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GRDC GROWNOTES™

GRDC GRAINS RESEARCH & DEVELOPMENT CORPORATION

BARLEY

SECTION 5

NUTRITION AND FERTILISER

ORGANIC MATTER | DECLINING SOIL FERTILITY | BALANCED NUTRITION | UNDERSTANDING SOIL PH | HIERARCHY OF CROP FERTILITY NEEDS | CROP REMOVAL RATES | SOIL TESTING | PLANT AND/OR TISSUE TESTING FOR NUTRITION LEVELS | IN-CROP NUTRITIONAL NEEDS | NITROGEN | PHOSPHORUS | POTASSIUM | SULFUR | MICRONUTRIENT DEFICIENCIES

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Nutrition and fertiliser

With the more frequent use of opportunity cropping, improved farming techniques, and higher yielding varieties, grain growers need to continually review nutrient management programs to ensure the sustainability of grain production.

Common nutrient deficiencies include nitrogen (N), phosphorus (P), potassium (K) and zinc (Zn). Sulfur (S), copper (Cu), manganese (Mn) and molybdenum (Mo) may also be lacking in some soil types and growing areas. [1]

Historically, rates of fertiliser application to barley crops have been low. Barley was perceived to perform well on poor soils and in low-fertility situations. This is not the case; in fertile soils, barley yields are often 20% higher than those of wheat. [2]

Typically barley yields should be 250–500 kg/ha above wheat. Some barley growers in WA are regularly achieving yields 750–1000 kg/ha better than wheat.

Management of N availability is vital to achieving optimal yields and quality in barley crops. Unlike wheat, which attracts premiums for high protein, malting barley protein content needs to be between 9.5–12.5% to attract a premium. A protein target of 10% will also maximise a barley crop's yield potential. [3]

To help grain growers with nutrition knowledge, the GRDC set up the More Profit from Crop Nutrition Initiative. The primary outcome will be delivering to grain growers the knowledge and skills necessary to enable them to determine whether their current NPK application practices are efficient and meet best management practice. [4]

5.1 Organic matter

Organic matter is primarily made up of carbon (45%) with the remaining mass consisting of water and other nutrients. [5] It has a fundamental role in soils and helps to ameliorate or buffer the harmful effects of plant pathogens and chemical toxicities. It enhances surface and deeper soil structure, with positive effects for infiltration and exchange of water and gases, and for keeping the soil in place (i.e. reducing erosion). It improves soil water-holding capacity and, through its high cation-exchange capacity (CEC), prevents the leaching of essential cations such as calcium (Ca), magnesium (Mg), K and sodium (Na). Most importantly, it is a major repository for the cycling of nutrients and their delivery to crops and pastures.

5.2 Declining soil fertility

The natural fertility of cropped agricultural soils can decline over time. As a result, management programs need regular review to ensure the long-term sustainability of high-quality grain production. Legume pasture phases, pulse rotations and regular liming applications all play an important role in maintaining the chemical, biological and physical fertility of soils (Photo 1).

Paddock records, including yield and protein levels, fertiliser test strips, crop monitoring, and soil and plant tissue tests all assist in the formulation of an efficient cropping program.

1 DAF Qld (2012) Wheat—nutrition. Department of Agriculture and Fisheries Queensland, http://www.daff.qld.gov.au/plants/field-crops-and-pastures/broadacre-field-crops/wheat/nutrition

2 N Fettell, P Bowden, T McNee, N Border (2010) Barley Growth & development, PROCROP. Industry & Investment NSW/NSW Department of Primary Industries, http://www.dpi.nsw.gov.au/__data/assets/pdf_file/0003/516180/Procrop-barley-growth-and-development.pdf

3 DAF Qld (2012) Barley planting, nutrition and harvesting. Department of Agriculture and Fisheries, Queensland, http://www.daff.qld.gov.au/plants/field-crops-and-pastures/broadacre-field-crops/barley/planting-nutrition-harvesting

4 M Blumenthal, I Fillery (2012) More profit from crop nutrition. GRDC Ground Cover Supplement, 16 February 2012, http://www.grdc.com.au/Media-Centre/Ground-Cover-Supplements/Ground-Cover-issue-97-MarApr-2012-Supplement-More-profit-from-nutrition/More-profit-from-crop-nutrition

5 DAFWA (2016) Soil organic matter. Department of Agriculture and Food, Western Australia, https://www.agric.wa.gov.au/soil-carbon/soil-organic-matter-frequently-asked-questions-faqs

Although crop rotations with pulses and legume 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. The higher yielding the crop, the greater the amount of nutrient removed.

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. Sometimes, poor crop response can also be linked to acidity, sodicity or salinity, pathogens, or a lack of beneficial soil microorganisms. [6]

Photo 1: *The natural fertility of cropped agricultural soils can decline over time.*

5.3 Balanced nutrition

To obtain the maximum benefit from investment, fertiliser programs must provide a balance of required nutrients. There is little point in applying N if a P or Zn deficiency is limiting yield. To make better crop nutrition decisions, growers need to consider the use of paddock records, soil and tissue tests as well as fertiliser test strips. This helps to build an understanding of which nutrients the crop removes at a range of yield and protein levels.

The use of paddock grain protein to detect N deficiency is well established for wheat and barley. Grain protein lower than 10% is likely to indicate loss of yield due to inadequate N supply. [7]

Monitoring of crop growth during the season can assist in identifying factors such as water stress, P or Zn deficiency, disease or other management practices responsible for reducing yield. [8]

5.3.1 Paddock records

Paddock records help to:

- establish realistic target grain yield and protein levels prior to planting

6 DAF Qld (2010) Nutrition management. Overview. Department of Agriculture and Fisheries Queensland, http://www.daff.qld.gov.au/plants/field-crops-and-pastures/broadacre-field-crops/nutrition-management/overview

7 P Matthews, D McCaffery, L Jenkins (2015) Winter crop variety sowing guide. NSW Department of Primary Industries, http://www.dpi.nsw.gov.au/agriculture/broadacre/guides/winter-crop-variety-sowing-guide

8 DAF Qld (2010) Nutrition management. Overview. Department of Agriculture and Fisheries Queensland, http://www.daff.qld.gov.au/plants/field-crops-and-pastures/broadacre-field-crops/nutrition-management/overview

- modify target yield and protein levels based on previous crop performance (yield and protein), planting soil moisture, planting time, fallow conditions, expected in-crop seasonal conditions and grain quality requirements
- determine appropriate fertiliser type, rate and application method
- compare expected with actual performance per paddock and modify fertiliser strategies to optimise future yield and protein levels

The longer paddock records are kept, the more valuable they become in assessing future requirements. [9]

5.4 Understanding soil pH

Soil acidity is a major constraint to farming in WA. Extensive surveys of soil pH profiles across the south-west show more than 70% of surface soils and almost half of subsurface soils are below appropriate pH levels.

Soil acidity is an economic and natural resource threat. Production loss and sustainability are of major concern to growers, with more than 14.25 million ha of wheatbelt soils currently estimated to be acidic or at risk of becoming acidic to the point of restricting production. The estimate of production loss for the wheatbelt due to acidity is $498 million, or about 9% of the annual crop. [10]

Getting pH right is the most important factor affecting barley nutrition and production. All the other nutrition falls into line once the optimum pH is achieved.

A soil pH in calcium chloride ($CaCl_2$) of 5.2–8.0 provides optimum conditions for most agricultural plants. All plants are affected by extremes of pH, but there is wide variation in their tolerance of acidity and alkalinity. Some plants grow well over a wide pH range, whereas others are very sensitive to small variations in acidity or alkalinity. Barley is generally sensitive to soil pH <5.0.

Microbial activity in the soil is also affected by soil pH, with most activity occurring in soils of pH 5.0–7.0. Where extremities of acidity or alkalinity occur, various species of earthworms and nitrifying bacteria disappear.

Soil pH affects the availability of nutrients, and affects how the nutrients react with each other.

At low pH, beneficial elements such as Mo, P, Mg, S, K, Ca, and N become less available and others may become toxic (Figure 1). Maintain soil pH ($CaCl_2$) at 5.5–6.5 to achieve maximum P availability for cereals. [11]

9 DAF Qld (2010) Nutrition management. Overview. Department of Agriculture and Fisheries Queensland, http://www.daff.qld.gov.au/plants/field-crops-and-pastures/broadacre-field-crops/nutrition-management/overview

10 DAFWA (2016) Soil acidity in Western Australia. Department of Agriculture and Food, Western Australia, https://www.agric.wa.gov.au/soil-acidity/soil-acidity-western-australia

11 B Lake (2000) Understanding soil pH. Acid Soil Management Series. NSW Department of Primary Industries, http://www.dpi.nsw.gov.au/__data/assets/pdf_file/0003/167187/soil-ph.pdf

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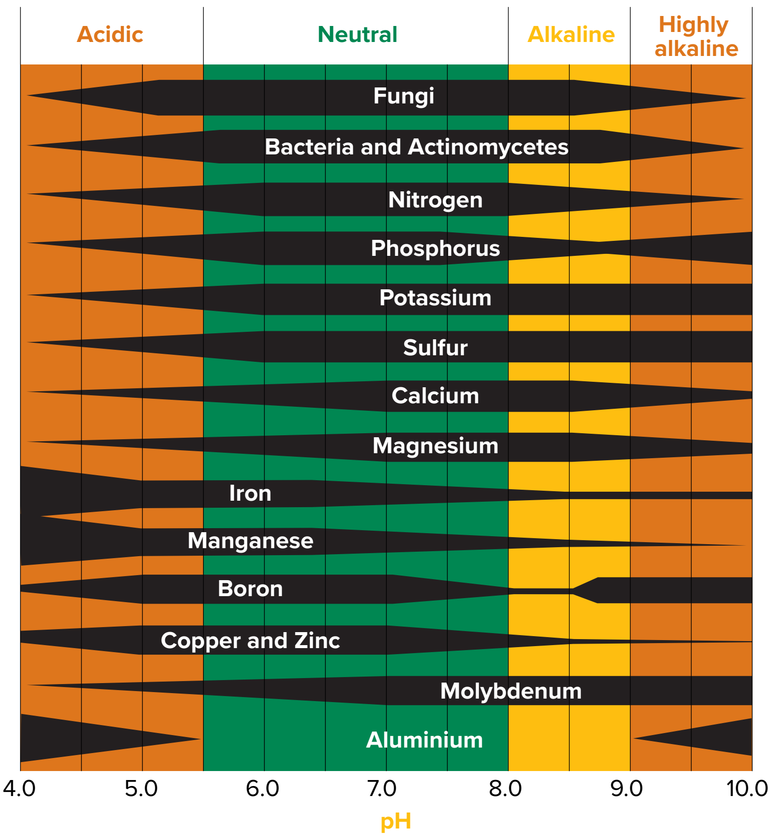

Figure 1: *Availability of nutrients and other elements varies with soil pH.*

Source: NSW DPI

5.5 Hierarchy of crop fertility needs

The hierarchy of crop fertility needs says there must be sufficient plant-available N to obtain a response to P, and there must be sufficient P for S and/or K responses to occur. [12]

Additive effects of N and P appear to account for most of the aboveground growth and yield response. [13]

Liebig's law of the minimum is a principle developed in agricultural science by Carl Sprengel (1828) and later popularised by Justus von Liebig. It states that growth is controlled not by the total amount of resources available, but by the scarcest resource (i.e. limiting factor) (Figure 2). [14]

12 D Lester, M Bell (2013) Nutritional interactions of N, P, K and S on the Darling Downs. GRDC Update Papers, 7 March 2013, http://www.grdc.com.au/Research-and-Development/GRDC-Update-Papers/2013/03/Nutritional-interactions-of-N-P-K-and-S-on-the-Darling-Downs

13 D Lester, M Bell (2013) Nutritional interactions of N, P, K and S on the Darling Downs. GRDC Update Papers 7 March 2013, http://www.grdc.com.au/Research-and-Development/GRDC-Update-Papers/2013/03/Nutritional-interactions-of-N-P-K-and-S-on-the-Darling-Downs

14 Liebig's law of the minimum. Wikipedia, http://en.wikipedia.org/wiki/Liebig's_law_of_the_minimum

Figure 2: *Liebig's law of the minimum.*

5.6 Crop removal rates

Ultimately, nutrients removed from paddocks will need to be replaced to sustain production. Table 1 shows amounts of nutrients removed by barley and wheat. Growers need to adopt a strategy of programmed nutrient replacement based on yields and protein taken off paddocks.

Table 1: *Average amounts of nutrients (kg/ha) removed per tonne of grain and stubble for barley and wheat*

	N	P	K	S	Mg	Ca	Cu	Zn	Mn
Wheat –Grain	21	3	4	2	1	0.4	0.003	0.02	0.02
Wheat – Straw	4–6	0.5–1	9–10	1–2					
Barley –Grain	21	3	4	2	1	0.4	0.003	0.02	0.03
Barley – Straw	4–6	0.5–1	10–11	1–2					

Source: CSBP

To attain optimum yields, an adequate supply of each nutrient is necessary. However, only a small proportion of the total amount of an element in the soil may be available for plant uptake at any one time. For nutrients to be readily available to plants, they must be present in the soil solution (the soil water), or easily exchanged from the surface of clay and organic matter particles in the root-zone, and be supplied when and where the plant needs it.

Temperature and soil moisture content affect the availability of nutrients to plants. The availability of nutrients also depends on soil pH, degree of exploration of root systems, and various soil chemical reactions, which vary from soil to soil. Fertiliser may be applied in the top 5–10 cm, but unless the soil remains moist, the plant will not be able to access it. Movement of nutrients within the soil profile in low-rainfall areas is generally low, except in very sandy soils, and some nutrients, such as P and Zn, are relatively immobile in the soil.

Lack of movement of nutrients, combined with current farming methods (e.g. no-till), is resulting in stratification of these nutrients, with concentrations building up in the surface of the soil where they are not always available to plants. Deep sowing is done into moisture that is below the layer where nutrients have been placed or are stratified, and this has implications for management and fertiliser practices. [15]

15 DAF Qld (2012) Wheat—nutrition. Department of Agriculture and Fisheries Queensland, http://www.daff.qld.gov.au/plants/field-crops-and-pastures/broadacre-field-crops/wheat/nutrition

5.7 Soil testing

Soil tests estimate the amount of each nutrient available to the plant. Information obtainable from a soil test includes current nutrient status, acidity or alkalinity (pH), soil salinity (electrical conductivity, EC) and sodicity (exchangeable sodium percentage).

Soil test information should not be used alone to determine nutrient requirements. It should be used in conjunction with tissue tests (especially for trace elements) along with test-strip and previous crop performance to determine nutrients removed by that crop, and previous soil test records, to obtain as much information as possible about the nutrient status of a particular paddock.

Care must be taken when interpreting soil test results. Nutrients can become stranded in the dry surface layer of the soil after many years of no-till or reduced tillage, or deep nutrient reserves may be unavailable because of other soil factors such as EC levels, sodicity or acidity. [16]

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, sodicity and salinity, which affect the crop demand as well as the ability to access nutrients
- zoning paddocks for variable application rates
- as a diagnostic tool, to identify reasons for poor plant performance [17]

Soil test results support decisions about fertiliser rate, timing and placement. However, to determine micronutrient status, plant tissue testing is usually more reliable.

5.7.1 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. The narrower the range the more reliable the data.

The critical value indicates whether nutrient supply is likely to result in a crop yield response. If the 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.

For values within the critical range, there is less certainty about whether a response will occur. If a response does occur, it will likely be small.

The values used to determine the soil test–crop response relationship have been derived from fertiliser rate trials, in which various fertiliser rates are applied and the crop yield response is measured. With many of these experiments, soil test values and crop responses can be graphed. [18]

5.7.2 Fertiliser test strips

Test strips within the paddock allows the fertiliser program to fine-tuned. To gain the maximum benefit:

- Run them over a number of years; results from any single year can be misleading
- Obtain accurate strip yield weights
- Protein-test a sample of grain from each strip
- Harvest strips before your main harvest, because the difference between the strips is more important than the moisture content

16 DAF Qld (2010) Nutrition management—Overview. Department of Agriculture and Fisheries Queensland, http://www.daff.qld.gov.au/plants/field-crops-and-pastures/broadacre-field-crops/nutrition-management/overview

17 GRDC (2014) Soil testing of crop nutrition. Western Region. Crop Nutrition Fact Sheet, GRDC, January 2014, https://grdc.com.au/Resources/Factsheets/2014/01/Soil-testing-for-crop-nutrition-West

18 GRDC (2014) Soil testing of crop nutrition. Western Region. Crop Nutrition Fact Sheet, GRDC, January 2014, https://grdc.com.au/Resources/Factsheets/2014/01/Soil-testing-for-crop-nutrition-West

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CSIRO Publishing (2016) Interpreting Soil Test Results What Do All the Numbers Mean

GRDC (2016) Enhancing the sustainability of the Western Australia cropping system by using soil and plant testing combined with nutrient balance calculations. GRDC Research Update.

PODCAST

GRDC (2014) Soil Testing. Driving Agronomy Podcasts.

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A number of local Grower Groups conduct nutrition trials.

GRDC (2016) Test strips reduce nitrogen risk. GRDC Radio (Western region) 123:

GRDC (2013) Better fertiliser decisions for crop nutrition. Fact sheet.

CSIRO Publishing, Australian Soil Fertility Manual.

When setting up a test-strip area:

- Ensure the stripscan be accurately located—a GPS reading would be valuable
- Repeat each fertiliser treatment two or three times
- Change only one product rate at a time
- Separate each strip of fertiliser by a control or nil-fertiliser strip
- Ensure that tests are done over a part of the paddock with a uniform soil type
- Keep clear of shade lines, trees, fences, headlands and any known anomalies in the field
- Ensure the test strip area is ~100 m long, with each strip 1–2 header widths [19]

5.7.3 Sampling guidelines

Choose the same soil test package each year (including methods); otherwise, comparisons between years will be invalid. For example, do not use Colwell-P in one year, then DGT-P the next; the two tests measure different forms of available P in the soil.

If a standard approach is not applied to sampling, a comparison of the data between different tests will not be reliable. Aim for data that represents the whole paddock, and mix the sample thoroughly.

For monitoring, sampling should cover roughly the same area each time to ensure meaningful comparisons between years. A handheld GPS or smartphone, will serve this purpose. It can be useful to follow up on a soil test site with an in crop tissue test to evaluate nutrient uptake.

Soil-testing laboratories should be able to provide information on appropriate soil sampling and sample-handling protocols for specific industries and crop types. [20]

5.7.4 Soil testing for nitrogen

The approximate amount of N available in the soil can be determined by soil testing. Soil tests can be taken at various places in each paddock down to a depth of 60 cm or to a known rooting depth. [21] However, deep soil testing for N is not commonly practised in WA as it can be unreliable on the sandy and loamy soil types.

Historical grain yield and protein levels from the paddock can be used to assist N-requirement decision making. [22]

Environmental conditions, including temperature, time and rainfall events can affect starting soil N. It is important to test later in summer and make adjustments to factor in mineralisation amounts as well as denitrification and leaching events if they occur.

Calculating N fertiliser application

If N fertiliser is required, the equation below can be used to obtain the quantity of fertiliser required:

Fertiliser product required (kg/ha) = rate of N required (kg/ha) × 100/% N in fertiliser product [23]

For example, if 40 kg N/ha is required, this rate of N can be supplied by applying 87 kg/ha of urea (46% N).

19 DAF Qld (2010) Nutrition management—Overview. Department of Agriculture and Fisheries Queensland, http://www.daff.qld.gov.au/plants/field-crops-and-pastures/broadacre-field-crops/nutrition-management/overview

20 GRDC (2013) Better fertiliser decisions for crop nutrition. Crop Nutrition Fact Sheet, GRDC, 4 November 2013, http://www.grdc.com.au/GRDC-FS-BFDCN

21 NSW DPI District Agronomists (2007) Wheat growth and development. PROCROP Series, NSW Department of Primary Industries, http://www.dpi.nsw.gov.au/__data/assets/pdf_file/0006/449367/Procrop-wheat-growth-and-development.pdf

22 DAF Qld (2010) Nutrition management—Overview. Department of Agriculture and Fisheries Queensland, http://www.daff.qld.gov.au/plants/field-crops-and-pastures/broadacre-field-crops/nutrition-management/overview

23 DAF Qld (2012) Wheat—nutrition. Department of Agriculture and Fisheries Queensland, http://www.daff.qld.gov.au/plants/field-crops-and-pastures/broadacre-field-crops/wheat/nutrition

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GRDC (2010) Plant tissue testing-uncovering hidden hunger. Driving Agronomy Podcast.

GRDC (2011) Current nutrition issues in the cropping zone of Southern Australia. GRDC Update Paper.

5.7.5 Soil testing for phosphorus

While a number of different P tests are used in Australia, the vast majority of calibration data for soil phosphorus in cropping is for Colwell P. Recent research has led to the introduction of the DGT-P test for cropping. Colwell P is not used in isolation in WA, but with PBI. DGT-P was developed for more alkaline soils such as those found in SA, so is not preferable in WA's more acidic soils

It is crucial that growers use the same test across paddocks and across years. [24]

5.8 Plant and/or tissue testing for nutrition levels

Tissue testing is the best way to diagnose nutrient deficiencies accurately when a crop is growing, whether it is macronutrients, or micronutrients such as Zn and Cu.

Successful use of plant-tissue analysis depends on sampling the correct plant part, at the appropriate growth stage. Sampling of whole tops is easily the most common sampling method in WA. The critical concentration of most nutrients changes with age. [25]

For these reasons, critical tissue concentrations should be associated specifically with defined stages of plant growth or plant part rather than growth periods (i.e. days from sowing). Growers are advised to follow laboratory guides or instructions for sample collection.

Plant nutrient status varies according to plant age, variety, levels of other nutrients, weather conditions, and stresses such as frost.

When applying fertiliser to treat a suspected deficiency, leave a strip untreated. Either a visual response (a yield difference <20% is difficult for the human eye to detect) or a harvester yield map will confirm whether the micronutrient was limiting. [26]

5.9 In-crop nutritional needs

5.10 Nitrogen

Among the mineral nutrients, nitrogen (N) is required in the largest amounts and is the most common nutrient deficiency in non-legume plants. Increased vegetative growth (and tillering in cereals) is often seen with N application and protein content is also enhanced. Nitrogen is mobile in both the soil and the plant. Most of the N in soils (98% or more) occurs in organic forms. This must be mineralised to the inorganic ammonium and nitrate forms before plant roots can utilise this N.

Nitrogen is required for protein formation and determines yield and grain quality.

Nitrogen deficiency can occur on most WA soils but is most common in the following situations:

- In cold, wet conditions that slow nitrogen mineralisation and uptake of nitrogen
- Soils with very low organic matter
- High rainfall on sandy soils can result in nitrogen leaching [27]

Predicting N supply to crops is complex. Nitrogen demand by the crop is related to actual yield, which is determined by seasonal conditions including the amount and timing of growing season rainfall.

24 GRDC (2014) Crop Nutrition News. GRDC, https://grdc.com.au/Media-Centre/GRDC-E-Newsletters/Crop-Nutrition-News

25 James Easton, CSBP. Pers comm.

26 GRDC (2013) Micronutrients. Northern, Southern and Western Regions. Crop Nutrition Fact Sheet, GRDC, November 2013, http://www.grdc.com.au/GRDC-FS-CropNutrition-Micronutrients

27 DAFWA (2015) Diagnosing nitrogen deficiency in barley, Department of Agriculture and Food, Western Australia, https://www.agric.wa.gov.au/mycrop/diagnosing-nitrogen-deficiency-barley

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DAFWA (2014) Factor nitrogen into crop program.

L Barton et al. (2015) Increasing soil organic carbon increases soil nitrogen: Implications for crop production on sandy soils.

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GRDC (2015) Legume effects on soil N dynamics—comparisons of crop response to legume and fertiliser N. GRDC Update Paper.

GRDC (2014) Nitrogen management—how much is enough and how much is too much? GRDC Update Paper.

GRDC (2011) Management effects on barley varieties—nitrogen management and time of sowing. GRDC Update Paper.

BCG: Barley and wheat disease management using foliar and fertiliser fungicides

BCG: Late nitrogen application to increase grain protein in barley

BCG: Management effects on barley varieties—row spacing, nitrogen and weed competition

The pattern of crop demand for N during the growing season should be considered. The highest demand is when the crop is growing most rapidly. [28]

In WA, fertiliser recommendations for N are generally based around a budgeting approach, using a series of relatively simple, well-developed equations that estimate plant demand for N and the soil's capacity to supply N.

These equations attempt to predict the soil processes of mineralisation, immobilisation, leaching, volatilisation, denitrification and plant uptake. They are built into decision support tools such as Yield Prophet® and Select Your Nitrogen (SYN). Yield Prophet® requires a detailed characterisation of the physical and chemical properties of the soil profile explored by the roots. [29]

Plant tissue testing is also a very useful in season tool to refine initial recommendations. [30]

5.10.1 Time of application

Most responses to nitrogenous fertiliser in WA are the result of an increased number of ears or grains.

The response is largely caused by increased tillering, which is determined early in the life of a barley plant. The number of grains per ear is also determined early. Therefore, a good supply of N is needed early in crop growth. Early application is preferred in the production of malting barley because it is more likely to increase yield without raising grain protein levels.

The other consideration is that in sandy soils in higher rainfall areas, the application should be split or delayed 3–4 weeks. This allows the crop to establish a reasonable root system and avoid large leaching losses.

The best time of application in any one season can vary depending largely on the incidence of leaching rains in relation to time of application. Profitable responses can often be obtained up to 10 weeks after sowing. Late applications are more likely to result in increased grain protein. In high yielding sites this can be beneficial to stay in the malt window and can result in lower yielding environments it results in excess protein.

Generally, the later the application, the lower the response and the greater the risk of not getting a payable response. Responses to later applications are generally a result of better survival of tillers and to increased photosynthetic area. [31]

FAQ

5.10.2 Nitrogen supply and grain protein content

Nitrogen is a primary constituent of protein; therefore, adequate soil N supply is essential for producing cereal grain protein. Supply of N is shaped by a number of factors in the farming system (Figure 3) and the N cycle (Figure 4).

28 GRDC (2014) Soil testing for crop nutrition. Western Region. Crop Nutrition Fact Sheet, GRDC, January 2014. https://grdc.com.au/Resources/Factsheets/2014/01/Soil-testing-for-crop-nutrition-West

29 GRDC (2014) Soil testing for crop nutrition. Western Region. Crop Nutrition Fact Sheet, GRDC, January 2014. https://grdc.com.au/Resources/Factsheets/2014/01/Soil-testing-for-crop-nutrition-West

30 J. Easton, CSBP. Pers comm.

31 DAFWA (1995) The Barley Book. Department of Agriculture and Food, Western Australia, http://researchlibrary.agric.wa.gov.au/bulletins/44/

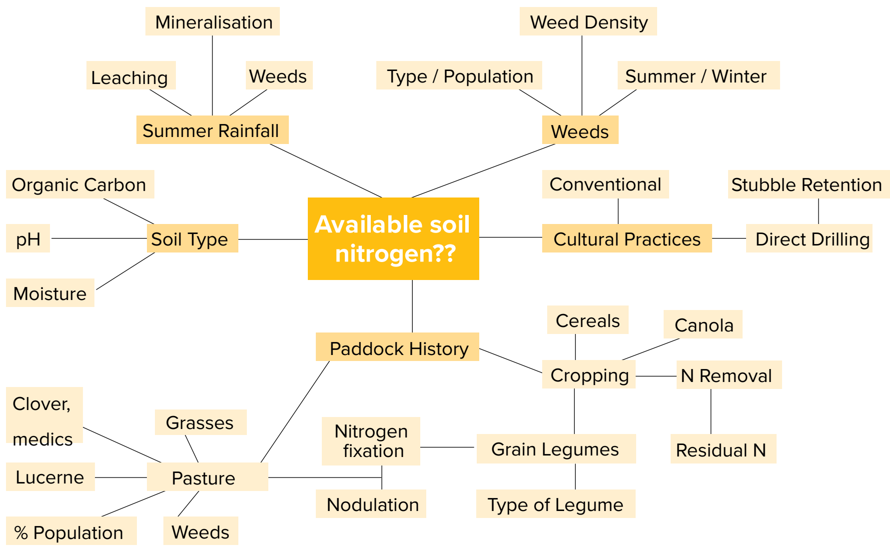

Figure 3: *Factors influencing available soil nitrogen.*

Source: Incitec Pivot Ltd

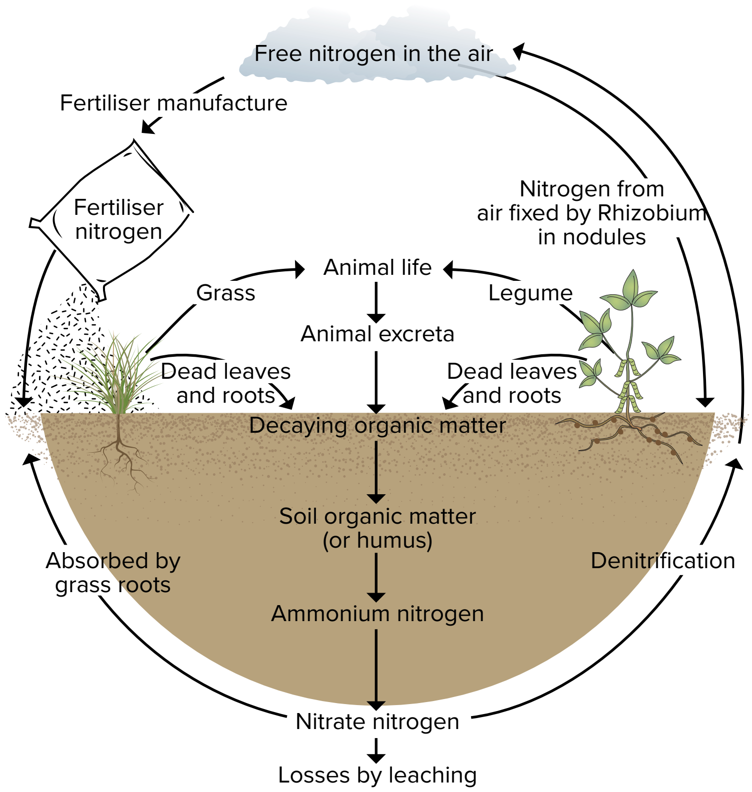

Figure 4: *The soil nitrogen cycle.*

Source: Agriculture Victoria

Besides its role in plant growth, the availability of soil N at grainfill, along with soil moisture, is the key determinant of grain protein. Crop rotation and management are key factors in determining the accumulation of soil N. The availability of N in the soil will be affected by many factors: soil organic matter, paddock history, soil type, moisture content, time of year, and tillage methods.

High yields are a drain on soil N. Conversely, low yields and summer rain which mineralise N can mobilise soil N for the next crop. Soil tests for N should be done as close as possible to sowing time. [32]

Grain protein content

Grain protein is modified by the grain yield of the crop—increasing grain yield has a diluting effect on grain protein, (i.e. yield and protein are inversely proportional) (Figure 5). This explains why in drier seasons or seasons of low grain yield, a larger proportion of the crop has a high protein content. In wetter years, high yields can be produced but may be at a lower protein level. A barley crop's N requirement can be extremely variable from one year to the next.

As the rate of N supply is increased, yield will generally increase to a maximum level, whereas protein may continue to increase with further N application. Drier or wetter than expected seasonal conditions can significantly change yield potential mid-season, which consequently changes N requirements to meet target protein contents. [33]

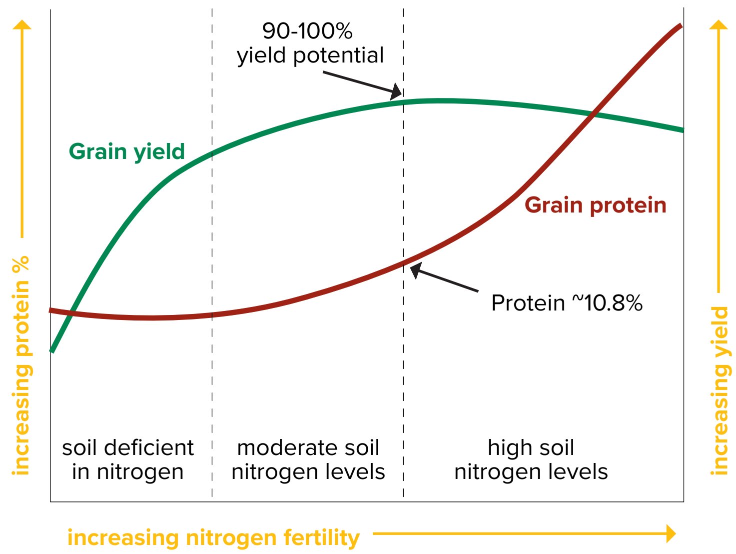

Figure 5: *Relationship between grain yield and protein.*

Source: Incitec Pivot Ltd

5.10.3 Plant-available (nitrate)-N in the root-zone

Nitrogen in the plant-available, mineral form is a major driver of crop production. Almost all of the N taken up by crops is in the form of nitrate. The other mineral form, ammonium, is present in most soils at low levels.

32 Agriculture Victoria (2012) Growing wheat. DEDJTR Victoria, http://agriculture.vic.gov.au/agriculture/grains-and-other-crops/crop-production/growing-wheat

33 N Fettell, P Bowden, T McNee, N Border (2010) Barley Growth & development, PROCROP. Industry & Investment NSW/NSW Department of Primary Industries, http://www.dpi.nsw.gov.au/__data/assets/pdf_file/0003/516180/Procrop-barley-growth-and-development.pdf

MORE INFORMATION

GRDC (2015): Where does fertiliser nitrogen finish up? GRDC Update Paper.

PODCAST

GRDC (2015) Nitrogen Management. Driving Agronomy Podcast.

In some soils, subsoil constraints will limit the root-zone to <1 m. In other soils that are particularly well structured, the root-zones of long-season or particularly vigorous crops can be as deep as 1.8 m.

5.10.4 Nitrogen deficiency symptoms

Description:

- Plants are pale green with reduced bulk and tiller formation (Photo 2 and Photo 3)
- Symptoms first occur on the oldest leaf, which becomes paler than other leaves, with marked yellowing beginning at the tip and gradually merging into light green
- Other leaves begin to yellow and oldest leaves change from yellow to almost white
- Leaves may not die for some time
- Grain yield and protein levels are reduced

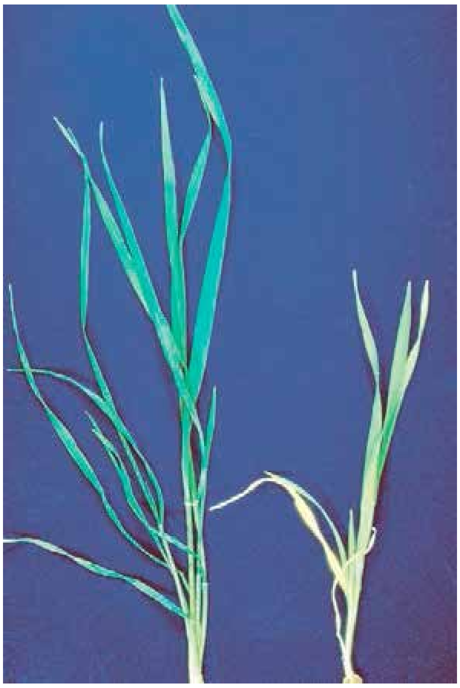

Photo 2: *Adequate (left) and inadequate (right) nitrogen nutrition.* [34]

Source: Mel Mason, Agriculture WA

34 GRDC (2007) Winter cereal nutrition: the Ute Guide. GRDC, https://grdc.com.au/resources-and-publications/all-publications/publications/2007/05/uteguide-wintercerealnutrition

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[L Barton et al. (2015) Where does the nitrogen go? Soil sources and sinks in Western Australia cropping soils.]

[GRDC (2014) Nitrogen volatilisation: Factors affecting how much N is lost and how much is left over time. GRDC Update Paper.]

[Soil Quality (2017) Soil nitrogen supply. Fact sheet.]

Photo 3: *Inadequate nitrogen nutrition expressed as pale green plants with reduced bulk and tiller formation.*

Similar symptoms

Deficiencies of K and P show similar yellowing of the oldest leaves, but these leaves die quickly. Reduced grain yield and protein levels may occur for other reasons. [35]

5.10.5 Nitrogen-use efficiency

Efficient use of N is crucial to economic production of cereals. Over-application of N may increase susceptibility of the crop to disease and increase water use early in the growing season. This creates excessive early growth, causing crops to 'hay off'.

Split application

Site and N rate are the primary determinants of grain protein levels in barley; the impact of variety and split applications are secondary. However, splitting N applications offers growers the capacity to tailor N inputs to the crop growth and seasonal forecast. Nitrogen application generally decreases average grain weight in barley and this can result in increased screenings.

While the rate applied is significant, timing is still an important component of getting the rate right. Research shows that growers can split N applications and sow with a starter amount of N and then delay the second application out to stem elongation or beyond.

The advantage of this is a better assessment of the yield potential of each crop as its growth reflects seasonal challenges such as disease pressure, growing conditions and the ability to factor in seasonal forecasts for spring rainfall. It is critical to match yield potential with the level of N required to achieve that yield potential. [36]

Late applications

Applying N after tillering offers farmers advantages, such as better estimates of the overall rate required based on likely yield potential and it avoids excessive tiller numbers in varieties that tiller profusely in response to early applications of N. Logistically, later applications can also be made when another operation such as disease control is being done.

Nitrogen applied as late as flag leaf emergence does not increase screenings more than those made earlier in the season at tillering. The stem elongation stage

35 GRDC (2007) Winter cereal nutrition: the Ute Guide. GRDC, https://grdc.com.au/resources-and-publications/all-publications/publications/2007/05/uteguide-wintercerealnutrition

36 A Hills and B Paynter (2008) Managing nitrogen inputs in malting barley. Agribusiness Crop Updates 2008, https://www.researchgate.net/publication/273135464_Managing_nitrogen_inputs_in_malting_barley

of growth appears to be sensitive to N and may produce higher screenings than N applied earlier or later.

Maintaining a high grain yield is important in the southern region of WA as weather conditions at harvest can result in the downgrading of grain into feed segregations. [37]

As a rough rule of thumb plan to apply 10–20% more N to barley crops than to a wheat crop in a similar rotation because barley usually has a higher yield potential than wheat (400-800 kg/ha).

Agronomist's view

5.11 Phosphorus

Native soils in WA are among the most highly phosphorus (P) deficient in the world. Although N and K are required in larger amounts for plant growth, P deficiency was one of the major limitations to agriculture in WA for many years. Apart from the very sandy soils with little clay or organic matter, most WA soils retain P tightly. In the year of application, 80–95% of the P applied in fertilisers reacts with soil particles before it can be taken up by the plant roots. This process is known as adsorption.

Over time, as more and more P is added to the soil, the adsorbed P builds up and can return to the soil solution to be utilised by plants.

Phosphorus is an essential element for plant and animal growth and is important during cell division and growth (e.g. during development of roots, flowering and seed formation). Complex soil processes influence the availability of P applied to the soil, with many soils able to 'tie up' P, making it unavailable to plants. [38]

Nearly all soils in WA were P deficient but continual use of P fertiliser means that P responses are less common and most grain growers now fertilise to maintain soil P levels with the exception of Darling Range gravels where soil acidity and water repellence markedly reduce P uptake. Phosphorus deficiency is often transitory and compounded by dry soil with symptoms disappearing when the topsoil is re-wet following rainfall. [39]

Roots of all plant species can only take up water-soluble P from soil solution. Plant roots intercept P in moist soil as the roots grow through the soil, and P moves through the soil solution to the root by diffusion. [40]

5.11.1 Phosphorus deficiency

P deficiency symptons include (Photo 4 and Photo 5):

- Early growth and vigour are reduced, with spindly plants under severe deficiency
- All leaves are dull dark green
- Slight mottling is visible on oldest leaf and tip begins to yellow
- Yellow area moves down the leaf, with the base remaining dark green (no 'arrow', so not like K deficiency)
- Yellow areas die quite quickly, with the tip becoming orange to dark brown and shrivelling, with the remainder of the leaf turning yellow [41]

MORE INFORMATION

Soil Quality (2017) Phosphorus–Western Australia. Fact sheet.

DAFWA (2015) Diagnosing phosphorus deficiency in barley.

GRDC (2015) Phosphorus—are we going to hit the wall and how much P in 2015? GRDC Update Paper.

GRDC (2015) Subsoil manuring. GRDC Update Paper.

GRDC (2012) Crop nutrition—Western Region phosphorus management. Fact Sheet.

MDA Bolland and DG Allen (2003) Sorption of phosphorus by soils: how it is measured in Western Australia.

GRDC (2015) Phosphorus—are we going to hit the wall and how much P in 2015? GRDC Update Paper.

GRDC (2015) Subsoil manuring. GRDC Update Paper.

37 A Hills and B Paynter (2009) Time of nitrogen application effects on grain yield and quality of malting barley. 14th Australian Barley Technical Symposium, 13–16 September 2009. https://www.researchgate.net/publication/274067552_Time_of_nitrogen_application_effects_on_grain_yield_and_quality_of_malting_barley

38 Soil Quality (2017 Phosphorus–WA. Fact sheet, http://www.soilquality.org.au/factsheets/phosphorus

39 DAFWA (2015) Diagnosing phosphorus deficiency in barley, Department of Agriculture and Food, Western Australia, https://agric.wa.gov.au/n/2538

40 MDA Bolland and DG Allen (2003) Sorption of phosphorus by soils: how it is measured in Western Australia, Department of Agriculture and Food, Western Australia, http://researchlibrary.agric.wa.gov.au/cgi/viewcontent.cgi?article=1035&context=bulletins

41 GRDC (2014) Winter cereal nutrition: the Ute Guide. GRDC, https://grdc.com.au/resources-and-publications/all-publications/publications/2007/05/uteguide-wintercerealnutrition

Photo 4: *Adequate (left) and inadequate (right) phosphorus nutrition.* [42]

Photos: Nigel Wilhelm, SARDI

Photo 5: *Phosphorus deficiency on the right-hand side of the image.*

Source: Nigel Wilhelm, SARDI

Similar symptoms

Nitrogen deficiency also has yellowing of the oldest leaves, but death of the yellow tissue occurs more rapidly in P deficiency than with N deficiency.

5.11.2 Crop demand for phosphorus

Crop demand for P can be considered in two distinct phases: during early development (from emergence to the end of tillering, but before stem elongation), and then during the growth and grain-filling period.

42 GRDC (2014) Winter cereal nutrition: the Ute Guide. GRDC, https://grdc.com.au/resources-and-publications/all-publications/publications/2007/05/uteguide-wintercerealnutrition

MORE INFORMATION

GRDC (2014) Soil testing for crop nutrition Western Region. Fact sheet.

Large increases in soil pH can improve the availability of soil phosphorus if the supply of other nutrients is adequate http://www.giwa.org.au/_literature_209549/Scanlan,_Craig_et_al_-_The_interaction_between_soil_pH_and_phosphorus_fertiliser_is_dynamic

During early development, the requirement for P is small (perhaps 1 kg/ha P), but the root system is small and inefficient, so the crop responds to a concentrated P source close to the seed and developing roots. Ensuring these young plants have adequate P is essential to determine grain number (i.e. yield potential) and to ensure vigorous seedling development. Hence, it is important to apply 'starter fertilisers' with the seed.

Subsequent P requirement is much larger, and largely mirrors the accumulation of crop biomass. As a rule, crops require ~5 kg P plant-accumulated to produce 1 t of grain yield, so a typical crop of 3 t/ha will take up ~15 kg/ha P. Only 1–2 kg will be taken up from the banded P fertiliser applied at planting (either in, below or beside the seeding row). The rest comes from the soil profile, with about half coming from the top 10–15 cm and the rest from the next 15–30 cm. These proportions will change with seasonal conditions; root activity in surface layers will be minimal in dry periods. Having plant-available P in the immediate subsoil (i.e. 10–30 cm preferably) becomes a critical factor for crop performance. [43]

5.11.3 Phosphorus availability

Many studies suggest that the timing and quantities of P release vary and that they are not well explained by the total amount of P or the carbon (C)P ratio in the residues.

The chemical composition of crop stubble plays an important role in the rate of nutrient release. The quality of crop stubble is usually assessed by considering its C:N:P ratio, because this ratio influences the proportion of P that follows pathways of immediate release or incorporation by microorganisms and subsequent release back to the soil.

This occurs because the microbial population requires a C source for energy, which is provided by the stubble, as well as certain amounts of nutrients such as N and P to continue to grow. How crop stubble affects soil P availability will therefore depend on the balance between direct release of P (and C and N) from the stubble and microbial uptake and release. The presence of different chemical P forms in the stubble is also likely to influence the proportion of P that undergoes direct release or microbial uptake and decomposition.

Research indicates that P release is strongly controlled by the size of the stubble pieces, and studies that use ground stubbles are likely to over-predict the rate at which P is released from stubble in the field. [44]

Where soil pH is below recommended levels, yield potential is reduced as is the availability of soil P. Both of these factors are major drivers of the profit achieved from P fertiliser. In WA trials, when yield was constrained by soil pH, treatments where 20–30 kg P/ha were applied did not achieve the same grain yield as treatments with soil pH at or above recommended levels with no or low P fertiliser applied. In this scenario, it seems logical to adjust fertiliser inputs to realistic yield potentials and shift investment to lime. [45]

5.11.4 Reduced tillage

Reduced tillage or no-tillage may accentuate the responsiveness of a soil to phosphate fertiliser. This is due to the stratificationof phosphate in the soil surface. Phosphorus is immobile in the soil—unlike nitrate-N, it does not move in soil water. Phosphate fertilisers are most effective when applied at planting in direct contact with, or just below, the seed. Table 5 shows the actual rate of fertiliser product required to apply various rates of P.

43 DAF Qld (2012) Wheat—nutrition. Department of Agriculture and Fisheries Queensland, https://www.daf.qld.gov.au/plants/field-crops-and-pastures/broadacre-field-crops/wheat/nutrition

44 S Noack, M McLaughlin, R Smernik, T McBeath, R Armstrong (2012) The value of phosphorus in crop stubble. GRDC Update Papers, 23 February 2012

45 W Pluske, C Scanlan, R Norton (2014) Best practice nutrient management: beyond the rhetoric, http://www.giwa.org.au/pdfs/2014/Presented_Papers/Pluske%20Wayne_Best%20practice%20nutrient%20management%20beyond%20the%20rhetoric_PAPER%20DR.pdf

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[GRDC (2016) Monitoring of soil phosphorus potassium and sulfur in the southern region how to get the most out of your fertiliser dollar. GRDC Update Paper.]

[GRDC (2014) Soil acidity and phosphorus in western spotlight. GRDC Ground Cover 108.]

[GRDC (2014) Crop Nutrition: Region by Region. GRDC Ground Cover 108.]

5.11.5 Phosphorus application

The traditional practice of banding P below or with the seed seeks to provide a rapid boost to root growth, promoting vigorous root systems, which can then set the plant up for good yields. In the presence of root diseases such as nematodes and rhizoctonia starter P is very critical as early root growth is reduced.

On soils that have the capacity to retain P, such as the ironstone gravel soils east of the Darling Range, it is best to drill fertiliser with the seed.

Spreading P by top dressing during the growing season is highly inefficient and should be avoided on cereal crops. Because crop requirements for P tend to be greatest during early growth, it is essential that the P management is implemented correctly at sowing. It is very difficult to correct mistakes later in the season. Foliar P is not yet considered sufficiently reliable to be recommended for broadacre cropping. [46]

5.11.6 Alternative forms of phosphorus

Phosphorus is not very mobile in the soil, so placing it at or near the seed at sowing is the most efficient way to ensure it is readily available to the growing plant.

Manures

Manures generally contain fairly low concentrations of nutrients. [47] While manure might seem cheaper by the tonne, available nutrients are released very slowly (only 50% of P is available in the first year); therefore, larger quantities are needed to supply enough nutrients for plants to use in the first year.

When using manures, always ensure that the manure being applied is analysed for available nutrients, because the nutrient content varies greatly depending on source and storage. [48]

The cost of transporting and applying manure may be greater than traditional fertiliser, and should be added to budget comparisons. [49]

5.12 Potassium

In high and medium rainfall areas of WA, many sandy soils have low native levels of potassium (K) and so K fertilisers are required. Deficiencies of K were first noted in the 1950s in pasture legumes. Although K levels in other areas were initially adequate for plant growth, continual K export in agricultural products over many decades has resulted in declining K reserves and increased incidence of K deficiency.

K is required for photosynthesis, transport of sugars, enzyme activation, maintenance of water status and regulation of stomata (openings that allow carbon dioxide into the leaf and water vapour out). Potassium is critical for controlling water balance within plant cells. [50]Potassium is a major nutrient that is increasingly required as soil reserves become depleted. [51] Factors such as soil acidity, soil compaction and waterlogging will modify root growth and the ability of crops to extract subsoil K.

A crop's requirement for K will increase as yield increases. High yielding cereal crops put large demands on soil nutrient supply, particularly on light to medium soils. While a soil with low K levels may be able to supply sufficient K for a low yielding crop, when the yield potential is increased, K deficiency may develop. Management factors that can affect crop demand for K include cropping intensity, crop yield levels,

46 GRDC (2012) Western Region Phosphorus Management. Fact sheet, https://grdc.com.au/Resources/Factsheets/2012/11/Crop-Nutrition-Phosphorus-Management-Fact-Sheet

47 James Easton, CSBP. Pers comm.

48 GRDC (2009) Profitable nutrient use starts with knowing the reserve. Targeted Nutrition at Sowing Fact Sheet, GRDC, 2009, https://grdc.com.au/resources-and-publications/all-publications/factsheets/2010/02/targeted-nutrition-at-sowing

49 GRDC (2009) Profitable nutrient use starts with knowing the reserve. Targeted Nutrition at Sowing Fact Sheet, GRDC, 2009, https://grdc.com.au/resources-and-publications/all-publications/factsheets/2010/02/targeted-nutrition-at-sowing

50 CSBP (2012) Soil and plant nutrition. https://csbp-fertilisers.com.au/research-trials/research/soil-and-plant-nutrition

51 DAFWA (2015) Diagnosing potassium deficiency in barley. Department of Agriculture and Food, Western Australia, https://agric.wa.gov.au/n/2539

increased nitrogenous and phosphatic fertiliser rates, sowing date, weed control, timeliness of operations and removal of stubble residues. [52]

Crop requirements for potassium change during the growing season. For cereals, potassium uptake is low at the beginning of the growing season when plants are small, but increases to a peak during the late vegetative and flowering stages. The soil must be able to supply the crop's potassium needs during periods of peak demand. [53]

Most heavy soils in WA contain adequate amounts of naturally occurring K for optimum crop and pasture growth. Sandy soils in higher rainfall areas are prone to K deficiency, as both native and fertiliser applied K is held poorly and is subject to leaching. Soil types of the west midlands in WA and southern sandy soils are commonly K deficient.

Until the early 1990s duplex soils rarely showed responses to potassium, however responses to the application of K on these soils are now well documented in the central and southern wheat-belt of WA. [54]

There does not appear to be a single mechanism by which K deficiency limits yield. Restricted K supply during early growth stages may be more harmful than later deficiency. Potassium deficiency can affect leaf area, dry matter produced in upper internodes and ears, the number of grains per head or the seed weight. The root system of K deficient plants may also be poorly developed. [55]

5.12.1 Deficiency symptoms

- Stunted plants with short, stout stems and pale yellow-green stems and leaves; appear limp or wilted
- Symptoms develop first on old leaves, but eventually move to younger leaves
- Tips of old leaves become dark yellow, moving down the edges of the leaves
- Yellow areas die and turn grey
- In some varieties, dark brown spots and streaks appear in the yellow areas or the green tissue close by; eventually the whole leaf becomes yellow, dies and turns pale to dark brown (Photo 6) [56]

52 DAFWA (1995) The Barley Book. Department of Agriculture and Food, Western Australia, http://researchlibrary.agric.wa.gov.au/bulletins/44/

53 DAFWA (1995) The Barley Book. Department of Agriculture and Food, Western Australia, http://researchlibrary.agric.wa.gov.au/bulletins/44/

54 Soil Quality (2017) Potassium fact sheet, http://www.soilquality.org.au/factsheets/potassium

55 DAFWA (1995) The Barley Book. Department of Agriculture and Food, Western Australia, http://researchlibrary.agric.wa.gov.au/bulletins/44/

56 GRDC (2014) Winter cereal nutrition: The Ute Guide. GRDC, https://grdc.com.au/resources-and-publications/all-publications/publications/2007/05/uteguide-wintercerealnutrition

Photo 6: *Barley leaf on the right shows adequate potassium nutrition; the others show inadequate K.* [57]

Source: Noel Grundon, QDPI

Similar symptoms

Nitrogen deficiency also shows yellowing of oldest leaves, but leaf death occurs much more rapidly with K deficiency.

Boron toxicity is similar, although symptoms usually occur later in crop development than K deficiency.

Contributing factors

Sandy soils with leaching potential can contribute to K deficiency. A history of high removal of hay stubble and/or grain will deplete K. [58]

5.12.2 Critical levels and inputs

Potassium soil tests are reported as exchangeable K (meq/100 g or cmol/kg) or, in the case of a Colwell-K test, as mg available/kg. Research is under way to improve definition of critical soil-test K levels.

Soil test levels in the range of 50 to 100 mg K/kg (Colwell K soil test) would indicate a maintenance application of K is required. Soils with Colwell K values >100 mg K/kg are unlikely to require applications of K.

Large amounts of potassium (K) can move out of the soil through leaching or plant uptake, especially in high rainfall (>750 mm), sandy areas. Potassium can also be removed by hay or windrow burning.

Testing for soil K in both the 0–10 and 10–30 cm layers is advisable. Tissue testing is a great tool for identifying K requirements after initial soil testing and K applications.

Potassium fertilisers can be side-banded at planting, drilled in pre-plant, or broadcast and cultivated in fallow or even prior to a preceding crop. The residual value of K fertiliser is excellent, so sporadic applications at higher rates can be an effective alternative to lower rates with each crop. However, K banded in the seed row can affect germination if applying >12 kg K/ha.

Once K fertility of the surface layers has been restored, deep application of K fertilisers is best for maintaining soil productivity. A proportion of the deep K taken

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Soil Quality (2017) Potassium. Fact sheet.

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57 GRDC (2014) Winter cereal nutrition: The Ute Guide. GRDC, https://grdc.com.au/resources-and-publications/all-publications/publications/2007/05/uteguide-wintercerealnutrition

58 GRDC (2014) Winter cereal nutrition: The Ute Guide. GRDC, https://grdc.com.au/resources-and-publications/all-publications/publications/2007/05/uteguide-wintercerealnutrition

up by the crop is returned to the soil surface in the litter and crop stubble, which replenishes the K fertility of these surface layers. [59]

5.13 Sulfur

Much of WA is dominated by sandy soils characterised by low amounts of organic matter and a poor ability to retain water and nutrients. Fertilisers are a critical part of WA agriculture, and crops and pastures grow poorly without the addition of nutrients.

Previous widespread use of superphosphate (which contains 10% S) means sulfur (S) deficiency is rare in WA cereal crops. Early deficiency is occasionally seen in crops growing on sandy soils in wetter areas but plants generally recover without any yield loss. Continual use of compound fertilisers that contain little or no S will increase the risk of sulfur deficiency. [60]

Sulfur deficiencies have become more common over the past few decades with the increased use of fertilisers lacking S, such as All Phos (triple superphosphate or TSP), monoammonium phoshate (MAP) and diammonium phosphate (DAP).

As with N and P, most of the S in the soil is in organic forms. Hence, soils with low amounts of organic matter are more prone to S deficiency.

Organic S must be mineralised into sulphate before it can be taken up by plant roots. Sulphate is relatively mobile in soils and can be leached out of the rooting zone during winter.

Sulfur has an important role in the formation of proteins and is essential for the production of chlorophyll. [61]Sandy-textured soils in WA are naturally low in S and applied S is readily leached from the top 10 cm, especially in high rainfall areas.

The use of fertilisers containing S somewhat masks the low levels of S present in the soil, however the introduction of more sensitive crops such as canola and the change to compound fertilisers that are low in S, has increased the frequency of S deficiency seen in crops. High rainfall can leach sulfate from the root zone early in the growing season, leaving young crops deficient. Other factors that can induce deficiency in crops include sub-soil constraints such as acidity, sodicity and hardpan, and the level of N in the soil can limit the crop's ability to access subsoil sulfate.

Most S present in the soil is bound in organic compounds but plants can only take up the mineral sulfate form. Cultivation releases S held in organic matter. In no-till systems soil organic matter breaks down slowly, releasing mineral S for crop use. Sulfur mineralisation is low in cooler months, as is root exploration, which can cause temporary deficiency in crops, seen as patches that disappear when the soil temperature increases. Mineralisation is higher in the warmer months and under moist soil conditions. Sulfate adsorption occurs in the soil layers below 10 cm, which can make a significant contribution to crop growth once crop roots have reached the subsoil.

The rate of sulfate leaching is highly variable, depending on seasonal conditions and the water holding capacity of the soil, and is closely related to the rate of nitrate leaching. These two nutrients are best considered together when planning fertiliser applications at seeding and post-seeding to compensate for the movement of these nutrients down the profile.

Sulfur nutrition in cropping systems is usually managed through the application of P or N fertilisers containing S, however if additional S is required, the most common

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59 DAF Qld (2012) Wheat—nutrition. Department of Agriculture and Fisheries Queensland, http://www.daff.qld.gov.au/plants/field-crops-and-pastures/broadacre-field-crops/wheat/nutrition

60 DAFWA (2015) Diagnosing sulfur deficiency in cereals. Department of Agriculture and Food, Western Australia, https://agric.wa.gov.au/n/1998

61 CSBP (2012) Soil and plant nutrition. https://csbp-fertilisers.com.au/research-trials/research/soil-and-plant-nutrition

sources of applied S are gypsum and ammonium sulfate. [62] The most commonly used S fertilisers are NPS and NPKS products. [63]

Gypsum is often preferred as it contains about 16–18% S, is relatively inexpensive and, unlike ammonium sulfate, is not acidifying. There are other fertilisers with varying N:S ratios achieved by blending ammonium sulfate with urea creating a product that absorbs water from the atmosphere, making it difficult to store and handle. [64]

However, depending on the sulphate of ammonia source, when granular ammonium sulphate is used, handling characteristics are acceptable. [65]

On sandy soils in WA only 15% of applied S remains one year after application in the top 0.5 m. [66] In the low to medium rainfall parts of the state, the residual value of S is much greater than this. [67]

In contrast, Gypsum-S applied to pasture grown on a non-leaching clay loam in WA has achieved a residual benefit on dry matter production for up to 3 years when applied at 34 kg S/ha. [68]

5.13.1 Deficiency symptoms

- Crops grow poorly, lack vigour and mature more slowly, resulting in reduced tillering, low grain yields and protein
- Initially all leaves are pale green, but old leaves turn darker green (Photo 7 and Photo 8)
- Youngest leaves turn pale yellow and eventually white, with the whole leaf affected not just the area between the veins
- Leaves generally do not die even when they have turned white
- Old leaves remain green
- In some varieties, margins and sheaths of old leaves become red or purple-red [69]

In severe deficiencies, the upper leaves are yellow to white in colour, with the lower leaves remaining pale green. Tiller number will also be reduced. [70]

Similar symptoms

Nitrogen deficiency symptoms are similar, with yellowing, but N deficiency occurs in the oldest leaves first rather than the whole plant.

Contributing factors

Low soil fertility (organic matter) and cold wet conditions reduce S mineralisation and uptake. Acid sandy soils are subject to S leaching. Commonly used starter fertilisers DAP and MAP are fertilisers such as DAP and MAP are low in S. [71]

62 GRDC (2015) Sulfur strategies for western region, https://www.grdc.com.au/Media-Centre/Hot-Topics/Sulfur-strategies-for-western-region/Details

63 James Easton, CSBP. Pers comm.

64 GRDC (2015) Sulfur strategies for western region, https://www.grdc.com.au/Media-Centre/Hot-Topics/Sulfur-strategies-for-western-region/Details

65 James Easton. CSBP. Pers comm.

66 GRDC (2015) Sulfur strategies for western region, https://www.grdc.com.au/Media-Centre/Hot-Topics/Sulfur-strategies-for-western-region/Details

67 James Easton, CSBP. Pers comm.

68 GRDC (2015) Sulfur strategies for western region, https://www.grdc.com.au/Media-Centre/Hot-Topics/Sulfur-strategies-for-western-region/Details

69 GRDC (2014) Winter cereal nutrition: The Ute Guide. GRDC, https://grdc.com.au/resources-and-publications/all-publications/publications/2007/05/uteguide-wintercerealnutrition

70 DAF Qld (2012) Wheat—nutrition. Department of Agriculture and Fisheries Queensland, http://www.daff.qld.gov.au/plants/field-crops-and-pastures/broadacre-field-crops/wheat/nutrition

71 GRDC (2014) Winter cereal nutrition: The Ute Guide. GRDC, https://grdc.com.au/resources-and-publications/all-publications/publications/2007/05/uteguide-wintercerealnutrition

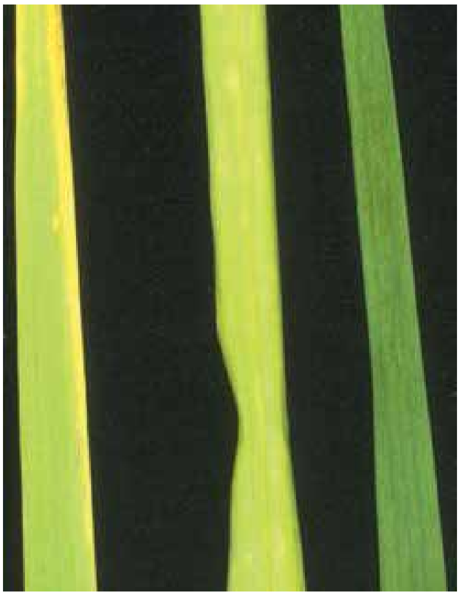

Photo 7: *Sulfur-deficiency symptoms on barley leaves (left and middle); adequate nutrition (right).*

Source: Hungry Crops, DAF Qld

Photo 8: *Sulfur-deficient barley plant (left); plant with adequate nutrition (right).*

Source: Noel Grundon, DAF Qld

MORE INFORMATION

[G Anderson et al. (2013) Soil sulfur—crop response calibration relationships and criteria for field crops grown in Australia. CSIRO Publishing.]

5.14 Micronutrient deficiencies

Micronutrient deficiencies can be difficult to diagnose and treat. However, by knowing the soil type, crop requirements and seasonal conditions, and using diagnostic tools and strategies, effective management is possible.

Key points:

- Significant yield losses can occur from trace element deficiencies before any visual symptoms become obvious
- The only reliable way to know a barley plant's trace element status is to tissue test

- Soil type is useful in determining the risk of micronutrient deficiencies.
- Soil testing is a poor indicator of trace element availability in WA
- Tissue testing is an accurate way to diagnose a suspected micronutrient deficiency
- When tissue-testing, the appropriate tissues should be sampled at the right time. In WA, whole tops are recommended. Plant nutrient status varies according to plant age, variety and weather conditions
- The difference between deficient and adequate (or toxic) levels of some micronutrients can be very small
- When applying fertiliser to treat a suspected deficiency, leave a strip untreated. Either a visual response or tissue testing can confirm whether the micronutrient was limiting [72]

5.14.1 Zinc

Zinc deficiency has become more common in young barley plants emerging in drying soil but this deficiency is usually transitory and disappears when rainfall re-wets the topsoil. [73]

Zinc is essential for protein and consequently important for enzyme function in many different tissues.

Deficiency symptoms appear as oily grey-green patches in the centre of leaves. Young leaves are most affected. Deficiency is typically associated with alkaline soils over a wide range of textures. Lime and gypsum can reduce Zn availability.

Critical tissue concentrations in the youngest expanded blade of barley are <14 mg/kg. [74] Zinc supplements can be applied with fertiliser as Zn oxide, chelated Zn or Zn sulfate. The products can also be used for foliar applications. Product efficacy varies with the time and placement of application. [75]

Deficiency symptoms (Photo 9 and Photo 10):

- Plants are stunted with short, thin stems and usually pale green leaves
- Young to middle leaves develop yellow patches between the mid vein and the edge of the leaf, extending lengthways towards the tip and base of the leaf
- These areas eventually die turning pale grey or brown
- Plants take on a water- or diesel-soaked appearance
- Affected areas may remain separate or join, with the death of the entire central leaf area, while the tip, base and margins remain green
- With severe deficiency, yellow areas and grey-brown lesions develop on the leaf sheath, resulting in reduced tillering with no or little grain produced
- Maturity is delayed. Mature plants are a dull grey colour compared with a bright yellow appearance of a healthy crop

Similar symptoms

The fungal disease yellow leaf spot has similar symptoms.

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72 GRDC (2013) Micronutrients. Crop Nutrition Fact Sheet GRDC, November 2013, http://www.grdc.com.au/GRDC-FS-CropNutrition-Micronutrients

73 DAFWA (2015) Diagnosing zinc deficiency in barley. Department of Agriculture and Food, Western Australia, https://agric.wa.gov.au/n/2540

74 R Norton (2014) What's new with zinc; maybe just some critical reminders. GRDC Update Papers, 11 February 2014, https://www.grdc.com.au/Research-and-Development/GRDC-Update-Papers/2014/02/Whats-new-with-zinc-maybe-just-some-critical-reminders

75 DAF Qld (2012) Wheat—nutrition. Department of Agriculture and Fisheries Queensland, http://www.daff.qld.gov.au/plants/field-crops-and-pastures/broadacre-field-crops/wheat/nutrition

Contributing factors

Application of some herbicides (especially Group B) makes the problem worse. Zinc deficiency occurs on many soil types but is most severe on highly alkaline clay soils and very infertile siliceous sands, yellow gravelly sands, yellow earths, highly alkaline peat soils and highly alkaline coastal sands. [76]

Photo 9: *Zinc deficiency in barley.*

Photos: DAFWA

Photo 10: *Zinc deficiency symptoms on barley leaves.*

Source: DAFWA

5.14.2 Copper

Most soils in WA are Cu deficient in their natural state. Copper is essential for pollen formation and has a role in formation of chlorophyll and lignification (cell wall strength). Deficiency causes sterile pollen, which, in turn causes poor grain formation and high yield losses. [77]

Wheat and barley are more responsive to Cu than canola.

Deficiency is common in sandy soils that are low in organic matter, as well as where there are high levels of iron (Fe), Mn or Al in the soil. Critical tissue levels have been reported as <1.5 mg/kg in the youngest expanded blade in wheat. [78]

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76 GRDC (2014) Winter cereal nutrition: The Ute Guide. GRDC, https://grdc.com.au/resources-and-publications/all-publications/publications/2007/05/uteguide-wintercerealnutrition

77 DAFWA (2015) Diagnosing copper deficiency in barley. Department of Agriculture and Food, Western Australia, https://agric.wa.gov.au/n/2534

78 R Norton (2014) Trace elements: copper and manganese. GRDC Update Papers, 20 August 2014, https://www.grdc.com.au/Research-and-Development/GRDC-Update-Papers/2014/08/Trace-elements-copper-and-manganese-their-role-requirements-and-options

Deficiency symptoms in barley are depicted in Photo 11 and Photo 12.

In the paddock:

- Before head emergence, deficiency shows as areas of pale, wilted plants with dying new leaves in an otherwise green healthy crop
- After head emergence, mildly affected areas have disorganised wavy heads Severe patches have white heads and discoloured late maturing plants
- Symptoms are often worse on sandy or gravelly soils, where root-pruning herbicides have been applied and recently limed paddocks

On the plant:

- Significant yield losses can occur from Cu with no visual symptoms
- Youngest growth is affected first and most severely
- The first sign of Cu deficiency before flowering is growing point death and tip withering, and/or bleaching and twisting of up to half the length of young leaves
- The base of the leaf can remain green
- Old leaves remain green and seemingly healthy
- Tiller production may increase but they die prematurely
- Heads may be white and withered or have a rat-tail appearance
- Maturity is delayed and very late tillers may be present
- Stems are weaker, although in less severe cases, plants heads may be more erect. Severely deficient plants have few immature heads on weak and dirty stems [79]

Similar symptoms

Drought stress, frost, take-all and Mo deficiency have similar symptoms. Boron and Ca deficiency also cause shoots to wither.

Contributing factors

Intensive cropping rotations with grain legume crops can contribute to deficiency. Additional N fertiliser can exacerbate the severity of the deficiency (crop still appears N-deficient). [80]

79 DAFWA (2015) Diagnosing copper deficiency in barley. Department of Agriculture and Food, Western Australia, https://agric.wa.gov.au/n/2534

80 GRDC (2014) Winter cereal nutrition: The Ute Guide. GRDC, https://grdc.com.au/resources-and-publications/all-publications/publications/2007/05/uteguide-wintercerealnutrition

Photo 11: *Copper deficiency n barley: head sterility causes delayed maturity.*

Source: DAFWA

Photo 12: *Copper deficiency symptoms on barley leaves.*

Source: Hungry Crops, DAF Qld

Photo 13: *Copper deficiency in barley: severely affected plants have no grain.*

Source: DAFWA

Photo 14: *Deformed barley heads indicating copper deficiency.*

Source: Nigel Wilhelm, SARDI

Alleviation

Copper can be applied as an additive to fertilisers, or as foliar spray as Cu sulfate, Cu oxychloride or chelated Cu. [81] However, the effectiveness of his strategy depends upon incorporation. Banding liquid Cu fertilisers at seeding can also be relatively effective. [82] One foliar spraying at booting may still be necessary in dry years.

5.14.3 Boron

Boron deficiency is rare in cereals in WA and will impact broadleaf crops such as lupin and canola before affecting cereals like wheat and barley. Boron does not easily move around the plant therefore a deficiency is most likely to be seen in the younger tissues first. [83]

Boron toxicity

Boron is essential for plants, but in some soils, it accumulates to toxic levels. Symptoms are yellowing and death of leaf tips, starting on the oldest leaves first (Photo 15). Symptoms often do not appear in early vegetative growth and are more extreme in a drying soil.

Similar symptoms

Spot-type net blotch has similar symptoms but is not soil-type specific.

Contributing factors

Boron toxicity can occur with high boron levels in subsoil and when growing B-intolerant varieties. [84]

Photo 15: *Symptoms of boron toxicity on barley leaves: Hamelin (left), Mundah (right).*

Source: DAFWA

MORE INFORMATION

Soil Quality (2017) Boron–Western Australia. Fact sheet.

81 DAF Qld (2012) Wheat—nutrition. Department of Agriculture and Fisheries Queensland, http://www.daff.qld.gov.au/plants/field-crops-and-pastures/broadacre-field-crops/wheat/nutrition

82 James Easton, CSBP. Pers comm.

83 DAFWA (2015) Diagnosing boron deficiency in barley. Department of Agriculture and Food, Western Australia, https://www.agric.wa.gov.au/mycrop/diagnosing-boron-deficiency-barley

84 GRDC (2014) Winter cereal nutrition: The Ute Guide. GRDC, https://grdc.com.au/resources-and-publications/all-publications/publications/2007/05/uteguide-wintercerealnutrition

5.14.4 Manganese

Liming programs and increasing water repellence is increasing the incidence of manganese (Mn) deficiencies in WA. [85]

Manganese deficiency

Key points:

- Manganese is a common enzyme cofactor for chlorophyll and photosynthesis
- Deficiency symptoms are often preceded by wilting and then chlorosis of younger leaves, often at the base of the leaf
- Deficiency is mainly a problem on soils with high organic matter, and those with free lime present. It may be toxic at low pH (<5)
- For cereals, tissue concentrations of <12 mg Mn/kg in the youngest mature leaf or <20–30 mg/kg in whole tops are considered deficient
- In some cases, foliar Mn can be more efficient than soil-applied Mn, because the latter can result in Fe or phosphate precipitates [86] However, there are cases where two to three foliar applications are required to overcome deficiencies and where soil applied Mn is very effective [87]
- Chelated formulations are also available, but they are expensive

Symptoms

- Deficiency often appears as patches of pale, floppy plants in an otherwise green, healthy crop
- Pale green stripes usually develop on young leaves and blotches develop that may have a thin brown rim (Photo 16)
- Leaves are weak and tear easily
- Tillering is greatly reduced with extensive leaf and tiller death (Photo 17). With extended deficiency, the plant may die
- Surviving plants produce fewer and smaller heads

Photo 16: *Manganese deficiency symptoms.*

Source: Nigel Wilhelm, SARDI

85 James Easton, CSBP. Pers comm.

86 GRDC (2014) Winter cereal nutrition: The Ute Guide. GRDC, https://grdc.com.au/resources-and-publications/all-publications/publications/2007/05/uteguide-wintercerealnutrition

87 James Easton, CSBP. Pers comm.

Photo 17: *Manganese deficiency in barley (left); adequate (right).*

Source: Nigel Wilhelm, SARDI

Similar symptoms

Zinc deficiency causes patches of pale stunted plants but not they are not 'floppy'.

Contributing factors

Deficiency tends to occur on coastal alkaline soils and high PRI, water repellent gravels associated with wandoo powderbark wandoo, brown and blue mallet, and blue mallee vegetation.

Manganese deficiency is worsened by dry soil, high soil pH, alkaline fertilisers and root pruning herbicides (particularly groups A and B).

Treatment

Manganese deficiency is controlled by:

- Foliar spray
- Acidifying ammonium nitrogen fertilisers can reduce manganese deficiency by lowering pH and making manganese more available to growing crops
- Manganese fertiliser is effective but expensive as high rates and several applications are required to generate residual value [88]

MORE INFORMATION

DAFWA (2015) Diagnosing manganese deficiency in barley.

5.14.5 Molybdenum

Key points:

- Molybdenum is important for nitrate reductase activity in all plants
- Deficiency symptoms are similar to those of N deficiency
- Availability increases with high soil pH, and deficiencies are common on acid soils, especially in high-rainfall areas
- Levels <0.075 mg/kg in the youngest fully emerged leaf indicate deficiency [89]

88 DAFWA (2015) Diagnosing manganese deficiency in barley. Department of Agriculture and Food, Western Australia, https://agric.wa.gov.au/n/2536

89 DAFWA (2015) MyCrop. Diagnosing molybdenum deficiency in cereals. Department of Agriculture and Food, Western Australia, https://www.agric.wa.gov.au/mycrop/diagnosing-molybdenum-deficiency-cereals

- Very small quantities (50 g Mo/ha) applied with fertiliser are usually sufficient, usually in the form of Mo trioxide. Sodium or ammonium molybdate can be used as sprays [90]

Photo 18: *Wheat grown without (left) and with molybdenum (symptoms are similar in barley).*

Source: Snowball and Robson 1988

Symptoms (Photo 18):

- Symptoms are difficult to detect in the field, particularly early in the season
- At low levels of N, the crops are pale with some limpness
- As N levels increase, symptoms become more specific with all but the oldest leaves pale being green with adequate to high levels of N
- Middle leaves have a speckled flecking or yellow stripes
- Leaves appear limp and water-stressed
- Tip scorching of old leaves apparent at high N levels
- Severe deficiency causes delayed maturity and empty heads

Similar symptoms

Stem and head frost damage causes late tillering and shrivelled grain.

Contributing factors

Factors include acidic soils, moderate to high levels of available soil N, and soils high in Fe and Al oxides. [91]

5.14.6 Magnesium

Western Australian agricultural soils, particularly acidic sands, are inherently low in magnesium but deficiency is rare in broadacre crops. [92]

Symptoms (Photo 19):

- Young crops have poor growth with pale yellow leaves
- In more mature crops, plants are stunted with thin spindly stems and pale yellow foliage is marked with necrotic lesions
- Old leaves develop elongated grey to brown spots near the edges, usually near the mid-section of the leaf. Lesions spread rapidly towards the tip and base of the leaf
- With severe deficiency, old leaves turn brown and die

90 Incitec Pivot. Molybdenum fact sheet. Fertfacts. Incitec Pivot, http://www.incitecpivotfertilisers.com.au/en/Agronomy/~/media/Files/IPF%20Migration/FertFacts/MolybdenumFS/MolybdenumFSV3IIPLLM15102009.ashx

91 GRDC (2014) Winter cereal nutrition: The Ute Guide. GRDC, https://grdc.com.au/resources-and-publications/all-publications/publications/2007/05/uteguide-wintercerealnutrition

92 DAFWA (2015) Diagnosing magnesium deficiency in barley. Department of Agriculture and Food, Western Australia, https://www.agric.wa.gov.au/mycrop/diagnosing-magnesium-deficiency-barley

Similar symptoms

Potassium and N deficiency symptoms include pale plants starting from the oldest leaf, but no grey-brown lesions.

Contributing factors

In WA, Mg levels are normally improved with applications of lime. [93]

Photo 19: *Magnesium deficiency symptoms in barley.*

Photos: Noel Grundon, DAF Qld

MORE INFORMATION

DAFWA (2015) Diagnosing magnesium deficiency in barley.

93 James Easton, CSBP. Pers comm.