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FABA BEAN

SECTION 6

NUTRITION AND FERTILISER

KEY POINTS | DECLINING SOIL FERTILITY | NUTRIENT REQUIREMENTS AND FERTILISER RECOMMENDATIONS | SOIL TESTING | PLANT TISSUE TESTING | NUTRIENT DISORDERS | NITROGEN | PHOSPHORUS | POTASSIUM | SULFUR | MICRONUTRIENTS (TRACE ELEMENTS)

Nutrition and fertiliser

Key points

- **Fertilisers must supply a balance of required nutrients for a crop to achieve its potential yield. Nutrient budgeting and soil and plant tissue tests are tools to help determine fertiliser needs.**
- **Each tonne of faba bean grain removes about 40 kg/ha of nitrogen, 4 kg/ha phosphorus, 10 kg/ha sulfur, 1.3 kg/ha calcium and 1.2 kg/ha magnesium, as well as micronutrients. Faba bean should not normally require any nitrogen fertiliser, except for 'starter' nitrogen in soils with extremely low levels of nitrogen.**
- **Micronutrients are important, particularly zinc, boron, copper, manganese and molybdenum. Deficiencies of micronutrients can be overcome by applying granular or foliar nutrients. Liquid in-furrow treatments can be applied for immobile nutrients such as zinc and copper.**
- **Aluminium and manganese can become toxic to faba bean on acid soils. Boron can also reach toxic levels on alkaline soils. Toxicity from saline soils can be a problem.**
- **Micronutrient deficiencies and toxicities show specific symptoms in faba bean.**
- **Fertiliser applied too close to the seed can be toxic. Acid fertilisers can also inhibit nodulation.**
- **Understanding the nutrient status of a paddock is essential for optimum plant growth.**
- **Healthy plants are more likely to ward off disease, pest and environmental stresses and achieve higher yield and better grain quality.[1]**
- **Nutrients are removed as grain and need to be replaced to ensure adequate soil fertility for following crop yields.**
- **Fertilisers are a major cost of growing a crop. Fertiliser decisions are complex and although individual growers may have different objectives, regardless of circumstance they should know which nutrients are in short supply and which are adequate.[2]**
- **Both under-fertilisation and over-fertilisation can lead to economic losses due to unrealised crop potential or wasted inputs.**

1 Pulse Australia (2016) Agronomy. Southern faba and broad bean best management practices training course manual – 2016. Pulse Australia.

2 GRDC (2013) Crop nutrition fact sheet: Better fertiliser decisions for crop nutrition. Grains Research and Development Corporation, www.grdc.com.au/GRDC-FS-BFDCN

6.1 Declining soil fertility

The natural fertility of cropped agricultural soils is declining over time. For example, organic nitrogen in southern Australian soil declines at about 2–3% per year in cropped soils with a 'half-life' of 34–23 years. In the absence of legume-based pastures, mineral nitrogen from native organic matter or pasture residue declines and must be replaced with other legume or nitrogen fertiliser sources.[3]

Grain growers must continually review management programs to ensure the long-term sustainability of high-quality grain production. Pasture leys, legume rotations and fertilisers all play an important role in maintaining the chemical, biological and physical fertility of soils.

Nutrition programs should be reviewed regularly due to more frequent opportunity cropping from improved farming techniques and new higher-yielding varieties. Paddock records, fertiliser test strips, crop monitoring, and soil and plant tissue tests all assist in the formulation of an efficient cropping program.

Although crop rotations with grain legumes and ley pastures play an important role in maintaining and improving soil fertility, fertilisers remain the major source of nutrients to replace those removed by grain production. Fertiliser programs must supply a balance of the required nutrients in amounts needed to achieve a crop's yield potential. High-yielding crops remove large amounts of nutrients once harvested.

The yield potential of a crop will be limited by any nutrient the soil cannot adequately supply. Poor crop response to one nutrient is often linked to a deficiency in another nutrient or management technique. Sometimes, poor crop response can also be linked to acidity, sodicity or salinity, pathogens or a problem with beneficial soil microorganisms.[4]

6.2 Nutrient requirements and fertiliser recommendations

As for all crops, faba bean needs an adequate supply of nutrients for growth and to maximise yield.[5]

Plant nutrients are categorised as either macronutrients or micronutrients (or trace elements).

Macronutrients are those elements that are needed in relatively large amounts. They include nitrogen (N), phosphorus (P) and potassium (K), which are the primary macronutrients, with calcium (Ca), magnesium (Mg) and sulfur (S) considered to be secondary. Higher expected yields of crops for grain or forage will place greater demand on the availability of major nutrients such as phosphorus, potassium and sulfur. Nitrogen, phosphorus and at times sulfur are the main nutrients commonly lacking in Australian soils. Others can be lacking under certain conditions.

Micronutrients are those elements that plants need in small amounts, for example, iron (Fe), boron (B), manganese (Mn), zinc (Zn), copper (Cu), chlorine (Cl), and molybdenum (Mo).

Macronutrients and micronutrients are taken up by the roots and certain soil conditions are required for that to occur. Soil must be sufficiently moist to allow roots to take up and transport the nutrients. Plants that are moisture-stressed from either too little or too much moisture (saturation) can often exhibit deficiencies even though a soil test may show these nutrients to be adequate.

3 J Kirkegaard (2017) Opportunities and challenges for continuous cropping systems. GRDC Update Paper February 2017, https://grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2017/02/opportunities-and-challenges-for-continuous-cropping-systems

4 J Lamb, A Podder (2008) Grain Legume Handbook for the Pulse Industry. Grain Legume Hand Book Committee, https://grdc.com.au/grainlegumehandbook

5 T Yeatman, W Hawthorne, J Paull, J Bellati, J Egan, K Henry, R Kimber, M Seymour, J van Leur, K Lindbeck, P Matthews, I Rose (2009) Faba bean: The Ute Guide. Primary Industries and Resources South Australia, https://grdc.com.au/resources-and-publications/all-publications/publications/2009/11/faba-beans-the-ute-guide/

FEEDBACK

MORE INFORMATION

A paper on 'Maximising the fixed nitrogen benefits of pulses' was delivered by SARDI's Ross Ballard and the University of Adelaide's Maarten Ryder at the GRDC Updates in February 2017, https://grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2017/02/maximising-the-fixed-nitrogen-benefits-of-pulses

The optimum range of temperature, pH and moisture can vary for different pulse species. Soil pH has an effect on the availability of most nutrients and must be within a particular range for nutrients to be released from soil particles.

Soil temperature must be within a certain range for nutrients to be taken up.[6]

In addition to the usual nutrients needed by plants, legumes require the trace element molybdenum, which is critical for the enzyme responsible or nitrogen fixation.[7]

Fertiliser recommendations for faba bean are often generic, with excessive reliance on monoammonium phosphate (MAP) based 'starter' fertilisers.

Fertiliser recommendations should take into account:

- soil type;
- rotation (fallow length and impact on arbuscular mycorrhizae fungi levels);
- yield potential;
- plant configuration (row spacing, type of opener and risk of 'seed burn');
- soil analysis results; and
- effectiveness of inoculation techniques.[8]

6.2.1 Nutrient removal

If nutrients removed as grain from the soil are not replaced, crop yields and soil fertility will fall.

This means that fertiliser inputs must be matched to anticipated yields and soil type. The higher the expected yield, the higher the fertiliser input, particularly for the major nutrients (phosphorus, potassium and sulfur).

The nutrient removal by one tonne of grain in faba bean is shown in Table 1. Actual values may vary by about 3%, due to the differences in soil fertility, varieties and seasons. For example, phosphorus removed per tonne of faba bean grain can vary from 2.8 kg on low-fertility soils to 5.4 kg on high-fertility soils.

A 2.0 t/ha crop of faba bean will, on average, remove approximately 8.0 kg/ha of phosphorus; this is the minimum amount of phosphorus that needs to be replaced. Higher quantities may be needed to build up soil fertility or overcome soil fixation of phosphorus.

Table 1: Nutrients removed by 1 t of faba bean grain; wheat is shown as a comparison (this table is a guide only).

Source	Grain	Kilograms					Grams			
		Nitrogen	Phosphorus	Potassium	Sulfur	Calcium	Magnesium	Copper	Zinc	Manganese
CSIRO 2001	Faba bean at 10% moisture	38	3.8	9.7	1.5	1.3	1.2	10	28	30
Grain Legume Handbook 2008	Faba bean	41	4.0	10.0	1.5	1.3	1.2	10	28	30
	Wheat	23	3.0	4.0	1.5	0.4	1.2	5	20	40

Sources: Grain Legume Handbook (2008) and CSIRO (2001) as cited by Incitec Pivot

6 J Lamb, A Podder (2008) Grain Legume Handbook for the Pulse Industry. Grain Legume Hand Book Committee, https://grdc.com.au/grainlegumehandbook

7 E Drew, D Herridge, R Ballard, G O'Hara, R Deaker, M Denton, R Yates, G Gemell, E Hartley, L Phillips, N Seymour, J Howieson, N Ballard (2012) Inoculating Legumes, a Practical Guide. Grains Research and Development Corporation, https://grdc.com.au/GRDC-Booklet-InoculatingLegumes

8 Pulse Australia (2016) Agronomy. Southern faba and broad bean best management practices training course manual – 2016. Pulse Australia.

Soil types vary in nutrient reserves. Some soils may have substantial nutrient reserves that vary in availability during the growing season or are unavailable due to the soil pH. This can often be the case with micronutrients and foliar sprays can be used in these cases to correct any deficiencies.[9 10]

Figure 1 shows how the availability of nutrients and other elements to plants may be affected by soil pH in mineral soils. In highly organic soils, the influence of pH differs from mineral soils, with maximum availability of nutrients shifting towards the acid end.[11]

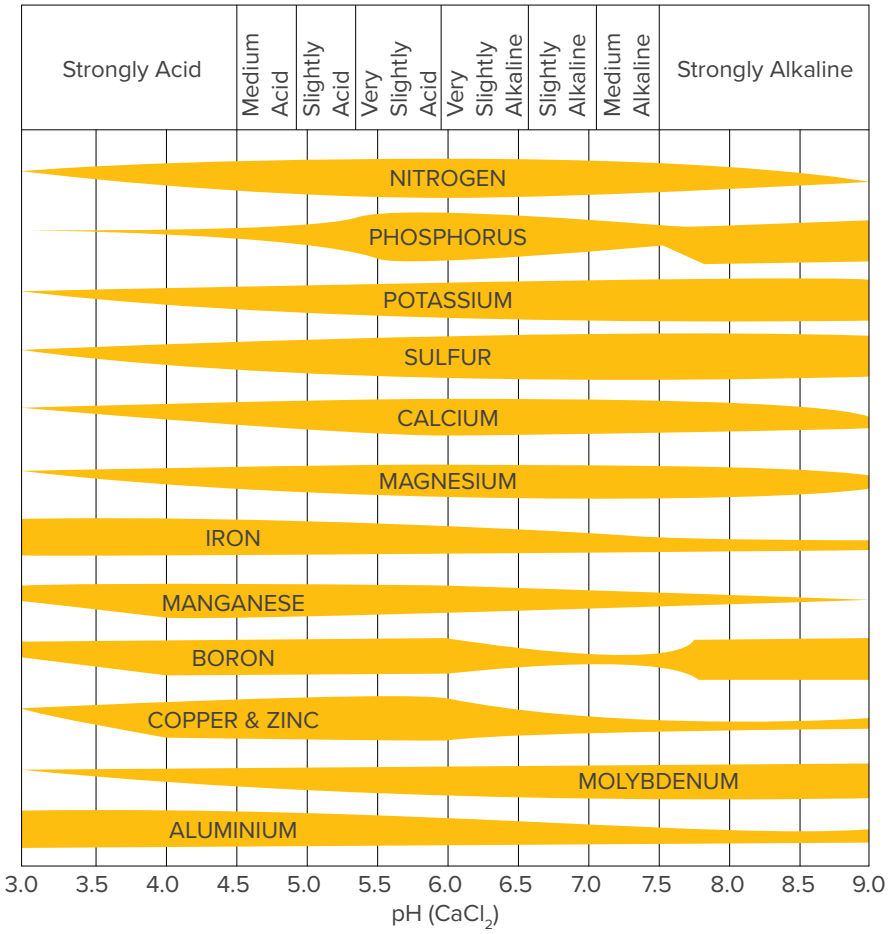

Figure 1: *Influence of soil pH on nutrient availability (wider bars indicate a nutrient is more available to plants at a given soil pH).*

Source: E Truog (1946), Soil reaction influence on availability of plant nutrients, Soil Science Society of America Proceedings

Nutrient removal data will vary with the source of information. Several apps for smartphones and tablets are available with nutrient removal data, such as the International Plant Nutrition Institute's Crop Nutrient Removal Calculator (http://www.ipni.net/article/IPNI-3346).

9 T Rose, P Damon, Z Rengel (2010) Phosphorus-efficient faba bean (Vicia faba L.) genotypes enhance subsequent wheat crop growth in an acid and an alkaline soil. Crop and Pasture Science 61(12). pp 1009–1016, http://epubs.scu.edu.au/plantscience_pubs/165/

10 Pulse Australia (2016) Agronomy. Southern faba and broad bean best management practices training course manual – 2016. Pulse Australia.

11 CSIRO (2006) Australian Soil Fertility Manual. 3rd edn. G Price (ed.). CSIRO Publishing.

6.2.2 Nutrient budgeting

A balance sheet approach to inputs is a good starting point in considering fertiliser amounts to apply. Other factors such as soil type, paddock history, soil test and tissue analysis results, as well as experience, all affect fertiliser decisions.

Precision agriculture can help growers manage land and crop variability; fertiliser rates can be varied to allocate higher rates to high-performing parts of a paddock. Fertiliser replacement maps can be created, based on previous crop yield.[12]

A simple nutrient budget, such as the one shown in Table 2, still requires careful interpretation.[13] This is a useful tool for assessing the nutrient balance of a cropping rotation. However, it needs to be considered in conjunction with other nutrient management tools such as soil and tissue testing, soil type, soil fixation and potential yields.[14]

Table 2: An example of a four-year nutrient budget of a cropping paddock including faba bean.

			Nutrients removed (kg/ha)			
			N	P	K	S
2014	Faba bean	2.2	90	9	22	3
2015	Wheat	3.8	87	11	15	6
2016	Barley	4.2	84	11	21	6
2017	Chickpea (desi)	1.8	59	6	16	4
Total			**230**	**37**	**74**	**19**
			Nutrients applied (kg/ha)			
	Fertiliser (N:P:K:S)	kg/ha	N	P	K	S
2013	0:20:0:0.5	50	0	10	0	1
2014	18:20:0:0.5	70	13	14	0	1
2015	18:20:0:0.5	70	13	14	0	1
	Urea	60	28	0	0	0
2016	0:16:0:20	80	0	13	0	16
Total		**53**	**0**	**51**	**0**	**19**
Balance			**–267**	**+14**	**–74**	**0**

Source: Modified from example in Grain Legume Handbook

The deficit of 267 kg/ha nitrogen in Table 2 needs to be countered by any nitrogen fixation. If this is estimated to be 50 kg/ha for each pulse crop, the budget suggests that the soil nitrogen status is declining and should be increased by using more nitrogen in the cereal phase. Estimating nitrogen fixation is not easy. One 'rule of thumb' to use is 20 kg nitrogen fixed for each tonne of plant dry matter at flowering.

The credit of 14 kg/ha of phosphorus (Table 2) will be used in the soil in building soil phosphorus levels. No soil fixation of phosphorus has been considered.

In this budget, the sulfur levels are in balance (Table 2).

Trace elements such as zinc and copper can also be included in a nutrient budget.

As there are many fertilisers available to use on pulses, for the best advice check with your local fertiliser reseller or agronomist.[15]

12 GRDC (2009) Precision agriculture fact sheet. Grains Research and Development Corporation, https://grdc.com.au/resources-and-publications/all-publications/factsheets/2010/02/precision-agriculture

13 GRDC (2014) GrowNotes™: Faba bean (northern region). Grains Research and Development Corporation, https://grdc.com.au/Resources/GrowNotes™

14 Pulse Australia (2016) Agronomy. Southern faba and broad bean best management practices training course manual – 2016. Pulse Australia.

15 Pulse Australia (2016) Agronomy. Southern faba and broad bean best management practices training course manual – 2016. Pulse Australia.

6.2.3 Acid fertilisers reduce nodulation

Inoculated seed and acidic fertilisers should not be sown through the same tube, as the acidity will kill large numbers of rhizobia. Neutral and alkaline fertilisers can be used (Table 3).

Table 3: Some acid, neutral and alkaline fertilisers used for faba bean crops. Acid fertilisers should not be sown through the same tube as inoculated seed but neutral and alkaline fertilisers can be used.

Acid	Neutral	Alkaline
Superphosphates (single, double and triple)	Super lime	DAP (also known as 18:20:0)
Fertilisers with copper and/or zinc		Starter NP
MAP (also known as 11:23:0 and Starter 12)		Lime

Source: Southern faba and broad bean best management practices training manual (2016)

6.3 Soil testing

Soil testing is the only quantitative nutrient information that can be used to predict yield response to nutrients. To determine how much fertiliser to apply, soil test results need to be considered in combination with information about potential yield, soil type and nutrient removal in previous seasons (see Section 2 Planning and paddock preparation for more information).

Soil samples should be taken before sowing so that results and recommendations are available in time to order the right fertiliser products. Regular planned sampling of paddocks (for example, every 3 years) allows monitoring of fertility trends over time.[16]

Soil test results are part of the information that supports decisions about fertiliser type, rate, timing and placement. Principal reasons for soil testing for nutrition include:

- monitoring soil fertility levels;
- estimating which nutrients are likely to limit yield;
- measuring properties such as pH, sodium (sodicity) and salinity, which affect the crop water demand as well as the ability to access nutrients;
- zoning paddocks for variable application rates; and
- as a diagnostic tool, to identify reasons for poor plant performance.[17]
- The soil test for measuring nitrogen, phosphorus, potassium and sulfur in the southern region are:
- bicarbonate extractable P (Colwell-P);
- diffusive gradients in thin-films (DGT) for P (DGT-P is a relatively new method currently being tested for use with Australian soils, and mimics the action of the plant roots in accessing available phosphorus (more information is available in the phosporus fact sheet from soilquality.org.au: http://www.soilquality.org.au/factsheets/phosphorus);
- bicarbonate extractable K (Colwell-K);
- 2 M KCl extractable inorganic N, which provides measurement of nitrate-N and ammonium-N; and
- KCl-40 extractable S test method (the KCl-40 test is also called the CPC or the Blair sulfur (KCl 40)) is also reported as the MCP test.[18]

16 GRDC (2013) Crop nutrition fact sheet: Better fertiliser decisions for crop nutrition. Grains Research and Development Corporation, www.grdc.com.au/GRDC-FS-BFDCN

17 GRDC (2014) Crop nutrition fact sheet: Soil testing for crop nutrition (southern region). Grains Research and Development Corporation, www.grdc.com.au/GRDC-FS-SoilTestingS

18 DEDJTR (2015) Interpreting soil and tissue tests. Victorian Department of Education, Jobs, Transport and Resources, http://agriculture.vic.gov.au/agriculture/farm-management/soil-and-water/soils/understanding-soil-tests-pastures

FEEDBACK

MORE INFORMATION

Listen to an interview on soil testing https://grdc.com.au/~/media/Audio/Driving-Agronomy/nigel-wilhelm-mp3.mp3

The soil P test needs to be interpreted in association with the soil's phosphorus-adsorption capacity, which is estimated by the phosphorus buffering index (PBI). The higher the PBI value, the more difficult it is for a plant to access phosphorus. Phosphorus is relatively immobile in soils and phosphorus applied to the 0–10 cm layer tends to remain in that layer, especially in no-till systems.[19]

Choose a laboratory that has the Australasian Soil and Plant Analysis Council (ASPAC) certification for the tests they offer. National Association of Testing Authorities (NATA) accreditation is also desirable.[20]

6.3.1 Critical values and ranges

A soil test critical value is the soil test value required to achieve 90% of crop yield potential. The critical range around the critical value indicates the reliability of that single value.

Recently, revised critical soil test values and ranges were established for nutrients, crops and soil classes in south-east Australia. While the revised values and ranges do not include faba bean, for field pea, the Colwell-P soil test critical value is 24 mg/kg, with a range of 21–28 mg/kg; field pea grain removes slightly less phosphorus per tonne than faba bean. Currently used critical values for faba bean are shown in Table 4.

Critical ranges are established for 0–10 cm; however, soil sampling to greater depth (60 cm) is important for more mobile nutrients, such as nitrogen, sulfur and potassium, as well as for pH, salinity and sodicity. Use local data and support services to help integrate soil test data into making profitable fertiliser decisions.[21]

19 GRDC (2014) Crop nutrition fact sheet: Soil testing for crop nutrition (western region). Grains Research and Development Corporation, www.grdc.com.au/GRDC-FS-SoilTestingW

20 GRDC (2013) Crop nutrition fact sheet: Better fertiliser decisions for crop nutrition. Grains Research and Development Corporation, www.grdc.com.au/GRDC-FS-BFDCN

21 GRDC (2014) Crop nutrition fact sheet: Soil testing for crop nutrition (southern region). Grains Research and Development Corporation, www.grdc.com.au/GRDC-FS-SoilTestingS

Table 4: Adequate nutrient levels for various soil test results. If a soil test value is less than the lower limit of the range, the site is highly likely to respond to an application of the nutrient.

Nutrient	Test used		
Phosphorus			
	Colwell (mg/kg)	Olsen	
Sand	20–30	10–15	
Loam	25–35	12–17	
Clay	35–45	17–23	
Potassium			
	Bicarbonate	Skene	Exchangeable K
Sand	50	50–100	Not applicable
Other soils	100	100	0.25 meq/100g
Sandy loam	–	–	–
– Faba bean	100–120	–	–
– Field pea	70–80	–	–
– Lupin	30–40	–	–
– Canola	40	–	–
– Cereals	30	–	–
Sulfur			
	KCl (mg/kg)		
Low	5		
Adequate	8		

Sources: Nutrition management (2010); Queensland DAF, https://www.daf.qld.gov.au/plants/field-crops-and-pastures/broadacre-field-crops/nutrition-management/overview; Soil testing for crop nutrition (2014)

6.4 Plant tissue testing

Tissue testing is the best way to accurately diagnose a suspected micronutrient deficiency.

Plant tissue testing is most useful for monitoring crop health, because by the time noticeable symptoms appear in a crop the yield potential can be markedly reduced. A plant tissue analysis can detect non-visible (sub-clinical) symptoms, and to fine-tune nutrient requirements.

When tissue testing, sample the appropriate tissues at the right time. Plant nutrient status varies according to the plant's age, variety and weather conditions. Technology is allowing quicker analysis and reporting of results to enable timely application of foliar or soil-applied fertiliser, for a rapid crop response.[22]

Different plants have different critical concentrations for a nutrient and in some cases varieties can vary in their critical concentrations.[23] Table 5 lists the plant analysis criteria for faba bean.

6.4.1 Critical nutrient levels

Table 5: Critical nutrient levels for faba bean at flowering. (These should be used as a guide only and care should be taken to use plant tissue tests for the purpose for which they have been developed; most tests diagnose only the nutrient status of the plants at the time they are sampled and cannot reliably indicate the effect of a particular deficiency on grain yield.)

Nutrient	Plant part	Critical Range *
Nitrogen (%)	Youngest open leaf	4.0
Phosphorus (%)	Youngest open leaf	0.4
Potassium (%)	Youngest mature leaf	1.0
Calcium (%)	Youngest mature leaf	0.6
Magnesium (%)	Youngest mature leaf	0.2
Sulfur (%)	Whole shoot	0.2
Boron (mg/kg)	Youngest open leaf	10
Copper (mg/kg)	Youngest mature leaf	3.0 to 4.0
Manganese (mg/kg)	Youngest mature leaf	<40
Zinc (mg/kg)	Youngest open leaf	20–25

* Any nutrient level below the critical range will be deficient; any level above will be adequate.
Source: Southern faba bean best management practices training course manual (2016)

22 GRDC (2013) Crop nutrition fact sheet: Micronutrients (northern, southern and western regions). Grains Research and Development Corporation, www.grdc.com.au/GRDC-FS-CropNutrition-Micronutrients

23 Pulse Australia (2016) Agronomy. Southern faba and broad bean best management practices training course manual – 2016. Pulse Australia.

6.5 Nutrient disorders

Visual symptoms of nutrient disorders do not develop until a major effect on yield, growth or development has occurred (Figure 2). This is called sub-clinical deficiency or toxicity.

Healthy plants have a greater potential to ward off disease, pests and environmental stresses leading to higher yields and better grain quality.

6.5.1 Diagnosing nutrient deficiency

The following points should be considered when diagnosing nutrient disorders:

- Visual symptoms on lentil may be caused by damage from herbicides, insects, and pathogens. Damage may also be from physiological disorders arising from adverse environmental effects such as salinity, drought, cold, heat or high temperature stresses. Such symptoms can be indistinguishable from nutrient deficiency, although it should be obvious if environmental conditions are limiting (moisture stress).
- Factors that influence both nodulation and nitrogen fixation can result in symptoms of nitrogen deficiency.
- There can be differences between cultivars in the manifestation of symptoms.
- Visual symptoms in one pulse do not necessarily mean that it is the same in other pulses.

Table 6 provides a key to diagnosing nutrient deficiencies in faba bean.

Figure 2: *Flow chart for the identification of deficiency symptoms.*

Source: T Reddy, G Reddi (1997)

FEEDBACK

Table 6: Key to nutrient deficiencies in faba bean.

Deficiency symptom	Old to middle leaves						Middle to new leaves					New leaves to terminal shoots					
	N	P	S	K	Mg	Zn	N	Mg	Mn	Zn	B	Mn	Fe	Zn	Cu	Ca	B
Chlorosis (yellowing)																	
Complete	X		X									X#	X				X#
Mottled	X	X	X		X					X	X						
Between veins					X						X						
On margins			X		X												
Necrosis (dead tissue)																	
Complete		X				X											
Distinct areas (including spotting)				X		X		X	X		X	X		X			
Margins													X			X	
Tips				X		X			X			X		X	X		
Pigmentation within necrotic or chlorotic areas																	
Purple	X	X	X	X		X		X	X	X		X				X	
Dark green		X									X						
Brown		X	X						X		X	X	X	X			
Red					X						X			X			
Malformation of leaflets																	
Rolling-in of margin				X				X					X			X	X
Wilting						X	X								X		
Twisting									X			X			X		X
Malformation of leaves																	
Cupping	X						X								X		
Umbrella formation								X			X						
Malformation of stems and roots																	
Internode shortening											X			X			X
Petiole collapse																X	
Root distortion											X		X			X	X

Mild

Sources: Snowball and Robson via Southern faba bean best management practices training course manual (2016); Symptoms of nutrient deficiencies and toxicities: faba beans and field peas (1991)

Many nutrient deficiencies may look similar. It is important to:

- know what a healthy plant looks like in order to recognise symptoms of distress;
- determine what the affected areas of the crop look like (for example, are they discoloured (yellow, red, brown), dead (necrotic), wilted or stunted);
- identify the pattern of symptoms in the field (patches, scattered plants, crop perimeters);
- assess affected areas in relation to soil type (pH, colour, texture) or elevation; and
- look at individual plants for more detailed symptoms such as stunting, wilting and where the symptoms are appearing (whole plant, new leaves, old leaves, edge of leaf, veins etc.).

If more than one problem is present, typical visual symptoms may not occur. For example, water stress, disease or insect damage can mask a nutrient deficiency. If two nutrients are simultaneously deficient, symptoms may differ to that when deficient alone.

Micronutrients are often used by plants to process other nutrients or work together with other nutrients, so a deficiency of one may look like another. For instance, molybdenum is required by pulses to complete the nitrogen fixation process.

6.5.2 Nutrient toxicity

Soil pH affects the availability of most nutrients. Occasionally some nutrients are made so 'available' that they inhibit plant growth. For example, on some acidic soils, aluminium and manganese levels may restrict faba bean growth, usually by restricting the rhizobia and the plants' ability to nodulate.[24]

The most common nutrient toxicities in subsoils of the medium and low-rainfall areas of south-eastern Australian are boron, sodium, carbonate and bicarbonate. In the high-rainfall regions, where high rates of leaching occur, subsoil acidity can develop. This causes specific nutrient toxicities, especially aluminium and manganese.

Under saline conditions, the presence of high concentrations of salts reduces growth by osmotic stress, in which the presence of high salt concentrations restricts water uptake, and by the direct toxic effect of sodium and chloride ions in the plant tissues.[25]

Table 7 shows the sensitivity of faba bean to boron, aluminium and manganese.

Table 7: Pulse crop sensitivity to toxic levels of manganese, aluminium and boron.

	Manganese	Aluminium	Boron
Faba bean	Sensitive	Sensitive	Tolerant
Field pea	Sensitive	Sensitive	Sensitive
Lentil*	Very sensitive	Very sensitive	Very sensitive
Chickpea	Very sensitive	Very sensitive	Sensitive
Lupin*	Tolerant	Tolerant	–

*These crops are not usually grown on alkaline/high boron soils.

Source: Southern faba bean best management practices training course manual, (2016), Pulse Australia Limited.

24 Pulse Australia (2016) Agronomy. Southern faba and broad bean best management practices training course manual – 2016. Pulse Australia.

25 D Adcock, R Armstrong, F Best, D Chittleborough, M Imhof, G McDonald, A McNeill, J Nuttall, N Wilhelm (2009) Nutrient deficiencies, toxicities and imbalances. Identifying, Understanding and Managing Hostile Subsoils For Cropping – A Reference Manual for Neutral-Alkaline Soils of South-Eastern Australia. The Profitable Soils Group. pp 31–39, http://vro.agriculture.vic.gov.au/dpi/vro/vrosite.nsf/pages/soil_mgmt_subsoil

Soil acidity

Soil acidity and alkalinity are measured in units of pH. The pH scale is from 0 (most acid) to 14 (most alkaline) and a pH of 7 is neutral. The pH of a soil will change over time influenced by factors including parent material, weathering and current agricultural practices. It will also fluctuate through the year. Soil pH will affect how plants grow[26] (Figures 3 and 4).

While faba bean is generally considered sensitive to soil acidity, it may be successfully grown on slightly acidic soils (pH ($CaCl_2$) >5.0– 6.0) in the high and medium-rainfall zones of south-eastern Australia with inconsistent yields.

Use appropriate lime rates to maintain pH ($CaCl_2$) >5.5 in the entire top 10 cm layer. Under no-till systems, lime topdressing with no incorporation is ineffective in neutralising acidity below about 5 cm depth. Acidic soil layers below 5 cm adversely affect root growth and architecture, nodulation, plant vigour and N_2 fixation potential of acid-sensitive pulses.[27]

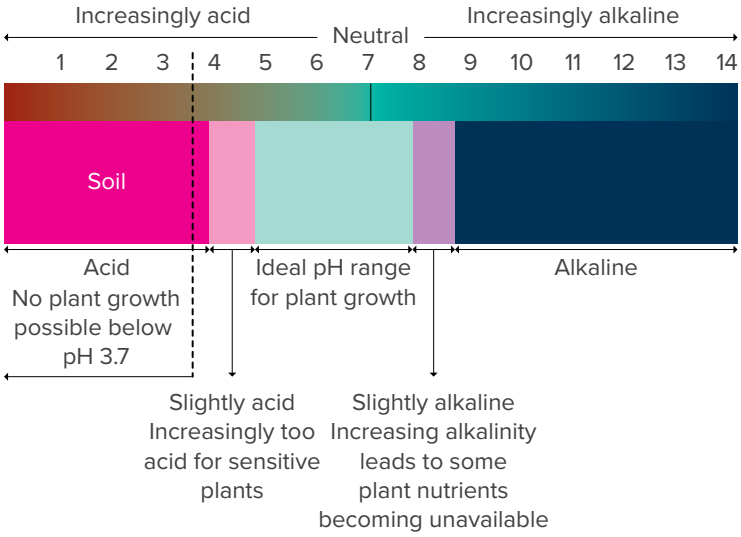

Figure 3: *Plant growth and pH ($CaCl_2$) scale*

Note: Faba bean prefers alkaline soils. The crop may benefit from lime application on acid soils.

Source: B Lake (2000) Understanding soil pH

26 CSIRO (2006) Australian Soil Fertility Manual. 3rd edn. G Price (ed.). CSIRO Publishing.

27 H Burns (2017) Topsoil pH stratification impacts on pulse production in South East Australia, GRDC Update Paper February 2017, https://grdc.com.au/Research-and-Development/GRDC-Update-Papers/2017/02/Topsoil-pH-stratification-impacts-on-pulse-production-in-South-East-Australia

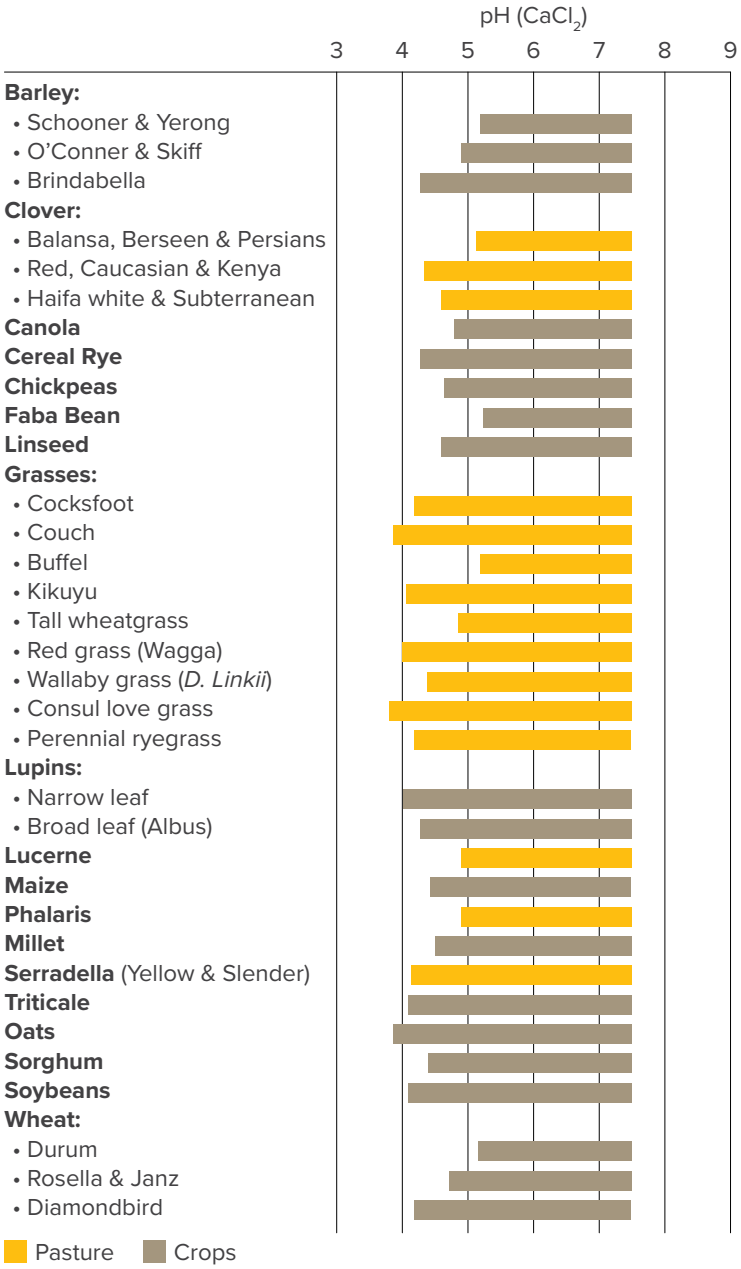

Figure 4: *Optimum pH ($CaCl_2$) range up to pH 7.5 for a number of crops and pastures. Above pH 7.5 the acidity/alkalinity is no longer the principal factor that controls growth. Other factors, such as phosphorus, zinc, cobalt or boron deficiency or the sodicity of soil are most likely to affect production.*

Source: B Lake (2000), Understanding soil pH

Concentrations of elements such as aluminium, iron and manganese can reach toxic levels because their solubilities increase in acid soils.

Nitrogen fixation (see Section 2 Planning and paddock preparation for more information) by faba bean and other legumes can be greatly reduced in acid soils. The optimal pH for nitrogen fixation is a narrow range for different crops. For example, in soybean, this is pH ($CaCl_2$) 6.0–6.2.

The availability of nutrients such as phosphorus and molybdenum is reduced on acid soils, while potassium may be more likely to leach (see Figure 1).

Manganese toxicity

Faba bean is very sensitive to aluminium and manganese toxicity, which often occur on acidic soils and are generally unsuited to the crop.[28] Manganese becomes more soluble in acid soils and can reach toxic levels.[29]

Symptoms of manganese toxicity appear on new leaves first (Photo 1). Small purple spots appear from the margins on young leaves. Symptoms later develop in middle and older leaves. Slightly older leaves take on a red colour.[30]

Leaf crinkling and cupping is also symptom of manganese toxicity in faba bean. The cupping is thought to be caused by manganese accumulation in the leaf margin area, slowing the growth of that area relative to the rest of the leaf.[31]

Hydroponic faba bean grown in high concentrations of manganese had less chlorophyll than healthy plants, while root and shoot development were more than halved in trials.[32]

Photo 1: *Manganese toxicity in faba bean in young leaflets (left) and middle leaflets (right).*

Photo: Alan Robson; Grain Legume Handbook (2008)

Where faba bean is grown on acid soils of 5.0 pH ($CaCl_2$), a topsoil test for aluminium and/or manganese should be carried out. Lime should be incorporated at 2.5–5.0 t/ha if manganese exceeds 50 mg/kg.[33]

Aluminium toxicity

Aluminium toxicity can develop in faba bean crops that are well-nodulated but grown in low pH soils. Aluminium becomes more soluble in acid soils, and can reach toxic levels.

Although aluminium has not been shown to be essential for plant growth, it becomes increasingly soluble as the soil pH ($CaCl_2$) falls below 5.0. The aluminium in the soil solution restricts cell wall expansion and root growth.

Aluminium toxicity is probably the most important growth-limiting factor for plants in many strongly acidic soils where pH ($CaCl_2$) is less than 4.5 (or pH in water <5.0).

Symptoms of aluminium toxicity in faba bean are delayed germination and miniature, dark green plants. Roots are extremely stunted and with many laterals appearing to

28 T Yeatman, W Hawthorne, J Paull, J Bellati, J Egan, K Henry, R Kimber, M Seymour, J van Leur, K Lindbeck, P Matthews, I Rose (2009) Faba bean: The Ute Guide. Primary Industries and Resources South Australia, https://grdc.com.au/resources-and-publications/all-publications/publications/2009/11/faba-beans-the-ute-guide/

29 CSIRO (2006) Australian Soil Fertility Manual. 3rd edn. G Price (ed.). CSIRO Publishing.

30 Pulse Australia (2016) Agronomy. Southern faba and broad bean best management practices training course manual – 2016. Pulse Australia.

31 KR Helyar (1981) The symptoms and effects on plants of nutrient disorders in acid soils. Proceedings The Acid Soils Affair: Riverina Outlook Conference. Riverina College of Advanced Education, www.regional.org.au/au/roc/1981/roc198147.htm

32 S Arya, BK Roy (2011) Manganese induced changes in growth, chlorophyll content and antioxidants activity in seedlings of broad bean (*Vicia faba* L.). Journal of Environmental Biology 32(6). pp 707–711, www.researchgate.net/publication/223983778_Manganese_induced_changes_in_growth_chlorophyll_content_and_antioxidants_activity_in_seedlings_of_broad_bean_Vicia_faba_L

33 J Carter (1999) Faba Bean and Broad Bean Growers Guide: A Guide for the Production of Faba Beans and Broad Beans. D Robey, M Raynes (eds.). Victoria Department of Natural Resources and Environment.

be dead. Under field conditions it is often difficult to observe root systems because affected plants are very susceptible to moisture stress and die easily.[34, 35]

Aluminium in plants upsets the phosphorus metabolism; symptoms may be confused with phosphorus deficiency.

Where faba bean is grown on acid soils a topsoil test for aluminium and/or manganese should be carried out. Lime should be incorporated at 2.5–5.0 t/ha if aluminium exceeds 20 mg/kg. Table 8 shows the effect of liming on the level of exchangeable aluminium.[36]

Table 8: Liming at 2.5 t/ha on a red chromosol in southern New South Wales reduced exchangeable aluminium content by 93%.

Treatment	Soil pH ($CaCl_2$)	Exchangeable aluminium (cmol(+)/kg)
No lime	4.2	1.08
Lime	5.0	0.08

Source: Australian Soil Fertility Manual (2006)

In a long-term trial in southern New South Wales, soil pH ($CaCl_2$) at 15–20 cm depth increased gradually from about 4.1–4.6 by liming the topsoil, while the topsoil pH was maintained. As the subsoil became less acidic, the percentage of exchangeable aluminium at 15–20 cm dropped from 42 to 10% by 2005, 13 years after initial liming.[37]

A trial in Hamilton, Victoria, found no differences in yield of faba bean due to lime application, with rates varying from 0–3.5 t/ha on a soil with pH ($CaCl_2$) 4.7 (pH 4.0 in water). The researchers concluded the results may have been due to the unusually low aluminium levels in the soil.[38]

Boron toxicity, salinity and sodicity

Faba bean are affected by high salinity (salt) and boron levels in alkaline subsoils in many parts of the southern region.[39] High boron and salt can restrict root growth and water uptake.[40] Salinity often occurs with sodicity (excessive sodium). Field research in Victoria and South Australia shows that soil salinity and sodicity can substantially reduce crop yields.

In south-eastern Australia, a short-term change in soil salinity is termed 'transient salinity', which often occurs with transient sodicity in semi-arid environments such as the Victorian Wimmera and Mallee. The constraints caused by saline and sodic soils operate at the same time to decrease the effective root zone of crops, limiting plant-available water.[41]

Developing varieties with boron and salt tolerance is a long-term aim of the pulse breeding programs in southern Australia, to help alleviate the effects of soil variability.[42]

MORE INFORMATION

Identifying, understanding and managing hostile subsoils for cropping – A reference manual for neutral-alkaline soils of south-eastern Australia, http://vro.agriculture.vic.gov.au/dpi/vro/vrosite.nsf/pages/soil_mgmt_subsoil

34 Pulse Australia (2016) Agronomy. Southern faba and broad bean best management practices training course manual – 2016. Pulse Australia.

35 CSIRO (2006) Australian Soil Fertility Manual. 3rd edn. G Price (ed.). CSIRO Publishing.

36 KR Helyar (1981) The symptoms and effects on plants of nutrient disorders in acid soils. Proceedings The Acid Soils Affair: Riverina Outlook Conference. Riverina College of Advanced Education, www.regional.org.au/au/roc/1981/roc198147.htm

37 G Li, M Conyers, B Cullis (2010) Long-term liming ameliorates subsoil acidity in high rainfall zone in southeastern Australia. Proceedings 19th World Congress of Soil Science for a Changing World 1–6 August 2010, Brisbane, vol. 1. pp 2375–2378, www.soilscienceaustralia.com.au/19th-world-congress-of-soil-science

38 S Holden, A Spiers (2000) Lime trial. Southern Farming Systems 1999 research manual. Southern Farming Systems, www.farmtrials.com.au

39 T Yeatman, W Hawthorne, J Paull, J Bellati, J Egan, K Henry, R Kimber, M Seymour, J van Leur, K Lindbeck, P Matthews, I Rose (2009) Faba bean: The Ute Guide. Primary Industries and Resources South Australia, https://grdc.com.au/resources-and-publications/all-publications/publications/2009/11/faba-beans-the-ute-guide/

40 S Arya, BK Roy (2011) Manganese induced changes in growth, chlorophyll content and antioxidants activity in seedlings of broad bean (*Vicia faba* L.). Journal of Environmental Biology 32(6). pp 707–711, www.researchgate.net/publication/223983778_Manganese_induced_changes_in_growth_chlorophyll_content_and_antioxidants_activity_in_seedlings_of_broad_bean_Vicia_faba_L

41 D Adcock, R Armstrong, F Best, D Chittleborough, M Imhof, G McDonald, A McNeill, J Nuttall, N Wilhelm (2009) Salinity and sodicity. Identifying, Understanding and Managing Hostile Subsoils For Cropping – A Reference Manual for Neutral-Alkaline Soils of South-Eastern Australia. The Profitable Soils Group. pp 41–50, http://vro.agriculture.vic.gov.au/dpi/vro/vrosite.nsf/pages/soil_mgmt_subsoil

42 J Carter (1999) Faba Bean and Broad Bean Growers Guide: A Guide for the Production of Faba Beans and Broad Beans. D Robey, M Raynes (eds.). Victoria Department of Natural Resources and Environment.

The most characteristic symptom of boron toxicity in pulses is chlorosis (yellowing) and, if severe, some necrosis (death) of leaf tips or margins. Older leaves are usually more affected. There appears to be little difference in reaction between current faba bean varieties.

Shallow (top 10 cm) and deep (10–90 cm) soil tests can be a good guide of the suitability of some soils for growing faba and broad bean to indicate which toxicities may impact on plant growth and rooting depth.[43]

The degree of salinity in the soil is measured as electrical conductivity (EC). Plants growing on saline soils often exhibit wilting even when the soil water is adequate.[44]

Photo 2: *Boron toxicity in old and middle faba bean leaves.*

Photo: Alan Robson; Grain Legume Handbook (2008)

6.6 Nitrogen

6.6.1 Nutrition effects on following crop

Agricultural legumes fix large quantities of Nitrogen. This represents a huge saving of fertiliser Nitrogen that would otherwise need to be applied, and has positive economic and environmental consequences. Assuming 80% conversion of fertiliser N into plant N, the 40 million t of biologically fixed Nitrogen has a fertiliser-N equivalence of 50 million t, or about 50% of current global inputs of nitrogenous fertilisers. The nominal annual value of the fixed Nitrogen is about $63 billion (assuming cost of fertiliser N of $1.25/kg).[45]

In Australia, 23 million ha of legume based pastures are estimated to fix around 2.5 million t of Nitrogen annually, based on average production of 3.0 t/ha of legume biomass and rates of Nitrogen fixation of 110 kg N/ha (Table x). Nitrogen fixation by the crop legumes is estimated at greater than 0.2 million t annually. Using

the assumptions above, the economic value of the Nitrogen fixed by legumes in Australian agricultural systems is greater than $4 billion annually.

43 Pulse Australia (2016) Agronomy. Southern faba and broad bean best management practices training course manual – 2016. Pulse Australia.

44 CSIRO (2006) Australian Soil Fertility Manual. 3rd edn. G Price (ed.). CSIRO Publishing.

45 D Herridge (2013). Managing Legume and Fertiliser N for Northern Grains Cropping (GRDC)

Table 9: Estimates of the amounts of N2 fixed annually by crop legumes in Australia

Legume	%Ndfa	Shoot DM[1] (t/ha)	Shoot N (kg/ha)	Root N[2] (kg/ha)	Total crop N (kg/ha)	Total N fixed[3] (kg/ha)
Soybeans	48	10.8	250	123	373	180
Lupins	75	5.0	125	51	176	130
Faba beans	65	4.3	122	50	172	110
Field peas	66	4.8	115	47	162	105
Peanuts	36	6.8	190	78	268	95
Chickpeas	41	5.0	85	85	170	70
Lentils	60	2.6	68	28	96	58
Mungbeans	31	3.5	77	32	109	34
Navy beans	20	4.2	105	43	148	30

%Ndfa, % of legume N derived from N2 fixation

1 DM = dry matter 2 Root N = shoot N x 0.5 (soybeans), 1.0 (chickpeas) or 0.4 (remainder) 3 Total N fixed = %Ndfa x total crop N

Source: Primarily Unkovich et al. (2010) via D Herridge (2013) Y Managing Legume and Fertiliser N for Northern Grains Cropping (GRDC).

6.6.2 Nitrogen fertiliser

Well-nodulated faba bean crops should be self-sufficient for nitrogen and should not normally need nitrogen fertiliser.[46]

Crops with larger biomass generally fix more nitrogen and also remove more nitrogen in grain. Table 9 shows how nitrogen is likely to be distributed in faba bean crops yielding between 0.5–3.0 t/ha of grain.

Table 10: Estimated nitrogen distribution and removal in faba bean crops with a range of grain and dry matter yields. The more dry matter, generally the more nitrogen fixed and removed from the soil.

Total plant dry matter (t/ha)	Total shoot dry matter yield (t/ha)	Grain yield (t/ha) at 40% harvest index*	Total crop nitrogen requirement (2.3% N) (kg/ha)	Nitrogen removal in grain (kg/ha)
1.75	1.25	0.5	40	17
3.50	2.50	1.0	80	33
5.25	3.75	1.5	120	0
7.00	5.00	20	160	66
8.75	6.25	2.5	200	83
10.50	7.50	3.0	240	100

Source: Southern faba bean best management practices training course manual (2016)

In southern Australia 'starter' nitrogen fertiliser, such as monoammonium phosphate (MAP) and diammonium phosphate (DAP), is not considered necessary in most situations, except for pulses growing in soils with extremely low levels of plant-available nitrogen.[47]

46 T Yeatman, W Hawthorne, J Paull, J Bellati, J Egan, K Henry, R Kimber, M Seymour, J van Leur, K Lindbeck, P Matthews, I Rose (2009) Faba bean: The Ute Guide. Primary Industries and Resources South Australia, https://grdc.com.au/resources-and-publications/all-publications/publications/2009/11/faba-beans-the-ute-guide/

47 E Drew, D Herridge, R Ballard, G O'Hara, R Deaker, M Denton, R Yates, G Gemell, E Hartley, L Phillips, N Seymour, J Howieson, N Ballard (2012) Inoculating Legumes, a Practical Guide. Grains Research and Development Corporation, https://grdc.com.au/GRDC-Booklet-InoculatingLegumes

Nitrogen fertiliser should be considered:

- with late sowing or low fertility situations, where rapid early growth is critical in achieving adequate height and sufficient biomass to support a reasonable grain yield; or
- where the grower is unwilling to undertake recommended inoculation procedures.

Many growers use starter fertilisers on pulses. Rates of 5–10 kg/ha of starter nitrogen may aid establishment of faba bean on light, slightly acid soils. Nodulation is not affected by low rates of nitrogen nor will it make the nodules 'lazy'; early plant vigour and yields are often improved.[48] Starter MAP or DAP. can encourage early root growth to establish a stronger plant.

This is supported by pot experiments, where nodule development in the faba bean variety Fiord was slightly stimulated in the presence of low levels of nitrate, which compensated for the poor early seedling growth that occurred when plants were grown without mineral nitrogen. However, doubling or trebling the concentration of nitrate delayed nodulation, decreased nodule number and decreased nodule activity of Fiord.[49]

Excessive use of starter nitrogen fertiliser, or high levels of soil nitrate can delay or reduce nodulation and reduce nitrogen fixation.[50]

6.6.3 Nitrogen deficiency symptoms

The first sign of nitrogen deficiency in faba bean is a general paleness of the whole plant.[51] The middle to new leaves may 'cup'. A mottled yellowing (chlorosis) of old leaves slowly develops with little sign of dead tissue (necrosis). Oldest leaves are most affected.[52] Nitrogen-deficient plants are also stunted[53] (Photo 3).

Nodulation failure

If nitrogen deficiency is suspected, assess nodulation (Photo 4).

Nodulation should be assessed 10–12 weeks after sowing until early flowering.

48 J Carter (1999) Faba Bean and Broad Bean Growers Guide: A Guide for the Production of Faba Beans and Broad Beans. D Robey, M Raynes (eds.). Victoria Department of Natural Resources and Environment.

49 A Herdin, JH Silsbury (1989) Nodulation and early growth of faba bean (*Vicia faba* L.) and pea (*Pisum sativum* L.) as affected by strain of *Rhizobium*, NO_3- supply, and growth temperature. Australian Journal of Agricultural Research 40(5). pp 991–1001, http://www.publish.csiro.au/cp/AR9890991

50 BASF (undated) Nodulaid N/T. Group F faba bean inoculant label. BASF Australia Ltd, http://www.agro.basf.com.au/images/Labels/NODULAID-NT-Group-F-Favabean-TXT-LABEL.pdf

51 Pulse Australia (2016) Agronomy. Southern faba and broad bean best management practices training course manual – 2016. Pulse Australia.

52 CSIRO (2006) Australian Soil Fertility Manual. 3rd edn. G Price (ed.). CSIRO Publishing.

53 M Wurst, W Hawthorne, A Nikandrow, M Ramsey, T Bretag, J Davidson, R Gilbert, W MacLeod, G Murray, K Panagiotopoulos, M Schwinghamer (2002) Winter Pulse Disorders: The Ute Guide. Primary Industries and Resources South Australia.

Photo 3: *Nitrogen deficiency in faba bean. Plants show signs of stunting, yellowing and poor growth compared with well-nodulated plants.*

Photo: Wayne Hawthorne, formerly Pulse Australia

Photo 4: *When plants show signs of nitrogen deficiency, check nodulation and nodule colour to confirm nodulation failure and nitrogen deficiency.*

Photo: Wayne Hawthorne, formerly Pulse Australia

Photo 5: *Good nodulation (left), poor nodulation (right).*

Photos: Maarten Ryder

Nodulation has failed where few or no nodules are present on the root system and those present lack red pigmentation inside[54] (Photo 5). Nodulation around the crown of the taproot are more effective than nodules scattered along lateral roots.[55]

Poor nodulation may be caused by low number of viable rhizobia due to:

- incorrect strain of rhizobia;
- incompatibility with some seed dressings and superphosphate;
- inoculant not stored on-farm in cool conditions;
- inoculated seed left for more than two days before sowing; or
- inoculated seed left in hot, dry or windy conditions or in direct sunlight for some time.

Alternatively, poor nodulation may be caused by a poor method of inoculation:

- inoculant is used but seed covering is poor;
- there are poor conditions for nodulation; or
- the crop under stress (for example, herbicide injury, waterlogging, nutritional deficiency or toxicity) (see Section 4.4 Inoculation for more information).

54 M Wurst, W Hawthorne, A Nikandrow, M Ramsey, T Bretag, J Davidson, R Gilbert, W MacLeod, G Murray, K Panagiotopoulos, M Schwinghamer (2002) Winter Pulse Disorders: The Ute Guide. Primary Industries and Resources South Australia.

55 M Raynes, K Wansink (2000) Growers' guide to assessing nodulation in pulse crops. Topcrop fact sheet. Victorian Department of Natural Resources and Environment.

6.7 Phosphorus

Phosphorus is the major nutrient required for faba bean. Fertiliser programs are built on the amount of phosphorus needed, as phosphorus is the basis of soil fertility.

6.7.1 Occurrence of phosphorus deficiency

Phosphorus deficiency may be more limiting to world crop production than other deficiencies, toxicities and diseases. Most Australian soils do not have sufficient phosphorus. Many factors affect the availability of applied and residual phosphorus to plants (Table 10).

Table 11: The availability of phosphorus to crops varies with several factors.

Factor	Details
Soil pH	Availability is best when pH ($CaCl_2$) is between 5.0 and 6.0.
Clay content	High clay soils 'tie-up' (fix) more phosphorus than sandy soils.
Type of clays	Soils high in certain types of clay fix more phosphorus; including those common in high-rainfall areas and soils formed from volcanic ash.
Phosphorus buffer capacity	The ability of a soil to resist a change in the status of plant-available phosphorus.
Time of application	The longer the phosphorus is in contact with the soil, the more is fixed.
Aeration	Makes more phosphorus available by allowing organic matter breakdown.
Compaction	Makes less phosphorus available by reducing aeration.
Moisture	Optimum levels improve phosphorus availability.
Phosphorus status of soil	Soils that have received more phosphorus than removed may have more available phosphorus. This may be enough to reduce current fertiliser needs.
Temperature	Warm temperatures encourage organic matter decomposition. If too hot or too cold, phosphorus uptake can be restricted. This is why crops may respond well to starter phosphorus in cold soils, even when soil phosphorus levels are high.
Other nutrients	Added nutrients can stimulate phosphorus uptake. Calcium on acid soils or ammonium-nitrogen or sulfur on acid soils increase uptake of phosphorus. Zinc fertilisation on soils with marginal phosphorus can restrict phosphorus uptake further.
Crop	Deeply rooted crops and crops infected with arbuscular mycorrhizal fungus (AMF) can have better phosphorus uptake.

Source: Australian Soil Fertility Manual (2006)

6.7.2 Phosphorus deficiency symptoms

Symptoms of phosphorus deficiency take time to develop because of initial seed reserves of phosphorus. When symptoms start to appear, phosphorus-deficient faba bean plants have smaller leaves and less growth than those with adequate phosphorus.

Phosphorus deficiency is difficult to detect visually in field crops, often because the whole paddock is affected.

Visual symptoms in faba bean and broad bean first appear on the oldest leaves as a mildly mottled chlorosis (yellowing) over much of the leaf. These symptoms could be confused with either nitrogen or sulfur deficiency, but middle and new leaves remain a healthy green so that the whole plant does not appear pale.

As symptoms on old leaves develop, round purple spots may appear within areas of dark green, in an otherwise mildly chlorotic leaf (Photo 6).[56, 57]

Photo 6: *Symptoms of phosphorus deficiency in old leaflets of faba bean. Note the spotting within darker green areas of an otherwise mildly chlorotic leaf.*

Photo: Alan Robson; Grain Legume Handbook (2008)

6.7.3 Phosphorus management

Table 11 shows the rates of phosphorus and equivalent rates of various fertilisers (each tonne of faba bean grain removes about 4 kg/ha of phosphorus).

Apply enough phosphorus to replace that removed in grain as well as soil 'tie-up' to maintain soil phosphorus levels. More is required on soils with a high buffering index such as calcareous soils.[58] If the soil phosphorus status is sufficient, there may be an opportunity for growers to save money on phosphorus fertiliser by cutting back to a maintenance rate.

Phosphorus should be applied at rates of at least 12 kg/ha, and up to 22 kg/ha, for faba bean. In Victoria, growers are advised to add 6 kg/ha of phosphorus for every tonne per hectare of faba bean grain expected to be harvested.[59] The phosphorus rate should be higher (about 15 kg/ha) on medium acid soils (pH ($CaCl_2$) 5.0 to 5.7) due to unavailability of the nutrient.[60]

Field research in Victoria and SA shows that soil salinity and sodicity can substantially reduce crop yields.[61] While faba bean is very responsive to phosphorus fertiliser, the zinc status must be adequate to achieve a phosphorus response. High phosphorus rates can induce zinc deficiency on 'black' soils with pH ($CaCl_2$) more than 8.0. High soil phosphorus levels also increase the rate of nodule growth.[62]

Most crops only recover 20–30% of the fertiliser phosphorus applied during the year of application.[63] The remainder may become available to subsequent crops over several seasons.

MORE INFORMATION

GRDC 2012 Crop nutrition Fact Sheet: Phosphorus management (southern region) www.grdc.com.au/GRDC-FS-PhosphorusManagement

VIDEO

GroundCover™ TV: Phosphorus uptake https://www.youtube.com/watch?v=qSiQlKRb9bA

56 Pulse Australia (2016) Agronomy. Southern faba and broad bean best management practices training course manual – 2016. Pulse Australia.

57 CSIRO (2006) Australian Soil Fertility Manual. 3rd edn. G Price (ed.). CSIRO Publishing.

58 T Yeatman, W Hawthorne, J Paull, J Bellati, J Egan, K Henry, R Kimber, M Seymour, J van Leur, K Lindbeck, P Matthews, I Rose (2009) Faba bean: The Ute Guide. Primary Industries and Resources South Australia, https://grdc.com.au/resources-and-publications/all-publications/publications/2009/11/faba-beans-the-ute-guide/

59 B Robinson, M Raynes (2013) Growing faba bean, Department of Environment and Primary Industries, Victoria. Agnote AG0083, http://agriculture.vic.gov.au/agriculture/grains-and-other-crops/crop-production/growing-faba-bean

60 J Carter (1999) Faba Bean and Broad Bean Growers Guide: A Guide for the Production of Faba Beans and Broad Beans. D Robey, M Raynes (eds.). Victoria Department of Natural Resources and Environment.

61 D Adcock, R Armstrong, F Best, D Chittleborough, M Imhof, G McDonald, A McNeill, J Nuttall, N Wilhelm (2009) Salinity and sodicity. Identifying, Understanding and Managing Hostile Subsoils For Cropping – A Reference Manual for Neutral-Alkaline Soils of South-Eastern Australia. The Profitable Soils Group. pp 41–50, http://vro.agriculture.vic.gov.au/dpi/vro/vrosite.nsf/pages/soil_mgmt_subsoil

62 Pulse Australia (2016) Agronomy. Southern faba and broad bean best management practices training course manual – 2016. Pulse Australia.

63 CSIRO (2006) Australian Soil Fertility Manual. 3rd edn. G Price (ed.). CSIRO Publishing.

Table 12: Granular fertiliser application rate calculator, based on phosphorus rates (all rates in kg/ha; ratios relate to the relative amounts of N:P:K:S).

Phosphorus	Some of the fertilisers used on pulses														
	Superphosphate						6 : 16 : 0 : 10 Legume special			10 : 22 : 0 MAP		18 : 20 : 0 DAP		0 : 15 : 0 : 7 Grain legume super	
	Single 8.6% P		Gold Phos 10 18% P		Triple 20% P										
	fertiliser	S	fertiliser	S	fertiliser	S	fertiliser	N	S	fertiliser	N	fertiliser	N	fertiliser	S
10	116	13	50	5	45	0.7	62	4	6	46	5	50	9	69	5
12	140	15	67	7	60	0.9	75	4	8	55	6	60	11	83	6
14	163	18	78	8	70	1.1	87	5	9	64	6	70	13	97	7
16	186	20	89	9	80	1.2	99	6	10	73	7	80	14	110	8
18	209	23	100	10	90	1.4	112	6	11	82	8	90	16	124	9
20	223	25	111	11	100	1.5	124	7	12	91	9	100	18	138	10
22	256	28	122	12	110	1.7	137	8	14	100	10	110	20	152	11
24	279	31	133	13	120	1.8	149	8	15	110	11	120	22	166	12

Source: GRDC (2014)

Birchip Cropping Group trials in Victoria's Wimmera and southern Mallee between 1999 and 2001 found yield responses in faba bean to phosphorus rates up to 18 kg/ha, even in sites with a Colwell P soil test result of 15 ppm or more. In contrast, wheat, barley, canola, lentil and field pea did not respond at sites with a good fertiliser history.[64]

Research in south-western Australia showed that phosphorus application can increase the number of faba bean pods per plant to boost yield by 50–100% on deficient soils. Phosphorus (or zinc) fertiliser did not affect the numbers of seeds per pod and seed weight.[65]

The availability of phosphorus to plants varies with the source of the nutrient. In Australian broadacre organic farming systems, superphosphate fertiliser is not permitted and low soil phosphorus availability commonly limits yield. A comparison of superphosphate with rock phosphate and poultry manure in pulses showed major differences in phosphorus use efficiency between the fertilisers in glasshouse trials, using the equivalent of 50 kg/ha of each fertiliser. Phosphorus uptake in faba bean and field pea grown, in both acidic sandy loam and alkaline clay, was very low (0–1.3%) for rock phosphate, which is sparingly soluble. In contrast, phosphorus uptake ranged from 1.8–12.7% for poultry manure and 6.1–9% for single superphosphate.[66]

Liquid phosphorus uses an efficient and flexible delivery method, but it has the disadvantages of requiring a separate delivery system and being expensive compared with granular phosphorus.

However, the benefits in crop production outweigh the extra expense only on highly calcareous soils and a small number of other cropping areas in southern Australia.[67]

64 BCG (2002) Optimising phosphorus fertiliser rates on alkaline soils. 2001/02 Crop and Pasture Production Manual. Birchip Cropping Group, www.farmtrials.com.au

65 M Bolland, K Siddique, R Brennan (2000) Grain yield responses of faba bean (*Vicia faba* L.) to applications of fertiliser phosphorus and zinc. Australian Journal of Experimental Agriculture 40(6). pp 849–857, www.publish.csiro.au/paper/EA99164.htm

66 G Nachimuthu, P Lockwood, C Guppy, P Kristiansen (2009) Phosphorus uptake in faba bean, field pea, and corn cultivars from different sources: preliminary studies of two options for organic farmers. Crop and Pasture Science 60(2). pp 183–189, https://e-publications.une.edu.au/vital/access/manager/Repository/une:4500

67 GRDC (2012) Crop nutrition fact sheet: Phosphorus management (southern region). Grains Research and Development Corporation, www.grdc.com.au/GRDC-FS-PhosphorusManagement

Australian researchers have shown variation between different faba bean genotypes (varieties) in their ability to use phosphorus efficiently. In alkaline soil, roots of the most phosphorus-efficient varieties exuded more of an organic compound called malate, which may increase the solubility of soil phosphorus, making it more available to the plant.[68]

6.7.4 Fertiliser placement and fertiliser toxicity

In recent years, Australian researchers have recommended fertilising the subsoil (10–30 cm depth) with phosphorus before sowing faba bean to maximise phosphorus use efficiency. They showed that faba bean responds to extractable subsoil phosphorus concentrations when measuring dry matter production and phosphorus concentration in plant tissue.[69] This is similar to the recommendation for lupin, where deep banding of fertiliser is often preferred as the crop is particularly sensitive to toxic concentrations of fertiliser during establishment and nodulation. Otherwise, growers can broadcast and incorporate, pre-drill or split fertiliser applications so that lower rates or no phosphorus is in contact with the seed.

All pulses can be affected by fertiliser toxicity. Ideally, fertilisers should be banded below or to the side of the seed at sowing. Drilling 10 kg/ha of phosphorus with the seed in 18 cm rows using 10 cm points rarely causes problems.

The use of starter nitrogen such as DAP, banded with the seed has the potential to reduce establishment and nodulation if higher rates are used. On sands, up to 10 kg/ha of nitrogen in 18 cm row spacing can be safely used. On clay soils, do not exceed 20 kg/ha of nitrogen in 18 cm row spacing.

However, the risk of fertiliser toxicity is higher with narrow sowing points or disc seeders with minimal soil disturbance, as well as wider row spacing. These techniques concentrate the fertiliser near the seed in the seeding furrow.

Fertiliser toxicity effects are greater in highly acidic soils, sandy soils and in drier soils at sowing.

Drilling concentrated fertilisers to reduce the product rate per hectare does not reduce the risk of fertiliser toxicity.[70]

6.7.5 AMF: arbuscular mycorrhizae fungi effects on phosphorus and zinc

Some soil fungi form a mutually beneficial relationship with plant roots to help plants more efficiently absorb nutrients such as phosphorus and zinc from soil and fertiliser. They are known as arbuscular mycorrhizal fungi (AMF), previously known as vesicular arbuscular mycorrhiza (VAM).

AMF colonise and build up on the faba bean and broad bean root system. The fungi produce filaments (hyphae) that colonise the root and then grow into the soil, much further than root hairs. Phosphorus and zinc are taken up by the hyphae and transported back for use by the plant.

Many crop species require only half the phosphate concentration in soil when they are colonised by AMF as they do without AMF for the same level of production.

Crops such as faba bean, chickpea, safflower and linseed have a high AMF dependency and promote its accumulation. AMF levels can be severely reduced by long periods of fallow, such as those induced by drought, or the growth of non-host crops. Winter cereals and field pea are less AMF-dependent but do allow AMF to

68 T Rose, P Damon, Z Rengel (2010) Phosphorus-efficient faba bean (*Vicia faba* L.) genotypes enhance subsequent wheat crop growth in an acid and an alkaline soil. Crop and Pasture Science 61(12). pp 1009–1016, http://epubs.scu.edu.au/plantscience_pubs/165/

69 T McLaren, M Bell, I Rochester, C Guppy, M Tighe, R Flavel (2013) Growth and phosphorus uptake of faba bean and cotton are related to Colwell-P concentrations in the subsoil of Vertosols. Crop & Pasture Science. 64. pp 825–833, http://www.publish.csiro.au/?act=view_file&file_id=CP13025.pdf

70 Pulse Australia (2016) Agronomy. Southern faba and broad bean best management practices training course manual – 2016. Pulse Australia.

MORE INFORMATION

Feri-tech SeedEnhancer VAM™, http://www.fertitech.com/site/DefaultSite/filesystem/documents/FTA%20Ferti%20Seed%20Enhancer%20VAM.pdf

build up. Canola, lupin and extended fallow do not host AMF, so AMF levels are reduced under these crops in rotation.

AMF can be important in faba bean and broad bean production and fertiliser responses. Faba bean and broad bean are considered to have a high crop requirement for phosphorus, and economic fertiliser responses to phosphorus are common.

Uptake of phosphorus can become far less efficient in winter crops with:

- soils with critically low phosphorus levels (below 6 mg/kg) and no history of phosphorus fertiliser application; and
- long fallow situations with low VAM levels (10 months or longer).

AMF products are commercially available as seed treatments, often in association with other seed enhancers that in combination can give the most potent means to ensure a highly successful AMF spore inoculation.

Where soil AMF levels are moderate to high, consistent responses to applied phosphate fertiliser are more likely where soil bicarbonate phosphorus levels fall below 6 mg/kg and are critically low. Double-cropped paddocks or short, 6-month fallows from wheat are more likely to have moderate to high AMF levels.

AMF levels become depleted with long fallows (more than 8–12 months) or after crops such as canola or lupin, which do not host AMF growth. In low-AMF situations, faba bean and broad bean can be very responsive to applied phosphorus and zinc and show a marked growth response to starter fertilisers, which may improve yield.[71] [72]

6.8 Potassium

6.8.1 Occurrence of potassium deficiency

As most Australian soils have ample potassium levels, it is feasible for growers to gradually use up some of the soil potassium before needing to replace it. Most clay soils have sufficient reserves of potassium to grow many crops. However, potassium deficiency has been confirmed in SA in grain-cropping regions. As potassium reserves are drawn down with higher yields, potassium replacement may need to be more widely addressed.

Potassium concentration in the stubble of both canola and wheat is higher than in the grain. Research in Canada has shown if the stubble is burnt, 30–40% of this potassium will be lost from the system.[73] If the stubble is retained, much of the potassium will be recycled through the topsoil and, unless the straw is spread, can accumulate under the windrows.[74]

6.8.2 Potassium deficiency symptoms

The older (lower) leave show symptoms of potassium deficiency first. Initially growth is stunted compared with other parts of the paddock with soil of higher potassium levels (for example, in old stubble rows). Older leaves show a slight curling and then a distinct black to grey colour on leaf margins, eventually shrivelling and dying (Photos 7, 8, 9, 10 and 11).[75] Lower leaves may also cup with some purple blotches.[76]

71 Pulse Australia (2016) Agronomy. Southern faba and broad bean best management practices training course manual – 2016. Pulse Australia.

72 N Seymour (2009) Mycorrhizae and their influence on P nutrition. Australian Grain July–August 2009. pp 23–24, http://www.ausgrain.com.au/Back%20Issues/192jagrn09/23_Mycorrhizae.pdf

73 J Heard, C Cavers, G Adrian (2006) Up in smoke – nutrient loss with straw burning. Better Crops 90(3). pp 10–11, www.ppi-ppic.org/ppiweb/bcrops.nsf/$webindex/896A64C047EA4DE5852571B1006A5BF1/$file/06-3p10.pdf

74 R Norton (2014) Do we need to revisit potassium? GRDC Update Paper 25 February 2014, https://grdc.com.au/Research-and-Development/GRDC-Update-Papers/2014/02/Do-we-need-to-revisit-potassium

75 M Wurst, W Hawthorne, A Nikandrow, M Ramsey, T Bretag, J Davidson, R Gilbert, W MacLeod, G Murray, K Panagiotopoulos, M Schwinghamer (2002) Winter Pulse Disorders: The Ute Guide. Primary Industries and Resources South Australia.

76 T Yeatman, W Hawthorne, J Paull, J Bellati, J Egan, K Henry, R Kimber, M Seymour, J van Leur, K Lindbeck, P Matthews, I Rose (2009) Faba bean: The Ute Guide. Primary Industries and Resources South Australia, https://grdc.com.au/resources-and-publications/all-publications/publications/2009/11/faba-beans-the-ute-guide/

The first evidence of potassium deficiency can be observed as poor good growth outside of old header windrows.[77]

Faba bean appear to be more susceptible to potassium deficiency compared with other pulses such as field pea and lupin.

Photo 7: *Potassium deficiency in faba bean. Note the necrosis (dead tissue) of leaf margins and purple blotches.*

Photo: Grain Legume Handbook

Photo 8: *Potassium deficiency in faba bean (left and middle plants), alongside a plant with adequate potassium. Plants were taken from the same paddock but the healthy plant was grown in a windrow of cereal stubble deposited by a harvester.*

Photo: Wayne Hawthorne, formerly Pulse Australia

77 R Norton (2014) Do we need to revisit potassium? GRDC Update Paper 25 February 2014, https://grdc.com.au/Research-and-Development/GRDC-Update-Papers/2014/02/Do-we-need-to-revisit-potassium

Photo 9: *Potassium deficiency in single faba bean leaflet.*

Photo: Alan Robson; Grain Legume Handbook (2008)

Photo 10: *Potassium deficiency in a faba bean crop showing loss of lower leaves and poorer height and vigour than healthy plants in the same paddock growing in header windrows of canola stubble.*

Photo: Wayne Hawthorne, formerly Pulse Australia

Photo 11: *Faba bean with adequate potassium. Here, plants show better height and vigour in header windrows of canola stubble.*

Photo: Wayne Hawthorne, formerly Pulse Australia

6.8.3 Potassium management

Some Australian cropping soils (usually white sandy soils) respond to potassium and applications may be needed to replace the potassium removed by the crop. Such soils with low or marginal levels of potassium (<50 mg/kg using the bicarbonate, or Colwell K soil test) may respond to applications of potassium fertiliser. When using the ammonium acetate soil test, fertiliser responses are likely where potassium levels fall below:

- 0.25 cmol (+)/kg (milliequivalents/100g) on black earths and grey clays; or
- 0.40 cmol (+)/kg on red earths and sandy soils.

Soil tests for potassium are reliable on sandy soils but less so on heavy soils.

Economic responses to 50–100 kg potassium/ha banded below the seed at sowing are likely where soil tests are below critical concentrations.[78]

For most annual crops, it is usual to apply all the potassium fertiliser at, or before, sowing; the application may be split in highly leaching soils with low nutrient-holding capacity (cation exchange capacity), such as sands. A more specific recommendation for faba bean is to apply potassium fertiliser 6–8 weeks after sowing. Widely used potassium fertilisers are shown in Table 12 (alternatively, consider a blend such as Crop King® 55[79]).

78 R Norton (2014) Do we need to revisit potassium? GRDC Update Paper 25 February 2014, https://grdc.com.au/Research-and-Development/GRDC-Update-Papers/2014/02/Do-we-need-to-revisit-potassium

79 Pulse Australia (2016) Agronomy. Southern faba and broad bean best management practices training course manual – 2016. Pulse Australia.

Table 13: Composition of common potassium fertilisers (as percentages).

Fertiliser	Potassium	Magnesium	Sulfur	Nitrogen	Chloride
Muriate of potash	50	–	–	–	46
Sulfate of potash	40–41.5	–	16–17	–	–
Potassium-manganese sulfate	18	11	22	–	–
Potassium thiosulfate	38	–	–	13	–
Potassium nitrate	30	–25	–	–	–

Source: CSIRO (2006) Australian Soil Fertility Manual

The addition of clay or organic matter to sandy soils can increase the capacity of soils to hold nutrients, including potassium.[80]

Responses to potassium are unlikely on most black earths and grey clays. Potassium fertilisers may be warranted on red earths but should be based on soil analysis.

Where soil test levels are critically low, apply 20–40 kg potassium/ha banded 5 cm to the side of, and below the seed row.

Alternatively, consider blends such as Crop King® 55 (13% nitrogen, 13% phosphorus, 13% potassium) at 80–120 kg/ha, where potassium levels are marginal.

6.9 Sulfur

While most other pulse crops remove more sulfur per tonne of grain than cereals, faba bean, like wheat, removes about 1.5 kg/ha of sulfur with each tonne of grain harvested.

6.9.1 Occurrence of sulfur deficiency

Infertile soils such as deep sands and those low in organic matter are more likely to experience sulfur deficiency, particularly in wet seasons. Basaltic, black earths are also prone to sulfur deficiency. Sulfur deficiency is most likely to occur with double-cropping, where available sulfur becomes depleted.

6.9.2 Sulfur deficiency symptoms

Youngest leaves of sulfur-deficient faba bean turn yellow (chlorosis) and plants are slender and small. Chlorosis of leaf edges can progress to necrosis within those chlorotic areas (Photo 11).

80 T Yeatman, W Hawthorne, J Paull, J Bellati, J Egan, K Henry, R Kimber, M Seymour, J van Leur, K Lindbeck, P Matthews, I Rose (2009) Faba bean: The Ute Guide. Primary Industries and Resources South Australia, https://grdc.com.au/resources-and-publications/all-publications/publications/2009/11/faba-beans-the-ute-guide/

Photo 12: *Sulfur deficiency in faba bean shows up as chlorosis (yellowing) of leaf edges (left) and can progress to necrosis (dead tissue) within those chlorotic areas (right).*

Photo: Alan Robson; Grain Legume Handbook (2008)

6.9.3 Sulfur management

Soil sampling to 60 cm is recommended for sulfur tests. A fertiliser response is likely if available sulfate is below 5 mg/kg (KCl-40 test). The level is critically low if less than 3 mg/kg.

Applying 5–10 kg/ha of sulfur will normally correct a sulfur deficiency. A low rate of gypsum is the most cost-effective long-term method of correcting sulfur deficiency where soil phosphate levels are adequate.

Often, a sulfur-fortified fertiliser is applied to pulse crops (Table 11). The 'grain legume' fertilisers provide a good supply of sulfur. However, if the paddock has a good history of single superphosphate, sulfur levels may be adequate, particularly on heavy clay soils. Where double or triple superphosphate has been used over severaL years, the sulfur level in the soil may be inadequate for faba bean.[81 82 83]

MORE INFORMATION

GRDC 2013 Crop nutrition Fact Sheet: micronutrients
www.grdc.com.au/GRDC-FS-CropNutrition-Micronutrients

MORE INFORMATION

GRDC 2014 Crop nutrition Fact Sheet: Soil testing for crop nutrition (southern region)
www.grdc.com.au/GRDC-FS-SoilTestingS

6.10 Micronutrients (trace elements)

Micronutrients are those elements that plants need in small amounts, for example iron (Fe), boron (B), manganese (Mn), zinc (Zn), copper (Cu), chlorine (Cl), and molybdenum (Mo).[84] The difference between deficient and adequate (or toxic) levels of some micronutrients can be very small.

Micronutrient deficiencies are best determined by looking at the overall situation: region, soil type, season, crop type and past fertiliser management.

The most likely limiting micronutrients in Australian cropping systems are zinc, boron, copper, manganese and molybdenum. Iron can also be important, especially on strongly alkaline soils. Other micronutrients are important for particular plants in particular situations. Zinc deficiency is a major risk on soil types across all Australian cropping regions. Copper deficiency is also a concern but is less widespread. Pulses are more susceptible to deficiencies of iron, boron, manganese and molybedenum. Micronutrient toxicity and deficiency symptoms of faba bean are listed in Section 6.5 Nutrient disorders.

Soil type is useful in estimating the risk of micronutrient deficiencies. Definitions of soil types can be found in the GRDC Crop nutrition Fact Sheet 'Soil testing for crop nutrition (southern region)' (www.grdc.com.au/GRDC-FS-SoilTestingS). Based on the soil properties, crop are most likely to be at risk of deficiency on particular soils, as follows:

81 Pulse Australia (2016) Agronomy. Southern faba and broad bean best management practices training course manual – 2016. Pulse Australia.

82 GRDC (2014) Crop nutrition fact sheet: Soil testing for crop nutrition (southern region). Grains Research and Development Corporation, www.grdc.com.au/GRDC-FS-SoilTestingS

83 J Carter (1999) Faba Bean and Broad Bean Growers Guide: A Guide for the Production of Faba Beans and Broad Beans. D Robey, M Raynes (eds.). Victoria Department of Natural Resources and Environment.

84 Queensland DAF Queensland (2010) Nutrition management. Overview. Queensland Department of Agriculture and Fisheries Queensland, 1 October 2010, https://www.daf.qld.gov.au/plants/field-crops-and-pastures/broadacre-field-crops/nutrition-management/overview

- boron deficiency on kurosols, podosols and tenosols;
- copper deficiency on kurosols;
- manganese deficiency on calcarosols;
- molybdenum deficiency on kurosols, podosols and tenosols; and
- zinc deficiency on calcarosols.[85]

In the southern region, calcarosols, sodosols and vertosols have a high risk of zinc deficiency. Manganese deficiency is likely to be a significant risk on soils with more than 60% free calcium carbonate.[86]

Growers can learn about likely soil types on their property with CSIRO's iPad app SoilMapp (https://www.csiro.au/en/Research/AF/Areas/Sustainable-farming/Decision-support-tools/SoilMapp).

Soil pH has an important effect on the availability of micronutrients to plants. Zinc, iron, boron, manganese and copper become less available as the pH increases (more alkaline), while molybdenum (and aluminium) become more available as soils become more alkaline.[87]

6.10.1 Micronutrient application

Traditionally, micronutrient treatment in crops first involved diagnosis of deficiencies and then treatment using solid fertilisers or foliar sprays.

For foliar applications to be effective, a large plant leaf area is required to absorb the product. Multiple applications may be necessary if applying to seedlings.

Growers may apply micronutrients as 'insurance' against possible deficiencies. Rates are generally much lower but will only have economic value if they prevent a deficiency.

Recent changes to micronutrient application include spraying micronutrients into the soil near seed rows in no-till systems. Liquid in-furrow application to the soil offers some advantages with immobile micronutrients (such as copper and zinc), as the distribution in the soil will be better over several years than conventional products. Depending on the soil type, annual applications may not be needed. Growers must take care to avoid germination effects on seeds when applying trace elements this way.

Another new trend is the application of immobile micronutrients to deeper layers of the soil, particularly where infertile A2 (lower topsoil) layers are present. Some sites are showing promising results using this approach.

For nutrients with low residual activity or where soils are likely to strongly bind micronutrients, annual or tactical in-furrow or in-crop foliar applications may be best.

Post-harvest grain nutrient testing can be used to support management decisions but will not provide a conclusive guide to the risk of micronutrient deficiency.

When applying fertiliser to treat a suspected deficiency, leave a strip untreated. Either a visual response or tissue testing can allow you to confirm whether the micronutrient was limiting.[88 89]

85 R Norton (2013) More profit from crop nutrition: micronutrient survey. A scoping study to develop a risk assessment for micronutrient deficiency in the grains industry. Final Project Report. Grains Research and Development Corporation, http://research.ipni.net/page/RANZ-2419

86 GRDC (2013) Crop nutrition fact sheet: Micronutrients (northern, southern and western regions). Grains Research and Development Corporation, www.grdc.com.au/GRDC-FS-CropNutrition-Micronutrients

87 CSIRO (2006) Australian Soil Fertility Manual. 3rd edn. G Price (ed.). CSIRO Publishing.

88 B Hughes (2012) Trace elements in the South East fact sheet. Natural Resources South East, www.naturalresources.sa.gov.au/southeast/land/soil-management/South-East-Soil-Issues

89 GRDC (2013) Crop nutrition fact sheet: Micronutrients (northern, southern and western regions). Grains Research and Development Corporation, www.grdc.com.au/GRDC-FS-CropNutrition-Micronutrients

6.10.2 Zinc

Zinc deficiency occurs mostly on highly alkaline soils, very infertile sand and soils with a low zinc fertiliser history. Zinc deficiency in faba bean can be exacerbated by a reaction with herbicide application or residues.[90]

While faba bean can be very responsive to zinc, phosphorus status must be adequate to achieve a response – and vice versa. However, high phosphorus rates can induce zinc deficiency on 'black' soils with pH ($CaCl_2$) of more than 8.0.

Zinc deficiency symptoms

Zinc-deficient faba bean plants are small. The stunted plants have pale green leaves. The areas between veins become mottled yellow, which is worse on the lowest leaves. Middle to lower leaves can have red-brown or pink-brown spots.[91] The top leaves are often smaller, while the older leaves may be wilted and distorted. Maturity may be delayed (Photos 13, 14, 15 and 16).

Photo 13: *Zinc deficiency in faba bean.*

Photo: Grain Legume Handbook (2008)

90 T Yeatman, W Hawthorne, J Paull, J Bellati, J Egan, K Henry, R Kimber, M Seymour, J van Leur, K Lindbeck, P Matthews, I Rose (2009) Faba bean: The Ute Guide. Primary Industries and Resources South Australia, https://grdc.com.au/resources-and-publications/all-publications/publications/2009/11/faba-beans-the-ute-guide/

91 M Wurst, W Hawthorne, A Nikandrow, M Ramsey, T Bretag, J Davidson, R Gilbert, W MacLeod, G Murray, K Panagiotopoulos, M Schwinghamer (2002) Winter Pulse Disorders: The Ute Guide. Primary Industries and Resources South Australia.

Photo 14: *Zinc-deficient faba bean (left) compared with faba bean grown with adequate zinc applied as solid fertiliser at sowing or early foliar application (right).*

Photo: Grain Legume Handbook

Photo 15: *Zinc-deficient middle leaves of faba bean (right).*

Photo: Alan Robson; Grain Legume Handbook (2008)

Photo 16: *Zinc-deficient leaves of faba bean, (from left) oldest to youngest.*

Photo: Alan Robson; Grain Legume Handbook (2008)

AMF can be extremely important to the zinc nutrition in faba bean, and responses can be expected in situations where AMF levels have become depleted due to long fallows (8–10 months) (see Section 6.7.5 AMF: arbuscular mycorrhizae fungi effects on phosphorus and zinc for more information).

Zinc management

Faba bean has a relatively high demand for zinc, but has evolved highly efficient mechanisms for extracting zinc from the soil.

Leaf tissue testing will determine the plant's zinc status at sampling.[92] Critical values for zinc levels in plant tissue test are shown in Table 5.

Research on zinc responses in faba bean is limited. Fertiliser recommendations are based on a general recommendation used for all crops where DTPA analysis of soil samples in the top 10 cm shows zinc levels:

- below 0.8 mg/kg on alkaline soils; or
- below 0.3 mg/kg on acid soils.

Zinc application is generally advisable for growing faba bean on alkaline soils.

Zinc is usually applied with the fertiliser at sowing or as a foliar spray. Zinc should be applied to the soil every 2–7 years, depending on soil type.

The best method is to spray the zinc onto the soil surface and incorporate by cultivation or use zinc-coated granule fertiliser formulation.[93]

A replicated trial at Rupanyup, in the Victorian Wimmera, in 2001 found no difference in faba bean yields when comparing zinc applied as granular fertiliser, seed dressing or foliar solution – as well as no zinc. This was at a site where zinc had previously been applied in 2 of the previous 5 years. The researchers recommended that granular zinc be applied every 3–4 years in the Victorian Wimmera and Mallee to avoid over-fertilisation, rather than every time a pulse is sown. They also recommended the use of zinc seed dressings or foliar applications only as a 'last resort', to overcome a deficiency in the year it is applied.[94]

Solid zinc fertiliser treatments

Zinc can be applied before sowing or during sowing.

92 T Yeatman, W Hawthorne, J Paull, J Bellati, J Egan, K Henry, R Kimber, M Seymour, J van Leur, K Lindbeck, P Matthews, I Rose (2009) Faba bean: The Ute Guide. Primary Industries and Resources South Australia, https://grdc.com.au/resources-and-publications/all-publications/publications/2009/11/faba-beans-the-ute-guide/

93 J Carter (1999) Faba Bean and Broad Bean Growers Guide: A Guide for the Production of Faba Beans and Broad Beans. D Robey, M Raynes (eds.). Victoria Department of Natural Resources and Environment.

94 BCG (2002) Is zinc required every time you sow a crop? Birchip Cropping Group 2001 Research Manual. Birchip Cropping Group, www.farmtrials.com.au

Zinc (and copper) is not mobile in the soil. When applying solid fertiliser, good physical distribution through the soil profile or topsoil is important to ensure roots interact with it. Unlike foliar sprays, solid fertilisers generally provide residual value.

Severe zinc deficiency can be corrected before sowing for 5–8 years with a soil application of 15–20 kg/ha zinc sulfate monohydrate, cultivated into the soil three to four months before sowing (Table 13).

In the first year after application, the pre-sowing soil-applied zinc sulfate monohydrate may not be fully effective and a foliar zinc spray may also be required.

Zinc can also be applied at sowing with a range of phosphate-based fertilisers that contain, or are blended with, a zinc additive.

While cultivation distributes zinc (and copper) through the topsoil, no-till and one-pass sowing equipment provide less physical distribution. Smaller granules of fertiliser, more of them and better placement, will be more effective than a fertiliser with larger granules, even if it is more concentrated.[95 96]

Table 14: Rates of zinc (g/ha) to correct deficiencies in pastures and cereals. (Note: faba bean has a higher demand for copper and zinc than cereals, see Table 1.)

Fertiliser type	Situation	Zinc (g/ha to apply)
Foliar	Confirmed deficiency	330
	'Insurance'	110
Soil-applied	Confirmed deficiency	2,000–2,500
	'Insurance'	500–2,000

Source: Hughes (2012)

Foliar zinc sprays

Foliar application of zinc is common, often fitting in with herbicide or early fungicide applications.[97] Foliar applications of trace elements can cause leaf burning.

A mild zinc deficiency will be corrected with a foliar spray of 1.0 kg/ha zinc sulfate heptahydrate plus 1.0 kg/ha urea with 1,200 mL of a 1,000 g/L non-ionic wetter in at least 100 L water/ha. One to two sprays should be applied within 6–8 weeks of emergence.

Hard water (high in carbonate) will produce an insoluble sediment (zinc carbonate) when the zinc sulfate is dissolved, with the spray mix turning cloudy. Use a buffer – such as L1-700 or Agri-Buffa – if only hard water is available. Zinc oxide products are highly alkaline with a pH of 9.5–10.5.

Zinc seed treatments

Zinc seed treatments may be a cost-effective option in situations where soil phosphorus levels are adequate but zinc is likely to be deficient.

Agrichem Broadacre Zinc® contains 650 g/L of zinc and is applied at 4 L of product per tonne of seed. Pre-mix with 1 L of water before application.

Apply Broadacre Zinc® and then allowed to dry before applying the inoculum, to minimise any damaging effect on rhizobia.

Broadacre Zinc® is compatible with either Thiraflo® or P-Pickel T®; the two products can be mixed to treat faba bean seed in one operation if needed.

95 GRDC (2013) Crop nutrition fact sheet: Micronutrients (northern, southern and western regions). Grains Research and Development Corporation, www.grdc.com.au/GRDC-FS-CropNutrition-Micronutrients

96 J Carter (1999) Faba Bean and Broad Bean Growers Guide: A Guide for the Production of Faba Beans and Broad Beans. D Robey, M Raynes (eds.). Victoria Department of Natural Resources and Environment.

97 Pulse Australia (2016) Agronomy. Southern faba and broad bean best management practices training course manual – 2016. Pulse Australia.

Teprosyn® Zn (Phosyn) contains 600 g/L of zinc and is applied at 4 L of product per tonne of seed. Pre-mix with 2–3 L of water to assist coverage. Apply inoculum first and allow to dry before applying the Teprosyn®.[98]

6.10.3 Iron

Occurrence of iron deficiency

Iron deficiency is usually observed on alkaline soils with high lime content in cold and wet conditions. It is usually associated with waterlogging after heavy rainfall or irrigation, which interferes with iron absorption and translocation (movement) into the foliage. Iron deficiency in faba bean is often worse in compacted areas, such as wheel tracks (Photo 16).

Plants often recover from iron deficiency as conditions become warmer.

Iron deficiency symptoms

Iron deficiency often appears in young plants. As iron is highly immobile in plants, symptoms may show up in youngest leaves first. Symptoms include a general yellowing of young leaves and poor growth. New leaves and young growth of faba bean may be small and unfolded or barely opened. The chlorotic (yellow) leaves roll along their margins. Symptoms can also include yellowing between leaf veins. Stems become yellow and shortened. Deficiency spreads to older leaves and young growth stops; it can progress to completely yellow plants.

In severe cases, young leaves become distorted, with necrosis (dead tissue) and shedding of terminal (top) leaflets. The leaf tips of severely deficient plants may die.

Iron deficiency symptoms tend to be very transient, with the crop making a rapid recovery once the soil begins to dry out. New growth can recover but symptoms are apparent on the remaining young leaves.

Iron deficiency can be confused with manganese and magnesium deficiency. Contrast in colour between old and new leaves is much stronger with iron deficiency compared with manganese deficiency.

Faba bean varieties show a marked difference in sensitivity to iron chlorosis (yellowing), and major problems with iron deficiency have largely been overcome through the efforts of plant breeders. The broad bean variety Aquadulce is more tolerant of iron deficiency than many faba bean varieties (Photo 17).[99 100 101]

98 Pulse Australia (2016) Agronomy. Southern faba and broad bean best management practices training course manual – 2016. Pulse Australia.

99 Pulse Australia (2016) Agronomy. Southern faba and broad bean best management practices training course manual – 2016. Pulse Australia.

100 T Yeatman, W Hawthorne, J Paull, J Bellati, J Egan, K Henry, R Kimber, M Seymour, J van Leur, K Lindbeck, P Matthews, I Rose (2009) Faba bean: The Ute Guide. Primary Industries and Resources South Australia, https://grdc.com.au/resources-and-publications/all-publications/publications/2009/11/faba-beans-the-ute-guide/

101 M Wurst, W Hawthorne, A Nikandrow, M Ramsey, T Bretag, J Davidson, R Gilbert, W MacLeod, G Murray, K Panagiotopoulos, M Schwinghamer (2002) Winter Pulse Disorders: The Ute Guide. Primary Industries and Resources South Australia.

Photo 17: *Iron deficiency visible in a faba bean crop in wheel tracks. This disorder is often worse in compacted soils.*

Photo: Wayne Hawthorne, formerly Pulse Australia

Photo 18: *Faba bean varieties have different tolerances to iron deficiency. The variety Aquadulce (between the pegs) is more tolerant (but not immune) compared with many other faba bean varieties.*

Photo: Wayne Hawthorne, formerly Pulse Australia

Iron management

An iron deficiency may be corrected with a foliar spray of iron.[102]

As iron deficiency may be transient, foliar iron applications may not necessarily be absorbed into the leaves if symptoms are severe.

102 Queensland DAF (2010) Nutrition management. Overview. Queensland Department of Agriculture and Fisheries, 1 October 2010, https://www.daf.qld.gov.au/plants/field-crops-and-pastures/broadacre-field-crops/nutrition-management/overview

6.10.4 Manganese deficiency

Occurrence of manganese deficiency

Manganese deficiency tends to be found on highly alkaline, calcareous soils. It is common in faba bean in the south-east of SA. It is usually associated with dry, loose ('fluffy') soils; wheel tracks or rolled areas may appear healthy while other parts of the paddock show manganese deficiency.

On acidic soils, well-nodulated faba bean crops grown can experience manganese toxicity (see Section 6.5.2 Nutrient toxicity for more information).

Manganese deficiency symptoms

Symptoms of manganese deficiency in faba bean first appear in new leaves, which show mild chlorosis (yellowing) due to a lack of chlorophyll in the leaves. This is followed by small dead spots or purple spotting at each side of the mid-rib and lateral veins of fully and partially opened new leaves and unopened leaves. Many affected new leaves become distorted, as if the margins are growing at different rates, causing twisted leaves. The leaves may turn yellow and die.

Manganese deficiency of faba bean late in the season may lead to discolouration, splitting and deformity of the grain; it can be hollow or have a cavity in its centre (called 'Marsh spot').

Symptoms may vary between plants. While some plants may have only a few brown spots on unopened new growth, for other plants, symptoms may extend to middle leaves and range from blackened tops of leaves and new growth to purple necrosis (dead tissues) over much of the leaf (Photos 19, 20, 21 and 22).[103 104 105 106]

Photo 19: *New, opening leaves of manganese-deficient faba bean (right), compared with healthy leaves (left).*

Photo: Alan Robson; Grain Legume Handbook (2008)

103 Pulse Australia (2016) Agronomy. Southern faba and broad bean best management practices training course manual – 2016. Pulse Australia.

104 T Yeatman, W Hawthorne, J Paull, J Bellati, J Egan, K Henry, R Kimber, M Seymour, J van Leur, K Lindbeck, P Matthews, I Rose (2009) Faba bean: The Ute Guide. Primary Industries and Resources South Australia, https://grdc.com.au/resources-and-publications/all-publications/publications/2009/11/faba-beans-the-ute-guide/

105 M Wurst, W Hawthorne, A Nikandrow, M Ramsey, T Bretag, J Davidson, R Gilbert, W MacLeod, G Murray, K Panagiotopoulos, M Schwinghamer (2002) Winter Pulse Disorders: The Ute Guide. Primary Industries and Resources South Australia.

106 F Salisbury, C Ross (1985) Mineral nutrition. Plant Physiology. 3rd edn. Wadsworth, Inc.

Photo 20: *New growth of manganese-deficient faba bean.*

Photo: Alan Robson; Grain Legume Handbook (2008)

Photo 21: *Middle leaf of manganese-deficient faba bean.*

Photo: Alan Robson; Grain Legume Handbook (2008)

Photo 22: *Middle leaves of manganese-deficient faba bean (right), compared with healthy leaves (left).*

Photo: Alan Robson; Grain Legume Handbook (2008)

Manganese management

Apply manganese at sowing in the fertiliser, by liquid injection, on the seed, or as a foliar application.

Table 15: Rates of manganese (g/ha) to correct deficiencies in pastures and cereals. (Note: faba bean has a lower demand for manganese than cereals, see Table 1 for details.)

Fertiliser type	Situation	Manganese (g/ha to apply)
Foliar	Confirmed deficiency	1,000
	'Insurance'	500
Soil-applied	Confirmed deficiency	3,000–5,000
	'Insurance'	Not applicable

Source: Hughes (2012)

6.10.5 Copper

Occurrence of copper deficiency

In southern Australia, copper deficiency is most common in sandy soils low in organic matter. Organic soils are also commonly copper deficient. While these soils usually contain reasonable amounts of copper, they hold it so tightly that only small amounts are available to the crop.

While heavy, clay soils are least likely to be copper deficient, grain crops grown on calcareous, alkaline soils in SA at risk of copper deficiency, regardless of texture.

Copper deficiency may also be included in some situations by land-forming operations where the surface soil is removed (for example, for flood irrigation layout). Zinc deficiency can also be brought about this way.

Excessive – but not moderate – liming and the presence of high concentrations of metals in the soil can induce copper deficiency in crops by affecting the availability of copper to plants. Such metals include iron, manganese and aluminium.

Copper is necessary for chlorophyll formation and catalyses several other plant reactions.

It has a role in cell wall constituents of plants, so plants with adequate copper are more resistant to fungal attack.

Copper deficiency symptoms

Copper deficiency does not appear until flowering, so vegetative growth is not particularly affected.

The first symptom of copper deficiency in faba bean is a wilting and rolling of the leaflet ends of fully opened leaves. Wilting is followed by incomplete opening of new leaflets, which in some cases appear puckered and kinked over towards the leaf ends (Photo 23). If deficiency is severe, wilting of fully formed leaves develops into a 'withertip' (Photo 24). Tips of each leaflet become pale green with a dried appearance, and then become twisted and necrotic (dead tissues).

Although flowering is not delayed in faba bean with copper deficiency, in contrast to field pea, few pods and seeds form. Flowers appear quite normal.

Photo 23: *New leaves of copper-deficient faba bean showing 'withertop'.*

Photo: Alan Robson; Grain Legume Handbook (2008)

Photo 24: *Fully opened leaves of copper-deficient faba bean showing 'withertop'.*

Photo: Alan Robson; Grain Legume Handbook (2008)

Management

Copper deficiency can be corrected by soil or foliar application. Copper sulfate is the most common form of copper fertiliser, but copper chelate and copper oxide can also be used.

In crops, copper can be applied to the soil at 2 kg/ha, which can be expected to last five years. Copper is not readily leached and applied copper may have long to very long residual availability of more than 15 years.

Foliar sprays of copper sulfate can also be effective. For pulses, this can be applied 3–5 weeks after emergence (using 2% with respect to volume or 2 kg per 100 L of water). Foliar burn can occur under adverse conditions, such as hot, dry weather.[107 108]

Table 16: Rates of copper (g/ha) to correct deficiencies in pastures and cereals. (Note: faba bean has a higher demand for copper and zinc than cereals, see Table 1.)

Fertiliser type	Situation	Copper (g/ha to apply)
Foliar	Confirmed deficiency	100
	'Insurance'	50
Soil-applied	Confirmed deficiency	2,000
	'Insurance'	500–1,000

Source: Hughes (2012)

6.10.6 Molybdenum

Molybdenum and cobalt are required for effective nodulation and should be applied as needed.

Occurrence of molybdenum deficiency

Molybdenum availability increases as soil pH rises – the opposite of other micronutrients. Deficiencies in Australia are more likely on acid soils.

Sandy soils are deficient more often than finer-textured, heavier soils except for the ferrosols (krasnozems) that are naturally low in molybdenum.

High rates of phosphorus fertilisers increase molybdenum uptake by plants while heavy sulfur applications reduce its uptake.

Molybdenum deficiency symptoms

Molybdenum deficiency symptoms show up as a general yellowing and stunting of the plant, similar to the general symptoms of nitrogen deficiency.

Molybdenum deficiency can cause nitrogen deficiency symptoms in faba bean (see Section 6.5.2 Nutrient toxicity for more information), because the rhizobia require molybdenum to fix nitrogen.

Molybdenum management

Molybdenum deficiencies can be corrected with applications of very small amount of molybdenum fertiliser. To achieve as uniform an application as possible, molybdenum fertilisers should normally be applied with a carrier such as other fertiliser, seed, or in water.

Molybdenum trioxide (60% molybdenum) can be applied as an additive in single superphosphate. Soluble forms of molybdenum such as ammonium molybdate (54% molybdenum) or sodium molybdate (39–41% molybdenum) can be applied in solution directly to the soil or to foliage.

107 CSIRO (2006) Australian Soil Fertility Manual. 3rd edn. G Price (ed.). CSIRO Publishing.

108 B Hughes (2012) Trace elements in the South East fact sheet. Natural Resources South East, www.naturalresources.sa.gov.au/southeast/land/soil-management/South-East-Soil-Issues

In some field crops, deficiencies can be corrected with soluble molybdenum applied with pre-emergence herbicides. Typical rates are 55–60 g/ha.[109]

6.10.7 Cobalt

Cobalt is required for effective nodulation and should be applied as needed. It is required by rhizobia for efficient nitrogen fixation.

6.10.8 Boron

Pulses have a high demand for boron. Many legumes are highly responsive to boron.

Occurrence of boron deficiency

Boron deficiency is widespread in many parts of the world. In Western Australia the areas most at risk have sandy, acid soils but deficiency is not severe in studied sites.[110] There is little information specific for southern Australia.

Note that boron toxicity (see Section 6.5.2 Nutrient toxicity for more information) is also a problem on some alkaline soils in southern Australia.

Boron deficiency symptoms

Boron-deficient faba bean roots become brown, with lateral extremities showing shortening and thickening. First symptoms are a darkening of leaves and reduced leaf growth with a waxy appearance (Photo 25). This is followed by a folding back of these leaves in an 'umbrella' fashion, leaving the leaflet folded over and twisted.[111] Stem internode length is shortened.

As the deficiency progresses, middle leaves develop a mottled chlorosis (yellowing) that forms between the vein.

As boron becomes deficient, the vegetative growing point of the affected plant becomes stunted, deformed or disappears altogether. When this occurs, side shoots may proliferate resulting in a 'witches broom' condition.

Deformed flowers are a common symptom of boron deficiency. Many plants show reduced flowering and improper pollination as well as thickened, curled, wilted and chlorotic (yellow) new growth.[112]

Photo 25: *Boron-adequate leaflet (left) and boron-deficient leaflets, (left to right) oldest to youngest.*

Photo: Alan Robson; Grain Legume Handbook (2008)

109 CSIRO (2006) Australian Soil Fertility Manual. 3rd edn. G Price (ed.). CSIRO Publishing.

110 R Bell, K Frost, M Wong, R Brennan (2002) Boron – should we be worried about it? Proceedings Crop Updates 2002: Farming Systems. Western Australian Department of Agriculture. pp 45–46, http://researchrepository.murdoch.edu.au/18874/1/Boron_-_should_we_be_worried_about_it.pdf

111 Pulse Australia (2016) Agronomy. Southern faba and broad bean best management practices training course manual – 2016. Pulse Australia.

112 Pulse Australia (2016) Agronomy. Southern faba and broad bean best management practices training course manual – 2016. Pulse Australia.

Management of boron deficiency

Use caution when using boron fertiliser and seek specific local advice. Ensure uniform application and use the appropriate rate because there is a narrow range between deficiency and toxicity.

Application rates of boron fertiliser depend on several factors, particularly the availability of soil boron, crop rotation weather conditions, farming practices and soil organic matter.

Boron fertiliser can be broadcast in the dry form to the soil or blended with other fertilisers.

Soluble boron fertilisers can be dissolved in water and applied as liquid. Foliar applications can be applied as one or more sprays.[113]

113 CSIRO (2006) Australian Soil Fertility Manual. 3rd edn. G Price (ed.). CSIRO Publishing.