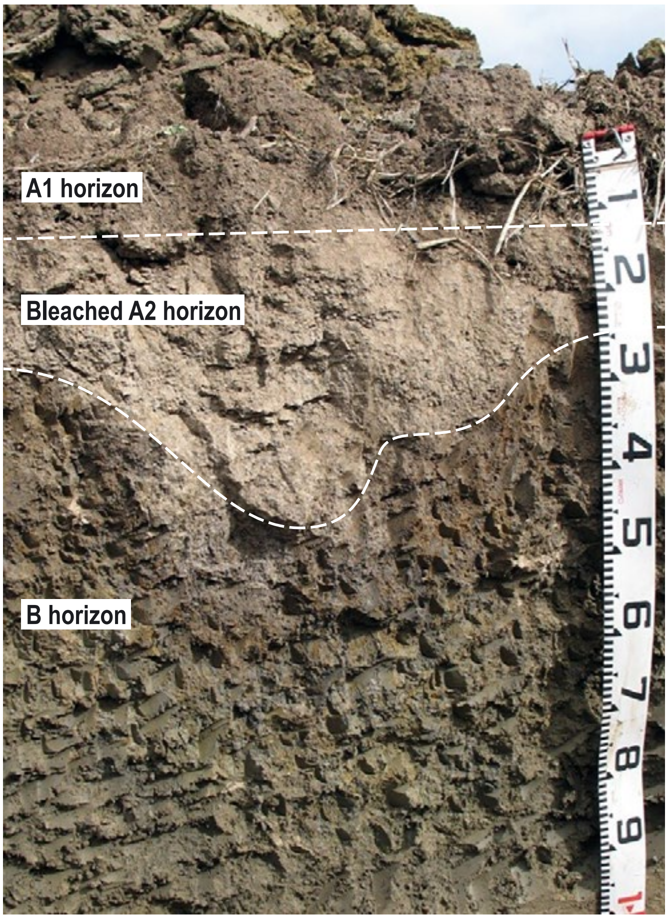


Figure 3.2 The wavy boundary between the A and B horizon of the Grey Sodosol near Derrinallum is typical of gilgai country in south west Victoria. Depth of the A horizon varies from 20–40 cm. There is an obvious bleached A2 horizon at about 12 cm and dense subsoil (B horizon). *Photo*: M Imhof

The chemical and physical properties of the B horizon influence water movement and internal drainage. Soils with an impermeable B horizon (subsoil) are likely to become waterlogged during periods of extended rainfall, creating a perched water table. The surface soil becomes saturated and plants are deprived of oxygen and root growth is restricted.

The main acidic soils of the HRZ of south eastern Australia

The soil pH and sodium level of the B Horizon are the main features used to classify duplex soils. If the exchangeable sodium percentage (ESP) of the cation exchange capacity of the B horizon is <6%, and the pH of the B horizon is >5.5 the soil is classifies as a **Chromosol**; if the pH of the B horizon is <5.5 the soil is a **Kurosol**; while a duplex soil with a sodic B horizon (ESP >6%) is classified as a **Sodosol**.

Most commercial crops monitored for this project grew on acidic, duplex soils that broadly fit into the Chromosol and Sodosol soil groups. It is beyond the scope of the project to include detailed soil descriptions that reflect the diversity of soils of the HRZ.

Information on distribution of major soil groups and soil characteristics in Victoria is available on the *Victorian Resources Online* website http://vro.agriculture.vic.gov.au/dpi/vro/vrosite.nsf/pages/soilhealth_soil_type

Chromosol soil group

Chromosol is the dominant soil group of southern New South Wales and north east Victoria. In these regions they usually occur on rises and slopes, often transitioning to relatively poorly drained Sodosols and/or Kurosols on low lying areas. Although the B horizon of Chromosols is not sodic, it can be dense and poorly structured (especially in soils with a calcium:magnesium ratio <2), in which case drainage is restricted and the soil may be subject to periods of waterlogging after heavy rainfall.

The Chromosol soil group is diverse, and includes most of the soil types of the medium to high rainfall zone of southern New South Wales and north east Victoria. These soils are also known as ‘podzolics’ or ‘red-brown earths’.

In their undisturbed state, Chromosols have favourable physical and chemical properties. However, evidence of structural degradation, acidification, and hard-setting surface layers are reported in areas with a long history of agricultural activity.

The A horizon (ranging in depths of 10 to >40 cm) is acidic, with pH increasing with depth to a subsoil that is slightly acidic to alkaline (pH_{Ca} >5.5). Texture and depth of the A horizon and pH stratification within the 5–20 cm subsurface layers is highly variable over quite small areas, usually associated with position in the landscape. The A2 horizon may be an obvious 'bleached', pale colour and include areas of grey mottling and/or buckshot (ironstone) and/or manganese nodules, which are associated with poor internal drainage, (e.g. Figure 3.3).

Colour of the soil in the top of the B horizon is often used to further describe the soil and is a very good indicator of soil drainage and the potential rooting depth of species that do not tolerate waterlogging, such as chickpea, lentil and lucerne.

The Red Chromosols are the most free-draining of the Chromosols and are most likely to occur in the slightly higher and better drained positions on the landscape. They are well suited to most legume species, depending on pH and depth of the A horizon. Red colouration indicates a free-draining B horizon (oxygen reacting with iron produces iron oxide i.e. rust) and is an indicator of good drainage/aeration.

Brown Chromosols can be reasonably well-drained, while the Yellow and Grey Chromosols are less permeable and may be more prone to waterlogging. Yellow and Grey Chromosols more commonly occur in lower areas of the landscape (Figure 3.3).

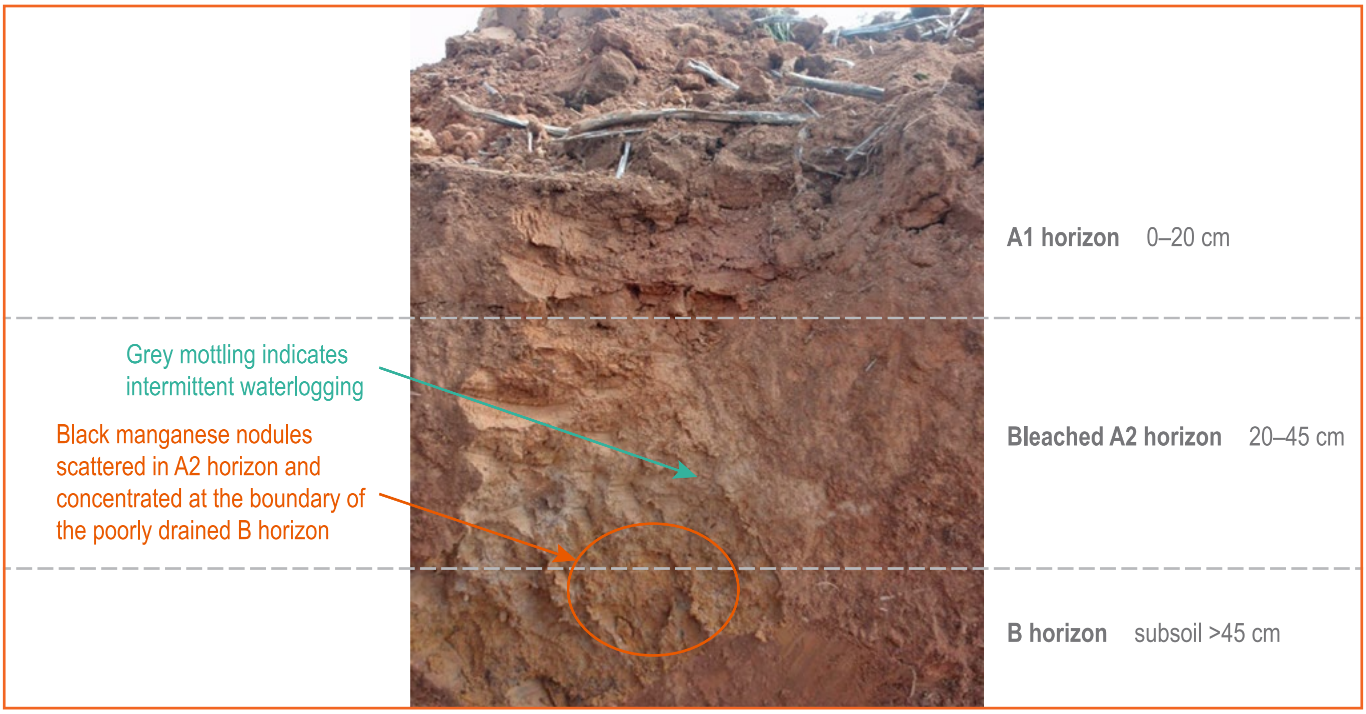


Figure 3.3 Yellow Chromosol near Henty in south east New South Wales. Grey mottling and ironstone or manganese nodules (concretions) in the lower layers of the A horizon are features typical of soils that experience periods of waterlogging.
Photo: H Burns

Sodosol soil group

Sodosol is the dominant acidic soil group in the 450–800 mm annual average rainfall zone of southern Victoria and in the Frances area of south east South Australia. Sodosols are commonly in lower areas of the landscape and often occur in association with other soil groups, including the **Chromosols**, which are usually on more elevated areas.

The distinguishing feature of soils of the Sodosol soil group is a sodic B horizon which is termed ‘sodic’ if the exchangeable sodium percentage (ESP) is >6–15% of cation exchange capacity, and ‘strongly sodic’ if ESP >15%. The clay particles of sodic soils disperse when wet, the soil ‘runs together’, clogging the fine soil pores and making the subsoil almost impermeable.

Depth and pH of the A horizon and sodicity of the B horizon influences rooting depth and should be used to guide crop choice (Table 3.1). The A horizon can range from 5–40 cm in depth and is usually more shallow in the upper slopes and rises.

Sodicity is often linked to topography, but may vary within a small area. The better drained Sodosols (Red or Brown Sodosols) are usually associated with higher production and commonly occur on the slightly higher positions in the landscape. Red colouration in the A horizon and top of the B horizon, and lack of mottling are indicators of good drainage and reasonable permeability of the B horizon (ESP about 6%). Red Sodosols may transition to Red Chromosols on the better drained tops of rises and upper slopes.

Grey or Black Sodosols are usually in the lower areas of the landscape. They are less permeable and associated with less reliable production than Sodosols higher in the landscape. The subsoils are often strongly sodic, poorly structured and relatively impermeable. The surface layer (A1 horizon) is usually dark grey to brown, with a mottled grey or pale, bleached subsurface (A2 horizon) (Figure 3.2).

Signs of poor internal drainage and waterlogging

Inspection of the soil profile is the best way to check the internal drainage of a soil. This is strongly recommended before sowing species that do not tolerate waterlogging, such as chickpea, lentil, lupin and lucerne.

A bleached A2 horizon, grey mottling and the presence of ironstone (red) or manganese (black) nodules at the boundary of the A and B horizons are common in poorly drained Chromosols (Figure 3.3) and Sodosols (Figure 3.2). These are all indicators that the soil is prone to seasonal waterlogging.

What are the options for soils prone to waterlogging?

> Depth of the A horizon and permeability of the B horizon are critical soil characteristics influencing yield potential of pulse crops in wet seasons and the persistence of lucerne stands on Chromosols and Sodosols.

Plant selection

Lentil and chickpea do not tolerate waterlogging and are grown most successfully in the HRZ on Red Chromosols, free-draining Dermosols and alluvial soils with pH_{Ca} >5.5 to depth. In these soils the plant roots can access deep moisture and are less susceptible to moisture stress and rising temperatures in spring, as the crop matures. Comparative yields may be achieved in soils with minor constraints that limit rooting depth, but only in seasons with moderate rainfall throughout the growing season and mild spring temperatures during grain fill, provided nodulation is effective.

Winter crops growing on soils with a dense, impermeable B horizon are likely to experience periods of waterlogging. Plant roots will not grow into saturated soil and are confined to the better drained surface layers. The roots will not penetrate the dense subsoil and access deep moisture as the soil dries in spring, leaving the maturing crop (or pasture) susceptible to moisture stress at the critical flowering and grain filling stages.

Figure 3.4 The faba bean crop in 'gilgai' areas of Grey Sodosols at Kybybolite, South Australia was inundated by water moving laterally over the impermeable subsoil. Crops growing on areas with shallow topsoil were most susceptible to periods of waterlogging during the wet winter of 2016.
Photo: H Burns

The only pulse options in soils prone to waterlogging are faba bean or broad bean. However, they are very susceptible to moisture stress. Assuming effective nodulation, yield potential is dependent on reliable spring rainfall and/or deep root systems that can tap into subsoil moisture reserves late in the season.

The legume pasture species most tolerant of waterlogging are Balansa clover and Yanninicum sub clovers. Although Trikkala is the Yanninicum variety commonly grown in the HRZ of south west Victoria, longer seasoned varieties, such as Napier or Leura, offer potential for greater N fixation and greater total dry matter production in these cool Mediterranean climates.

Soil Management

Raised bed technology is used by growers in the higher rainfall areas of southern Victoria to increase the depth of the A horizon, particularly in continuous cropping systems. Great care must be taken to ensure that the sodic subsoil is not exposed at the soil surface when forming raised beds or erosion or surface sealing can occur.

Technology aimed at improving productivity on soils with sodic subsoils in the medium to high rainfall zone of south eastern Australia is being investigated in a current GRDC project *Understanding the amelioration processes of the subsoil application of amendments* (GRDC research code: DAV00149).

3.3 PADDOCK CHECKLIST

Table 3.2 Paddock selection checklist

1	**Start planning at least 2 years before sowing acid-sensitive pulses**
2	**Most legumes favour pH_{Ca} >5.2 to a depth of at least 20 cm**
3	**Check for presence of acidic layers by sampling soils at intervals of 5 cm to a depth of 20 cm. A garden soil test kit provides a quick and cheap indicator of acidic layers**
4	**If in doubt, have samples analysed by an accredited laboratory**
5	**Avoid sowing acid-sensitive pulses and lucerne in soils with a shallow topsoil and an impermeable subsoil that is prone to waterlogging.**
6	**Avoid paddocks with heavy infestations of broadleaf weeds or herbicide resistant grass weeds that cannot be effectively controlled by a combination of pre-sowing control and in-crop herbicides**
7	**Check herbicide use in the previous 12–24 months and ensure maximum plant-back periods are satisfied, with particular attention to Group B, chlorpyralid and triazine herbicides:** • **Chlorpyralid (Lontrel™) persists in residue of treated crops and may severely damage legume species. Check plant-back intervals on herbicide labels** • **Avoid sowing sulfonylurea (SU) sensitive legumes in paddocks on which SU herbicides have been used in the last 12–24 months. Check herbicide labels – e.g. when surface (0–5 cm) soil pH_{Ca} >5.8, plant-back interval can be up to 22 months**
8	**Minimise disease risk in pulse crops by following cropping interval and crop separation guidelines**

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Numerous GRDC GrowNotes™–Southern Region:

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