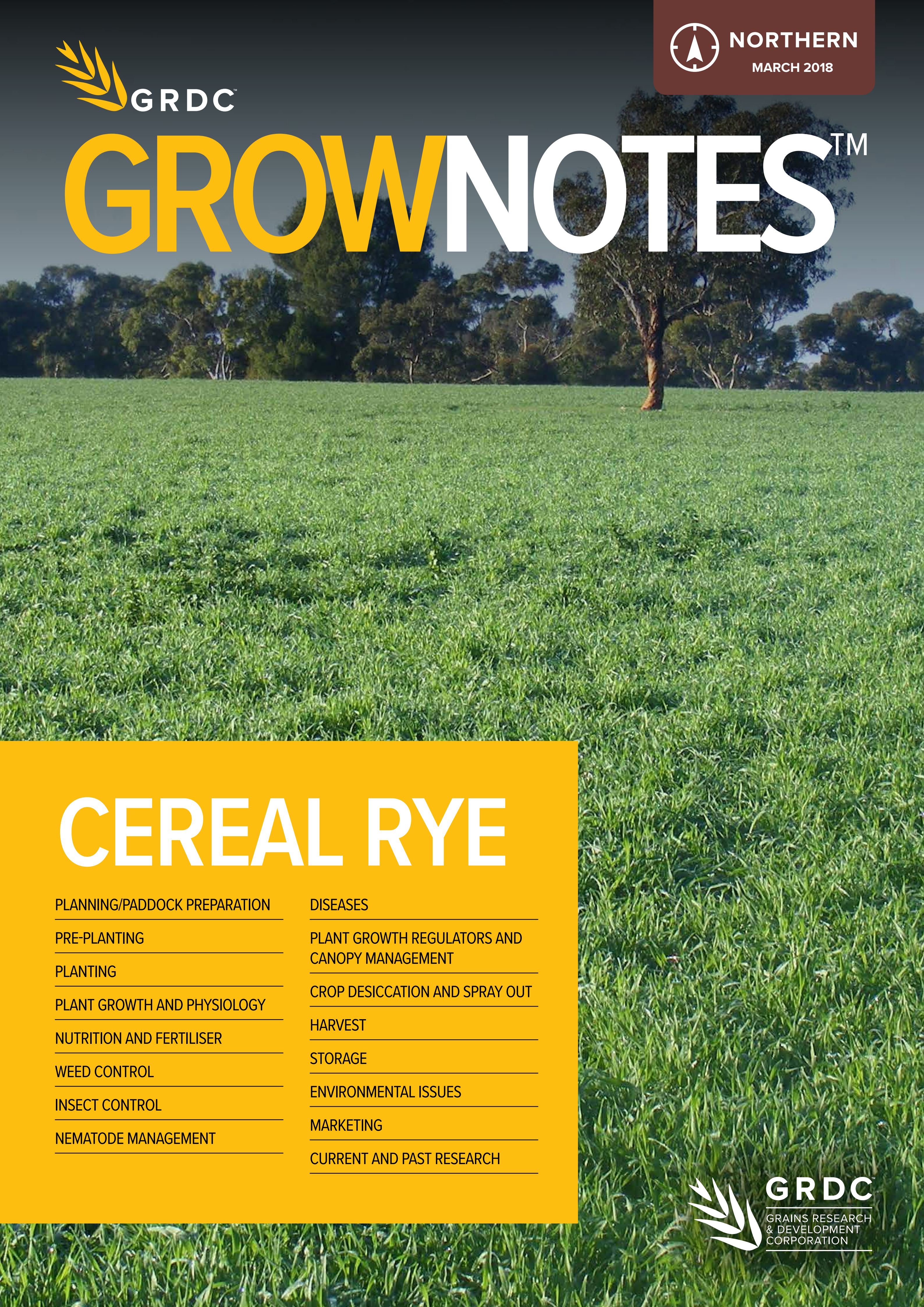

NORTHERN
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GRDC

GROWNOTES™

CEREAL RYE

GRDC
GRAINS RESEARCH & DEVELOPMENT CORPORATION

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Introduction

A.1 Crop overview

Cereal rye (*Secale cereale,* Photo 1) is a versatile crop, closely related to wheat and barley but a hardier variety. It is a comparatively modern cereal, first cultivated in northern Europe. Rye is thought to have originated from wild types of rye, which are weeds in wheat crops in Asia Minor. Rye is grown for grain, forage, green manure or as a cover crop for erosion and compaction control. Rye is the most productive of the cereal grain crops under conditions of low temperature, low fertility and drought.

Photo 1: *Cereal rye grain heads.*

Source: Plant Village

For more information on cereal rye as a cover crop, see Cover crops.

A.1.1 Comparative notes

- Rye is more cold- and drought-tolerant than wheat.
- Oats and barley do better than rye in hot weather.
- Rye is taller than wheat and tillers less. It can produce more dry matter than wheat and some other cereals on poor soil under drought conditions but is harder to burn down than wheat or triticale.
- Rye is a better soil renovator than oats, but brassicas and Sudan grass (*Sorghum x drummondii*) provide deeper soil penetration.
- Rye generally contains less nitrogen than brassicas, which scavenge nitrogen nearly as well as rye and are less likely to tie it up because they decompose more rapidly. [1]

A.1.2 Description

Rye has an erect slender stem topped with a curved spike 7–15 cm long (Photo 2). The head is made up of individual spikelets, each with two florets producing one or two kernels (Table 1). The spikelets are arranged alternately along the length of the head. The leaves of the plant grow from nodes on the stem and are lance-like blades,

1 A Clark (Ed.) (2007) Managing cover crops profitably, 3rd edn. Sustainable Agriculture Network, Beltsville, MD, http://mccc.msu.edu/wp-content/uploads/2016/08/ManagingCCProfitably.pdf

blue-green in colour. Rye can reach one to three metres in height, and it is grown as an annual (spring rye) or biennial (winter rye). [2]

Photo 2: *The rye seed head (left) is slender, and longer and somewhat nodding compared to the wheat seed head (right).*

Source: University of Nebraska

Table 1: *Characteristics that differentiate wheat from rye.*

Characteristic	Wheat	Rye
Stems	Erect and freely branching at base, 60–100 cm tall	Larger and longer than wheat
Leaves	Blade 1–2 cm wide, usually dark green in color	Coarser and more bluish than wheat
Ligules	Membranous with an irregular edge fringed with minute hairs	Membranous, short and somewhat rounded
Auricles	Purple changing to white, sharply curved and always present	White, narrow and withers early
Seed head	5–13 cm long, oblong or elliptical in shape	Slender, longer than wheat, and somewhat nodding
Seed	Roughly egg-shaped and light brown to darker red	Narrower than wheat and usually brownish-olive to yellow in colour

Source: NebGuide

Rye grain is smaller and darker than wheat, is harder to mill and produces a lower percentage of flour. Rye can be milled into flour or used whole or cracked in many recipes. Whole-grain rye flour includes the bran, germ and the endosperm and is slightly coarser and darker than the finer grades of flour. The protein concentration of rye is less than that of wheat. Rye flour does not have true gluten proteins but it does contain proteins that make a nutritious, dark, heavy leavened bread. Rye flour also has a higher content of soluble fibre. [3]

Hectolitre (hL) weight is normally about 70–75 kg, with a minimum of 70 kg/hL and maximum moisture of 12% for marketing purposes. Grain protein tends to be slightly lower than that of wheat. The dough lacks the elastic properties of wheaten dough. Bread made from rye flour has a close texture and a slight 'tang'.

Rye is a winter–spring cereal, with a growing period similar to the main winter–spring cereals such as wheat, oats and barley. Rye is sown in May–June for grain, and March–April for grazing. Harvesting is in October–December, depending on the region. Rye withstands adverse conditions better than other cereals. It can withstand cold and limited waterlogging. More importantly, its drought-tolerance and ability to withstand sand blast enables it to produce a soil-binding cover on land where other

2 Plant Village (2015) Rye: *Secale cereale*. Penn State University and École polytechnique fédérale de Lausanne, https://www.plantvillage.org/en/topics/rye/diseases_and_pests_description_uses_propagation

3 B Van Veldhuizen (2010) Growing small grains in your garden. Agricultural and Forestry Experiment Station Circular 135. University of Alaska Fairbanks, February 2010, http://www.uaf.edu/files/snras/C135.pdf

cereals will not grow. Under conditions where wheat, oats or barley will grow only a few centimetres high, or they may even be completely blown away, rye often will grow vigorously and reach a height of a metre or more.

Demand for cereal rye has been static for a number of years, with domestic consumption ~25,000 tonne per annum. Local use for rye is mainly in the form of kibbled rye or cracked grain for use in mixed-grain breads or for breads requiring more fibre. Demand has also increased, but to a lesser extent, for sourdough rye bread, rye flour and rye meal.

Production in Australia is generally erratic, with supply and demand very elastic and price-sensitive. Seasonal conditions, and the soil type and topography where rye is usually grown, greatly influence seasonal production. [4]

Grain is generally traded directly to merchants with prices fluctuating according to supply and demand. Some merchants may offer sowing contracts, usually with a guaranteed price based on a fixed area and estimated yield. Growers should confirm receival standards before entering into any contracts (see GTA Trading Standards). [5]

Cereal rye should not be confused with the aggressive weed annual ryegrass (*Lolium rigidum*). For more information, see Annual ryegrass or cereal rye?

A.1.3 Rye for human consumption

Cereal rye can be grown as a grain crop for alcoholic beverages and food. Cereal rye is quite distinct from wheat for bread making; the dough lacks elasticity and gas-retention properties. Used alone, it produces a distinctive black bread. Lighter rye loaves are produced from rye and wheat mixtures. Rye flour, rye meal and kibbled rye are all end-products (Photo 3). Rye flour and meal are used in rye bread and biscuits. Plump grain is highly sought after for kibbled rye manufacture. [6]

Photo 3: *Wholegrain rye flour (left) and kibbled rye (right) milled for human consumption.*

Source: Blue Lake Milling

4 Agriculture Victoria (2013) Growing cereal rye. AgNote no. 0403. Agriculture Victoria, May 2013, http://agriculture.vic.gov.au/agriculture/grains-and-other-crops/crop-production/growing-cereal-rye

5 P Matthews, D McCaffery L Jenkins (2016) Winter crop variety sowing guide. NSW Department of Primary Industries, https://www.dpi.nsw.gov.au/agriculture/broadacre-crops/guides/publications/winter-crop-variety-sowing-guide

6 P Matthews, D McCaffery L Jenkins (2016) Winter crop variety sowing guide. NSW Department of Primary Industries, https://www.dpi.nsw.gov.au/agriculture/broadacre-crops/guides/publications/winter-crop-variety-sowing-guide

A.1.4 Rye for animal consumption

Cereal rye can be grazed. When used as grazed forage, cereal rye is usually mixed with other cool-season species such as triticale. Rye can be cut for hay at the early heading stage of development. [7] Cereal rye should be mixed with other grains when fed to monogastrics, especially chickens. It has a high content of soluble pentosans (a class of polysaccharide, a type of carbohydrate molecule), which can cause decreased weight gain and sticky droppings in chickens. [8]

Grain

Rye grain has a feeding value about 85–90% that of maize, and contains more digestible protein and total digestible nutrients than oat or barley. Rye is most satisfactorily used when mixed with other grains at a proportion less than one-third, because it is not highly palatable and is sticky when chewed. [9]

One study compared the effectiveness of rye grain and wheat grain for feeding sheep. There was no significant difference in liveweight change between sheep fed rye and sheep fed wheat. Sheep with free access to grain (production group) ate more rye than wheat. The reason is not known, but rye did not depress feed intake compared with wheat. Sheep offered maintenance rations ate all of the grain on the day it was fed. The results indicate that rye and wheat perform equally as maintenance and production rations for sheep. However, farmers should observe their sheep closely when first using rye grain. [10]

Forage

Rye makes excellent forage, especially when combined with red or crimson clover (*Trifolium pratense, T incarnatum*) and ryegrass (*Lolium* spp.). For best quality, rye should be cut between early heading and the milk stage of growth. Rye matures earlier and has higher crude protein levels than wheat and triticale. However, rye forage yields are lower, resulting in somewhat lower crude protein yields and overall lower relative feed values. Thus, the main advantages of winter rye as a forage compared with winter wheat or winter triticale is that it is more winter-hardy and reaches optimum harvest maturity 7–10 days earlier.

Pasture

In the growth stage before heading, rye is used extensively as a pasture crop. Rye generally provides more forage than other cereals in late autumn and early spring because of its rapid growth and its adaptation to low temperatures. Although rye is a less palatable pasture crop, it is readily grazed when other green forages are not available. [11]

A.2 Growing regions

The Northern region takes in central and southern Queensland, and New South Wales (NSW).

Most rainfall in the north of the region tends to be over summer, allowing for dryland summer crop production. However, with the high moisture-storing capacity of the clay-based soils of these zones, supplemented by some winter rainfall, winter crops are also successfully produced. Winter crops in the north of the region are planted across a wide period, starting in March in central Queensland, through to July in central NSW. Consequently, harvest can stretch from September through to

7 PA Casey (2012) Plant guide for cereal rye (*Secale cereale*). USDA Natural Resources Conservation Service, May 2012, https://plants.usda.gov/plantguide/pdf/pg_sece.pdf

8 P Matthews, D McCaffery L Jenkins (2016) Winter crop variety sowing guide. NSW Department of Primary Industries, https://www.dpi.nsw.gov.au/agriculture/broadacre-crops/guides/publications/winter-crop-variety-sowing-guide

9 EA Oelke, ES Oplinger, H Bahri, BR Durgan, DH Putnam, JD Doll, KA Kelling (1990) Rye. In Alternative field crops manual. University of Wisconsin and University of Minnesota, https://hort.purdue.edu/newcrop/afcm/rye.html

10 B Ashton, D Rendell, A King (1992) The value of cereal rye as a grain for feeding sheep. Proceedings of the Australian Society of Animal Production, Vol. 19, http://www.asap.asn.au/livestocklibrary/1992/Ashton92.PDF

11 EA Oelke, ES Oplinger, H Bahri, BR Durgan, DH Putnam, JD Doll, KA Kelling (1990) Rye. In Alternative field crops manual. University of Wisconsin and University of Minnesota, https://hort.purdue.edu/newcrop/afcm/rye.html

December. Similarly, summer crops are planted from September through to February with harvest spanning February–May.

The south of the region is southern New South Wales (south of Dubbo). The rainfall pattern ranges from uniform in central New South Wales through to winter-dominant further south. Dry summers and comparatively reliable winter rainfall lend themselves to winter crop production. Planting of the winter crop depends on 'opening rains' and usually begins in May and can continue through until late July. The winter crop harvest can begin in late October and continue through to January. Summer crop production requires irrigation and the major field crop irrigated in this region is medium-grain rice in southern New South Wales. [12]

The main winter cereal crops in NSW are wheat, barley and oats, with lesser areas sown to rye and triticale. [13]

A.3 Brief history

Domesticated rye occurs in small quantities at a number of Neolithic sites in Turkey but is otherwise virtually absent from the archaeological record until the Bronze Age of Central Europe, circa 1800–1500 BCE. It is possible that rye traveled west from Turkey as a minor admixture in wheat, and was only later cultivated in its own right. Since the Middle Ages, rye has been widely cultivated in Central and Eastern Europe and is the main bread cereal in most areas east of the French–German border and north of Hungary. [14]

Around the world, the area of cultivated land dedicated to growing rye has decreased substantially since the 1970s. In 1986, the area harvested was 24 million hectares but this had dropped by 29% to 17 million hectares by 1996. The decrease in cultivated area was largely offset by an increase in yield. Yields during the late 1960s were as low as 11.5 centals (~520 kg) per hectare, but had increased by 57% to 18 centals (~816 kg) per hectare by the 1990s. This significant increase in yield was achieved through improvement of agronomic practices, especially in the use of chemical fertilisers and crop rotation, decline in the use of less fertile land, and development of high-yield cultivars. [15]

Cereal rye has been grown in Australia for more than 150 years. Production in Australia is generally erratic, with supply and demand very elastic and price-sensitive (Figure 1).

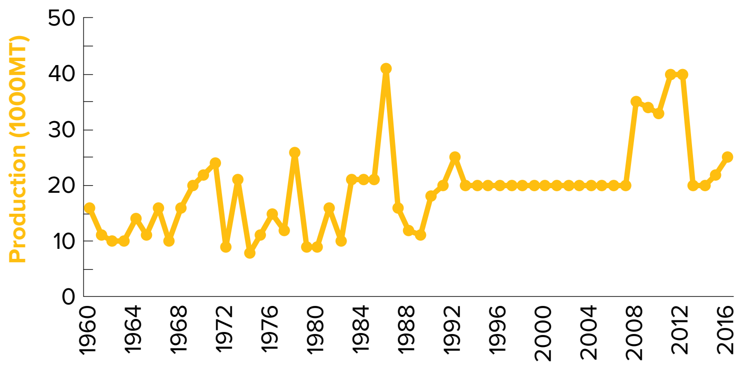

Figure 1: *Australian rye production by year.*

Source: IndexMundi

12 AEGIC (2016). Australian grain production—a snapshot. Australian Export Grains Innovation Centre, August 2016, http://aegic.org.au/australian-grain-production-a-snapshot/

13 JP Brennan, JD Sykes, JF Scott (2004) Trends in pulse and oilseed crops in winter cereal rotations in NSW. Economic Research Report No.26. New South Wales Department of Primary Industries, http://www.dpi.nsw.gov.au/content/research/economics-research/reports/err26

14 D Zohary, M Hopf, E Weiss (2012) Domestication of plants in the old world: the origin and spread of domesticated plants in south-west Asia, Europe, and the Mediterranean basin. Oxford University Press.

15 W Bushuk (2001) Rye production and uses worldwide. *Cereal Foods World* 46, 70–73, http://www.agmrc.org/media/cms/bushuk_C8B79BAB55BB0.pdf

Planning/Paddock preparation

Key messages:

- Relatively inexpensive and easy to establish, cereal rye (*Secale cereale*) outperforms all other cover crops on infertile, sandy or acidic soil or on poorly prepared land. It is widely adapted, but grows best in cool, temperate zones.
- Cereal rye prefers light loams or sandy soils and will germinate even in quite dry soil. It also will grow in heavy clays and poorly drained soils, and many cultivars tolerate waterlogging.
- The optimum pH($CaCl_2$) for cereal rye growth is ~4.5–7.5. [1] It is also tolerant of high levels of aluminium (Al). [2]
- Rye can establish in very cool weather. It will germinate at temperatures as low as ~1°C. Vegetative growth requires ~3°C or higher. [3]
- It is used for early sowings as a dual-purpose cereal, providing abundant, quick, early stock feed, as a grain-only crop, and for erosion control. [4]
- Cereal rye is adapted to all soils; however, its major fit is on the lighter acid soils where yields are usually 70–100% of wheat and triticale when sown between May and June. [5]

1.1 Paddock selection

1.1.1 Disease

Cereal rye is relatively tolerant of many cereal diseases (i.e. take-all, and rusts) making it a useful break crop following grassy pastures. [6]

Paddock selection is an important consideration for crown rot management in particular, and growers should select paddocks with a low risk of the disease. Paddock risk can be determined by visually assessing crown rot and root-lesion nematode (RLN; see later discussion) levels in a prior cereal crop, paying attention to basal browning and/or having soil samples analysed at a specialised testing laboratory (e.g. Predicta B). The presence of spores of tan (yellow) spot is also an important consideration, and effective management of this disease depends on decisions made before sowing.

Paddock histories likely to result in high risk of disease such as crown rot include:

- durum wheat in the past one to three years
- winter cereal or a high grass burden from last season—crown rot fungus survives in winter cereal residues, dense stubble cover or where dry conditions have made residue decomposition slow
- break crops, which can influence crown rot in cereals by manipulating the amount of nitrogen (N) and moisture left in the soil profile

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1 NSW Agriculture (2000) Understanding soil pH. Acid Soil Action Leaflet No. 2. NSW Department of Primary Industries, http://www.dpi.nsw.gov.au/__data/assets/pdf_file/0003/167187/soil-ph.pdf

2 B Upjohn, G Fenton, M Conyers (2005) Soil acidity and liming. AgFact AC 19. NSW Department of Primary Industries, http://www.dpi.nsw.gov.au/__data/assets/pdf_file/0007/167209/soil-acidity-liming.pdf

3 SARE (2007) Cereal rye. In Managing Cover Crops Profitably, 3rd Edition. Sustainable Agriculture Research and Education, http://www.sare.org/Learning-Center/Books/Managing-Cover-Crops-Profitably-3rd-Edition/Text-Version/Nonlegume-Cover-Crops/Cereal-Rye

4 P Matthews, D McCaffery, L Jenkins (2016) Winter crop variety sowing guide 2016. NSW Department of Primary Industries, https://www.dpi.nsw.gov.au/agriculture/broadacre-crops/guides/publications/winter-crop-variety-sowing-guide

5 P Matthews, D McCaffery, L Jenkins (2016) Winter crop variety sowing guide 2016. NSW Department of Primary Industries, https://www.dpi.nsw.gov.au/agriculture/broadacre-crops/guides/publications/winter-crop-variety-sowing-guide

6 P Matthews, D McCaffery, L Jenkins (2016) Winter crop variety sowing guide 2016. NSW Department of Primary Industries, https://www.dpi.nsw.gov.au/agriculture/broadacre-crops/guides/publications/winter-crop-variety-sowing-guide

- paddocks that have high levels of N at sowing and/or low stored soil moisture at depth [7]
- wheat varieties grown in previous year (Photo 1). [8]

Photo 1: *Rhizoctonia root rot: Diseased patches from previous crops vary in size from less than half a metre to several metres in diameter.*

Source: Department of Agriculture and Food Western Australia

For more information, see Section 9: Diseases.

1.1.2 Soil

Soil characteristics (surface and subsurface) such as soil pH, sodicity, salinity, acidity, texture, drainage characteristics and compaction will affect choice of crop. Cereal rye is relatively inexpensive and easy to establish, and it outperforms all other cover crops such as wheat on infertile, sandy or acidic soil or on poorly prepared land. [9]

Cereal rye performs well on light loams or sandy soils, and it will germinate even in quite dry soil. It also will grow in heavy clays and poorly drained soils, and many cultivars tolerate waterlogging. [10]

7 GRDC (2009) Crown rot in cereals. GRDC Fact Sheet, May 2009, https://grdc.com.au/resources-and-publications/all-publications/factsheets/2009/05/crown-rot-in-cereals-fact-sheet-southern-western-regions

8 R Brill, S Simpfendorfer (2013) Resistance of eighteen wheat varieties to the root-lesion nematode *Pratylenchus thornei*—Trangie 2011. In NSW DPI Northern Grains Region Trial Results Autumn 2013, pp. 129–131, http://www.dpi.nsw.gov.au/__data/assets/pdf_file/0004/468328/Northern-grains-region-trial-results-autumn-2013.pdf

9 UVM (2011) Cereal rye. University of Vermont Extension Crops and Soils Team, April 2011, http://northerngraingrowers.org/wp-content/uploads/RYE.pdf

10 SARE (2007) Cereal rye. In Managing Cover Crops Profitably, 3rd Edition. Sustainable Agriculture Research and Education, http://www.sare.org/Learning-Center/Books/Managing-Cover-Crops-Profitably-3rd-Edition/Text-Version/Nonlegume-Cover-Crops/Cereal-Rye

Cereal rye tolerates high Al levels in acid soils (critical concentration of $CaCl_2$-extractable Al 1.7–2.7 mg/L). [11] Cereal rye is even more tolerant of high Al levels than triticale, also regarded as an acid-soil-tolerant crop choice. [12]

Soil pH

Key points:

- Low pH values (<5.5) indicate acidic soils and high pH values (>8.0) indicate alkaline soils.
- Soil pH between 5.5 and 8 is not usually a constraint to crop or pasture production.
- Outside of the optimal soil pH range, microelement toxicity damages crops.
- The optimum soil pH($CaCl_2$) for growth of cereal rye is ~4.5–7.5. [13]

Soil pH is influenced by chemical reactions between soil components and water. It is affected by the various combinations of positively charged ions (sodium, potassium, magnesium, calcium, aluminum, manganese and iron) and negatively charged ions (sulfate, chloride, bicarbonate and carbonate). Soil pH directly affects the concentration of major nutrients and the forms of microelements available for plant uptake and can result in deficiencies or toxicities (Figure 1).

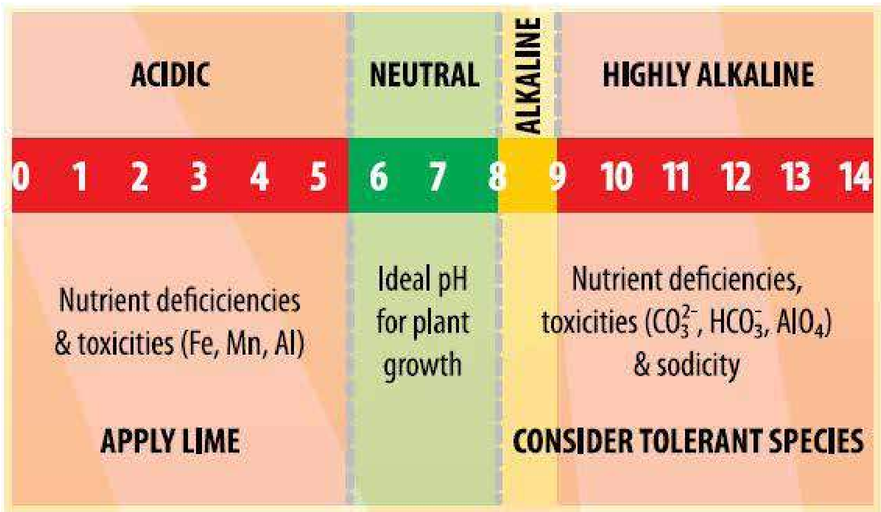

Figure 1: *Classification of soils on the basis of pH (1:5 soil:water), the implications for plant growth and some management options.*

Source: Soil Quality Pty Ltd

More than 500,000 ha of agricultural and pastoral land in Queensland has acidified or is at risk of acidification, and more than half of the intensively used agricultural land in New South Wales (NSW) is affected by soil acidity. Soils most at risk are lighter textured sands and loams with low organic matter levels, and the naturally acidic red clay loam soils commonly found in areas such as the South Burnett and Atherton Tableland. Soils least at risk are the neutral to alkaline clay soils (e.g. brigalow soils and the black clay soils of the Darling Downs and central Queensland).

Acidic soils result in significant losses in production, and where the choice of crops is restricted to acid-tolerant species and varieties, profitable market opportunities may be reduced. In pastures grown on acidic soils, production will be reduced and some legume species may fail to persist.

11 B Upjohn, G Fenton, M Conyers (2005) Soil acidity and liming. AgFact AC 19. NSW Department of Primary Industries, http://www.dpi.nsw.gov.au/__data/assets/pdf_file/0007/167209/soil-acidity-liming.pdf

12 P Matthews, D McCaffery, L Jenkins (2016) Winter crop variety sowing guide 2016. NSW Department of Primary Industries, https://www.dpi.nsw.gov.au/agriculture/broadacre-crops/guides/publications/winter-crop-variety-sowing-guide

13 NSW Agriculture (2000) Understanding soil pH. Acid Soil Action Leaflet No. 2, NSW Department of Primary Industries, http://www.dpi.nsw.gov.au/__data/assets/pdf_file/0003/167187/soil-ph.pdf

Management of acidic soils

Soil testing

Ideally, soil samples should be taken when soils are dry and have minimal biological activity. Soil samples should be taken from a number of locations across the paddock, as pH may vary from place to place. Samples should be taken at the surface (0–10 cm), and in the subsurface (50–60 cm) to detect subsurface acidity, which may underlie topsoils with an optimal pH. Samples need to be properly located (e.g. GPS) to allow monitoring. Sampling should be repeated every three to four years to detect changes and allow adjustment of management practices.

Farming practices to reduce acidification

Soil acidity must be treated early. If the acidity spreads to the subsoil, serious yield reductions may occur. Subsoil acidity is difficult and costly to ameliorate. Farming practices recommended to minimise acidification include:

- Match N fertiliser inputs to crop demand. Soil testing should be carried out to ensure that fertiliser rates match plant requirements.
- Use forms of N fertiliser that cause less acidification. Table 1 summarises the acidifying effect of different N fertilisers. Nitrate-based fertilisers such as calcium nitrate and potassium nitrate are the least acidifying, but their higher cost limits their use to high value horticultural crops.
- Apply N in split applications, if feasible. Application of a crop's entire fertiliser needs at planting time may contribute to soil acidification by allowing the leaching of nitrate N before the crop roots have developed.
- Sow early after fallow to ensure more rapid utilisation of available N.
- Grow deep-rooting perennial species to take up N from greater depths.
- Regularly apply lime to counter the acidification inherent in the agricultural system.
- Grow acid-tolerant crops or crop varieties more tolerant of acid soils.
- Irrigate efficiently to minimise leaching.

Table 1: *Acidification potential of nitrogen fertilisers assuming that some leaching loss of applied nitrogen occurs.*

Fertiliser	Acidification potential
Calcium nitrate, potassium nitrate	Low
Nitram, urea, animal manure	Medium
Ammonium sulfate, mono-ammonium phosphate (MAP), di-ammonium phosphate (DAP)	High

Source: Soil Quality Pty Ltd

Lime or dolomite application

When soils are too acidic for a particular crop, lime or dolomite can be used to increase soil pH to the desired level. The amount of lime or dolomite required to correct an acidic pH will depend on the soil and the crop.

Soils with high organic matter and clay content will be more resistant to changes in pH and will require higher application rates. To obtain an estimate of the amount of lime required to correct an existing soil acidity problem, a 'lime requirement' or 'buffer pH' soil test should be requested. The test is used to give a lime recommendation to raise the soil pH of the surface 10 cm of one hectare of soil to a target pH that will not limit crop yield. In general, a target pH of 5.5 is suggested.

Once the target soil pH is reached, additional lime or dolomite may be required depending on the crop. The acidifying effect of cropping systems is related to the amount of material removed at harvest, the amount and type of fertilisers normally used and the amount of leaching that occurs. Table 2 gives an indication of the

VIDEOS

WATCH: GCTV8: Liming acid soils.

amount of lime required to counter the inherent acidification associated with some cropping systems. There are opportunities to decrease these lime rates by adjusting N fertiliser rates or form of N fertiliser used. [14]

Table 2: *Lime required to counter the acidification inherent in some cropping systems.*

Cropping system	Lime required (t/ha/year)
Summer crop-winter fallow	0.1
Crop-pasture rotation	0.1
Sugarcane	0.2
Grass pasture for hay production	0.3

Source: Soil Quality Pty Ltd

Cereal rye on erosion-prone soils

Rye has the ability to withstand sand blasts, which enables it to produce a soil-binding cover on land where other cereals will not grow. Under conditions where wheat, oats and barley will grow to only a few centimetres high, or they may even be blown away, rye often will grow vigorously and reach a height of one metre or more.

A further reason for using cereal rye on erosion-prone soils is that its grain and straw are the cereal least preferred by sheep. Sheep provided with more than one choice of stubble within a paddock will preferentially graze other stubbles before they will eat rye stubble.

After the crop is harvested, the tough, resilient stubble is generally left as a protective cover to reduce blowing of the soil and to assist colonisation by other species. Stubble of rye breaks down more slowly than the stubble of other cereals, ensuring soil cover for a long period. [15]

In south-western New South Wales, cereal rye may have a role as a companion crop to cotton for stubble in sandy soils and loams of the lower rainfall area.

Subsoil constraints

Subsoil constraints are chemical, physical or biological properties in the subsoil that limit plant growth. Poor crop growth, despite good starting moisture and adequate in-crop rainfall, may be an indicator of the presence of subsoil constraints. The Northern grains region has generally high soil fertility, although there is increasing evidence that this has been run down over time.

For example, vertosol soils, which occur throughout the north-west of NSW and southern Queensland, are generally well structured and fertile and have pH close to neutral. On these soils, yield is constrained not by surface soil properties, but by subsoil constraints. These include low permeability, shallow rooting depths, sodicity, salinity and toxic concentrations of some elements.

In southern NSW, compaction, acidity and salinity/sodicity may occur and affect crop production. [16]

In the Northern region, both summer and winter crops are important for profit. Much of the region has relatively high seasonal rainfall and production variability compared with the western and southern regions. Much of the region experiences summer-dominant rainfall and grain yield is significantly dependent on conserving soil water from summer rain.

14 Soil Quality Pty Ltd. Soil acidity—Queensland. Soil Quality Fact Sheets, http://www.soilquality.org.au/factsheets/soil-acidity-qld

15 R Sonogan (2013) Growing cereal rye. Agriculture Victoria, May 2013, http://agriculture.vic.gov.au/agriculture/grains-and-other-crops/crop-production/growing-cereal-rye

16 T Swan *et al.* (2011) Production impacts of subsoil constraints on canola productivity in southern NSW. In 17th Australian Research Assembly on Brassicas, http://www.australianoilseeds.com/__data/assets/pdf_file/0009/8298/S6-P2-Swan.pdf

In the Northern grains region, the most significant yield constraints are low nutrient-use efficiency, low water movement through saturated soil (low saturated hydraulic conductivity) and high soil density.

Managing subsoil constraints

Good agronomic management helps to minimise the water and other physiological stresses imposed by subsoil constraints (Table 3). In paddocks where subsoil constraints exist, successful cropping can be achieved by:

- maximising fallow efficiency with short fallows
- ensuring effective weed control
- using suitable rotations that minimise disease
- matching nutrients to realistic yield expectations
- using appropriate species and cultivar selection
- undertaking timely crop sowing.

Table 3: *Some management options for soils with high chloride (Cl) and sodium (Na) concentrations in the top 1 m soil depth.*

Low constraints	Medium constraints	High constraints
(<600 mg Cl, <500 mg Na/kg)	**(600–1200 mg Cl, 500–1000 mg Na/kg)**	**(>1200 mg Cl, >1000 mg Na/kg)**
Use cereal–legume rotation Consider canola if soil profile is full Manage crown rot and nematodes Try opportunity cropping to use available water	Grow tolerant cereals (wheat, barley, canola) Match inputs to realistic yield Consider tolerant cultivars Manage crown rot and nematodes Avoid legumes and durum wheat Try opportunity cropping to use available water	Consider alternative land use (saline forage/pasture production, agro-forestry/ forestry system) Avoid crops or grow tolerant cereals Match inputs to realistic yield

Source: Soil Quality Pty Ltd

Soil testing guide

Key points:

- The approach taken will be defined by the purpose of the investigation, variability in the area sampled, and the analysis and accuracy required.
- For many soil quality parameters sampling is typically done to 10 cm.
- When sampling below 10 cm (e.g. 30 cm is required for carbon accounting purposes) stratification by depth increments is recommended (e.g. 10–20, 20–30 cm).
- The sampling strategy should either integrate or describe the variation within the sampling area.
- Samples should be air-dried or kept below 4°C prior to analysis. For biological measurements, analysis should be done as soon as possible.

Before deciding how to soil-sample, be clear about the purpose of your sampling. Different sampling approaches may be required depending on what you are sampling for, the soil type, the management unit (e.g. paddock), soil spatial variability (changes in soil type, dunes–swales, etc.), the accuracy required of the result, and the value placed on the information provided (Photo 2). So before you start, define clearly the question you are asking of your soil samples. Consult a professional soil scientist, agronomist or your analytical laboratory to be sure that your soil samples are taken at the right time, from the right depth, the right place, in the appropriate number and are stored in such way that the analysis required is not compromised. If quantitative soil analyses (kg/ha) are required then soil bulk density must also be measured and this requires considerable care. [17]

Photo 2: *To be meaningful, soil sampling needs to take into account spatial variation in the soil condition. Differences in soil type, nutrient status and other soil properties may be exhibited within a paddock.*

Source: Soil Quality Pty Ltd

1.1.3 Paddocks for forage cereals

If cereal rye is to be used as fodder to provide additional grazing, then a well-drained paddock that can resist pugging damage from stock should be chosen. A paddock of higher fertility that is well drained will provide maximum dry matter production. It is best to select a paddock that has a low level of pasture grasses to avoid the risk of cereal disease transmission, although cereal rye has tolerance to a number of cereal diseases. [18]

1.1.4 Topography

The topographic variations typical of large agricultural paddocks can have a substantial impact on dynamics of soil mineral N as well as on performance of crops. Spatial variations in soil organic matter, soil microbial biomass, natural drainage, plant growth and water and nutrient redistribution caused by topography are the main factors controlling the dynamics of soil mineral N. Along with weather, landscape topographic patterns accounted for most of the variations in plant available N.

There are potential environmental and economic benefits of site-specific, topography-driven cover-crop management. Management decisions regarding where to plant crops can vary depending on the management goals and complexity of the terrain. For example, cover crops seem to be particularly advantageous on eroded unfertile slopes where legumes bring the needed N inputs, and rye does not result in substantial N reductions, while all cover crops contribute to erosion control and carbon sequestration there. On the other hand, if N leaching is the major concern, low located depression areas are where rye cover crops can be particularly advantageous for scavenging N in the form of nitrate. [19]

17 M Unkovich. Soil sampling for soil quality—South Australia. Soil Quality Pty Ltd, http://www.soilquality.org.au/factsheets/soil-sampling-for-soil-quality-south-australia

18 Agriculture Victoria (2008) Establishing forage cereals. Agriculture Victoria, January 2008, http://agriculture.vic.gov.au/agriculture/grains-and-other-crops/crop-production/harvesting-forage-cereals

19 M Ladoni, AN Kravchenko, GP Robertson (2015) Topography mediates the influence of cover crops on soil nitrate levels in row crop agricultural systems. *PloS ONE* 10, e0143358, http://dx.doi.org/10.1371/journal.pone.0143358

IN FOCUS

Topography mediates the influence of cover crops on soil nitrate levels in row-crop agricultural systems

Supplying adequate amounts of soil N for plant growth during the growing season and across large agricultural fields is a challenge for conservational agricultural systems with cover crops. Knowledge about cover-crop effects on N comes mostly from small, flat research plots, and performance of cover crops across topographically diverse agricultural land is poorly understood. Our objective was to assess effects of both leguminous (red clover) and non-leguminous (cereal rye) cover crops on potentially mineralisable N (PMN) and nitrate-N levels across a topographically diverse landscape. This study looked at conventional, low input and organic managements in corn-soybean-wheat rotation. The rotations of low input and organic managements included rye and red clover cover crops. The managements were implemented in twenty large undulating fields in the United States from 2006. Data collection and analyses were conducted during three growing seasons of 2011, 2012 and 2013. Observational micro-plots with and without cover crops were laid within each field on three contrasting topographical positions of depression, slope and summit. Soil samples were collected four to five times during each growing season and analysed for nitrate-N and PMN. The results showed that all three managements were similar in their temporal and spatial distributions of nitrate-N. Red clover cover crop increased nitrate-N by 35% on depression, 20% on slope and 32% on summit positions. Rye cover crop had a significant 15% negative effect on nitrate-N in topographical depressions but not in slope and summit positions (Figure 2). The magnitude of the cover crop effects on soil mineral N across topographically diverse fields was associated with the amount of cover crop growth and residue production. The results emphasise the potential environmental and economic benefits that can be generated by implementing site-specific, topography-driven cover crop management in row-crop agricultural systems. [20]

20 M Ladoni, AN Kravchenko, GP Robertson (2015) Topography mediates the influence of cover crops on soil nitrate levels in row crop agricultural systems. *PloS ONE* 10, e0143358, http://dx.doi.org/10.1371/journal.pone.0143358

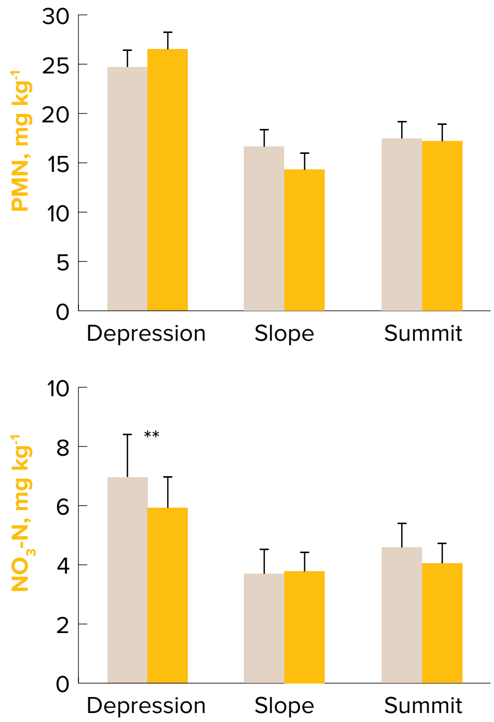

Figure 2: *Soil potential mineralisable N (PMN) and nitrate-N (NO3-N) in bare and cover micro-plots of the studied topographical positions following rye cover crops. Data shown are the averages from 2011, 2012 and 2013 results. Error bars represent standard errors. **Differences between cover and bare micro-plots were statistically significant at P = 0.05.*

Source: figure 2 of Ladoni et al. 2015

1.2 Paddock rotation and history

The hardiest of cereals, cereal rye can be seeded later in autumn than other cover crops and still provide considerable dry matter, an extensive soil-holding root system, significant reduction of nitrate leaching and exceptional weed suppression. Cereal rye has multiple environmental benefits because it can be used for groundcover, reducing wind erosion and increasing soil water retention. [21]

Paddocks with higher fertility are preferred as most crops are sown for the dual purposes of grazing and grain. Cereal rye is often used as a grazed cover crop undersown with subterranean clover pasture on lighter soil types, to provide groundcover while the clover establishes.

Tolerance to take-all disease makes cereal rye suitable for sowing after grassy pastures. This is particularly important in southern NSW, where take-all is a major disease.

21 L Martin (2015) Growing cereal rye to increase carbon and prevent wind erosion. Liebe Group, March 2015, http://www.liebegroup.org.au/wp-content/uploads/2015/03/Case-Study-Jeff-Pearse-March-2015.pdf

Cereal rye can be used to build up the fertility of sandy, infertile soils. Few other cool-season green-manure crops are as productive on poor soils. Rye used as a green manure serves as a storehouse of soil nutrients for a following cash crop.

Rye can also improve water quality because the plant's extensive root system can take up excess soil N that might otherwise leach to contaminate groundwater or surface water bodies. This N then slowly becomes available to subsequent crops as the residues gradually decompose. Rye roots can also extract potassium and other nutrients from deep in the soil profile and bring them to the surface, where they become available to subsequent crops. Expect considerable fertility improvement in the topsoil when growing rye. [22]

Rye is one of the best cool-season cover crops for outcompeting weeds, especially small-seeded, light-sensitive annuals. Rye can serve as an overwintering cover crop after maize, or before or after soybeans, fruits or vegetables. If used before a small-grain crop such as wheat or barley, it is important to ensure that no volunteer rye seed remains, which would lower the value of other grains. [23]

Cereal rye is the preferred cereal option for erosion control, withstanding adverse conditions such as cold, waterlogging, low soil pH and drought better than other cereals. Cereal rye has a more extensive root system in the top 30 cm than both wheat and oats. This root system increases soil stabilisation and allows the plant to explore more of the topsoil profile, increasing the plant's tolerance to dry conditions. [24]

Cereal rye's resistance and tolerance to take-all makes it a useful break crop for sowing before susceptible wheat, triticale or barley crops. It can also be sown in situations where take-all is expected—following grassy pasture on soils that are unsuitable for oats. [25]

Although rye is susceptible to the same insects that attack other cereals, serious infestations are rare.

The benefits and disadvantages of cereal rye in a crop rotations are summarised in Table 4.

22 H Valenzuela, J Smith (2002) Rye. Sustainable Agriculture Green Manure Crops, August 2002, University of Hawaii, http://www.ctahr.hawaii.edu/oc/freepubs/pdf/GreenManureCrops/rye.pdf

23 SARE (2007) Cereal rye. In Managing Cover Crops Profitably, 3rd Edition. Sustainable Agriculture Research and Education, http://www.sare.org/Learning-Center/Books/Managing-Cover-Crops-Profitably-3rd-Edition/Text-Version/Nonlegume-Cover-Crops/Cereal-Rye

24 P Matthews, D McCaffery, L Jenkins (2016) Winter crop variety sowing guide 2016. NSW Department of Primary Industries, https://www.dpi.nsw.gov.au/agriculture/broadacre-crops/guides/publications/winter-crop-variety-sowing-guide

25 Wrighton Seeds. Forage focus—southern green ryecorn. Wrighton Seeds, http://www.pggwrightsonseeds.com.au/products/cereals/southerngreenryecorn/

Table 4: *Benefits and disadvantages of including cereal rye as part of crop rotations.*

Benefits of cropping cereal rye	Disadvantages of cropping cereal rye
Lower input cost than other cereal crops	Low yielding
Provides good ground cover and helps to prevent soil erosion	Difficult to get grain to markets
Taller and quicker growing than wheat, can serve as a windbreak and hold rainfall over winter	Lots of trash, making it difficult to seed through
Can increase soil organic carbon	Can attract armyworms
Establishes well on poor sands	Has a weedy nature—volunteer rye will usually appear for two to three years after a crop has been grown
Extensive root system	
Requires less water than wheat crops	
Can fix up to 45 kg of excess nitrogen	
Increases the availability of exchangeable potassium in the topsoil [26]	
Can attract significant numbers of beneficial insects such as ladybird beetles (coccinellids) [27]	
Resistant to cereal cyst nematodes and a poor host to the RLN (*Pratylenchus neglectus*), providing an alternative management approach for these diseases [28]	

Allelopathic effects

Cereal rye produces several compounds in its tissues and releases root exudates that apparently inhibit germination and growth of weed seeds. These allelopathic effects, together with cereal rye's ability to smother other plants with cool weather growth, make it an ideal choice for weed control (Photo 3).

However, allelopathic compounds may suppress germination of small-seeded vegetable crops as well if they are planted shortly after incorporation of cereal rye residue. Large-seeded crops and transplants are rarely affected. There is some evidence that the amount of allelopathic compounds is lower in tillering plants than in seedlings. [29]

26 L Martin (2015) Growing cereal rye to increase carbon and prevent wind erosion. Liebe Group, March 2015, http://www.liebegroup.org.au/wp-content/uploads/2015/03/Case-Study-Jeff-Pearse-March-2015.pdf

27 SARE (2007) Cereal rye. In Managing Cover Crops Profitably. 3rd Edition. Sustainable Agriculture Research and Education, http://www.sare.org/Learning-Center/Books/Managing-Cover-Crops-Profitably-3rd-Edition/Text-Version/Nonlegume-Cover-Crops/Cereal-Rye

28 L Martin (2015) Growing cereal rye to increase carbon and prevent wind erosion. Liebe Group, March 2015, http://www.liebegroup.org.au/wp-content/uploads/2015/03/Case-Study-Jeff-Pearse-March-2015.pdf

29 V Grubinger (2010) Winter rye: a reliable cover crop. University of Vermont, October 2010, https://www.uvm.edu/vtvegandberry/factsheets/winterrye.html

Photo 3: *High level of weed suppression exerted by a rye cover crop.*

Source: Food and Agriculture Organization of the United Nations

1.2.1 Rotation issues

Self-sown cereal rye can be a problem in subsequent cereal crops because of a high level of seed dormancy, so generally it should be sown after other cereal crops. When sown the year before a broadleaf crop such as lupins, volunteer cereal rye can be controlled with herbicides. [30]

In rotations that include a cereal, rye may replace wheat, oats or barley. [31]

The highest yields of rye occur when it is planted on summer fallow. Growing rye repeatedly on the same land increases the chance of ergot (caused by the fungus *Claviceps purpurea*) and some other diseases. A varied crop rotation with less susceptible crops is recommended. [32]

1.2.2 Long fallow disorder

Soils naturally contain beneficial fungi that help the crop to access nutrients such as phosphorus (P) and zinc (Zn) by forming structural associations with the crop root, known as arbuscular mycorrhizae (AM). Many different species of fungi can have this association with the roots of crops, and many of these form structures called vesicles in the roots. The severe reduction or lack of AM shows up as long fallow disorder—the failure of crops to thrive despite adequate moisture. Long periods of drought have highlighted long fallow disorder, where AM fungi have died out through lack of host plant roots during long fallow periods. As cropping programs restart after dry years, a yield drop is likely due to reduced levels of AM fungi and hence reduced development of AM, making it difficult for the crop to access nutrients. Long fallow disorder is usually typified by poor crop growth. Plants appear to remain in their seedling stages for weeks and development is very slow.

Benefits of AM are:

- improved uptake of P and Zn
- improved crop growth

30 P Matthews, D McCaffery, L Jenkins (2016) Winter crop variety sowing guide 2016. NSW Department of Primary Industries, https://www.dpi.nsw.gov.au/agriculture/broadacre-crops/guides/publications/winter-crop-variety-sowing-guide

31 EA Oelke, ES Oplinger, H Bahri, BR Durgan, DH Putnam, JD Doll, KA Kelling (1990) Rye. In Alternative field crops manual. University of Wisconsin and University of Minnesota, https://hort.purdue.edu/newcrop/afcm/rye.html

32 M McLelland, H Brook (2016) Fall rye production. Alberta Government, ,http://www1.agric.gov.ab.ca/$department/deptdocs.nsf/all/agdex1269/$file/117_20-1.pdf

- improved N_2 fixation
- greater drought tolerance
- improved soil structure
- greater disease tolerance.

In general, the benefits of AM are greater at lower soil P levels because AM increase a plant's ability to access this nutrient. Crop species vary in their dependency on AM for growth. [33]

1.3 Fallow weed control

Paddocks with well-managed fallow periods significantly lower the risk of poor crop and financial performance. The best form of weed control is rotation and careful selection of paddocks largely free from winter weeds, for example, double-cropped from sorghum or cotton, or areas with a sequence of clean winter fallows (Photo 4).

Photo 4: *Spraying weeds when small is the key to effective long fallow.*

Source: Agronomo

Paddocks generally have multiple weed species present at the same time, making weed control decisions more difficult and often involving a compromise after assessment of the prevalence of key weed species. Knowing your paddock and controlling weeds as early as possible are both important for good control of fallow weeds.

Benefits of fallow weed control are significant:

- Conservation of summer rain and fallow moisture (this can include moisture stored from last winter or the summer before in a long fallow) is integral to winter cropping in the Northern region, particularly as the climate moves towards summer-dominant rainfall.
- Modelling studies show that the highest return on investment in summer weed control is for lighter soils or in situations where soil water that would support continued weed growth is present. [34]

The Northern Grower Alliance is trialing methods to control summer grasses. Key findings include:

33 QDAF (2010) Nutrition—VAM and long fallow disorder. Queensland Department of Agriculture and Fisheries, September 2010, https://www.daf.qld.gov.au/plants/field-crops-and-pastures/broadacre-field-crops/nutrition-management/nutrition-vam

34 GRDC (2012) Summer fallow management. GRDC Fact Sheet, January 2012, https://grdc.com.au/resources-and-publications/all-publications/factsheets/2014/08/grdc-fs-summerfallowspraying

VIDEOS

WATCH: IWM: Double knock applications—extent of herbicide resistance in the north.

WATCH: GCTV5: Managing summer fallow

- Glyphosate-resistant and -tolerant weeds are a major threat to our reduced tillage cropping systems.
- Although residual herbicides will limit re-cropping options and will not provide complete control, they are a key part of successful fallow management.
- Double-knock herbicide strategies (sequential application of two different weed control tactics) are useful tools but the herbicide choices and optimal timings will vary with weed species.
- Other weed management tactics can be incorporated, e.g. crop competition, to assist herbicide control.
- Cultivation may need to be considered as a salvage option to avoid seed bank salvage. [35]

1.3.1 The green bridge

A green bridge—that is, green weeds and crop volunteers that survive between seasons—provides a between-season host for insects and diseases (particularly rusts); these pose a serious threat to future crops and can be expensive to control later in the season.

Key points for control of the green bridge:

- Outright kill of the weeds and volunteers is the only certain way to avoid them hosting diseases and insects.
- Diseases and insects can quickly spread from the green bridge or summer weeds, jeopardising crops and current control methods including the effectiveness of chemicals and genetic breeding for resistance.
- Effective control of pest and disease risks requires neighbours to work together to eradicate weeds and crop volunteers simultaneously.
- Weed growth during summer and autumn also depletes soil moisture and nutrients that would otherwise be available to following crops, and can have an allelopathic effect. [36]

1.3.2 Management strategies

How farming land is managed in the months or years before sowing can be more important than in-crop management in lifting water-use efficiency. Of particularly high impact are strategies that increase soil capture and storage of fallow rainfall to improve crop reliability and yield.

Practices such as controlled-traffic farming and long-term no-till seek to change the soil structure to improve infiltration rates and improve plant access to stored water by removal of compaction zones.

Shorter term management decisions can also have a great impact on how much plant-available water is stored at sowing. These include decisions such as crop sequence or rotation that dictate the length of the fallow and amount of stubble cover, how effectively fallow weeds are managed, stubble management, and decisions to till (or not) at critical times.

Many factors influence how much plant-available water is stored in a fallow period; however, good weed management consistently has the greatest impact. [37]

35 R Daniel (2014) Weeds and resistance considerations for awnless barnyard grass chloris and fleabane. GRDC Update Papers, March 2014, https://grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2014/03/weeds-and-resistance-considerations-for-awnless-barnyard-grass-chloris-and-fleabane

36 GRDC (2009) Green bridge fact sheet. Grains Research and Development Corporation, https://grdc.com.au/resources-and-publications/all-publications/factsheets/2010/01/grdc-fs-greenbridge

37 GRDC (2012) Summer fallow management fact sheet. Grains Research and Development Corporation, January 2012, https://grdc.com.au/resources-and-publications/all-publications/factsheets/2014/08/grdc-fs-summerfallowspraying

1.3.3 Stubble retention

Key points:

- Retaining stubble can decrease soil erosion, increase soil water content and increase soil biological activity.
- Stubble burning, grazing and cultivation are management practices that can decrease stubble cover.
- Where stubble retention is in place, it is important to ensure adequate N availability in order to reach full yield potential.

Historically, stubble has been burnt because it improves weed control and creates easier passage for seeding equipment. However, the practice of burning stubble has declined due to concerns about soil erosion and loss of soil organic matter. Instead of being burnt, stubble is now more commonly retained, which has several advantages for soil fertility and productivity (Photo 5).

In southern NSW, stubble retention is being seen as a priority for farmers and many farmers believe that burning should now only be used strategically. [38]

Photo 5: *Cereal paddock where stubble has been retained, reducing erosion risk and improving fertility.*

Source: Soil Quality Pty Ltd

Reduced erosion risk

One of the main benefits of stubble retention is reduced soil erosion (Figure 3). Retaining stubble decreases erosion by reducing the raindrop energy at the soil surface and decreasing run-off. In order to protect the soil from erosion, crops need to be managed so that at least 30–40% groundcover is maintained throughout the year, especially during the summer months when there is a greater chance of high-intensity rainfall. The amount of cover produced by crops will vary according to seasonal conditions and crop variety. However, as a rule-of-thumb, a 1.5 t/ha grain yield should typically provide 90% stubble cover. This cover may decrease over the fallow period, however, depending on whether the site is subsequently burnt, grazed or cultivated.

38 K Condon (2013) FarmLink. Stubble management practices and research in southern New South Wales. FarmLink Research, http://www.farmlink.com.au/_literature_146390/Stubble_Management_Practices_and_Research_in_southern_NSW

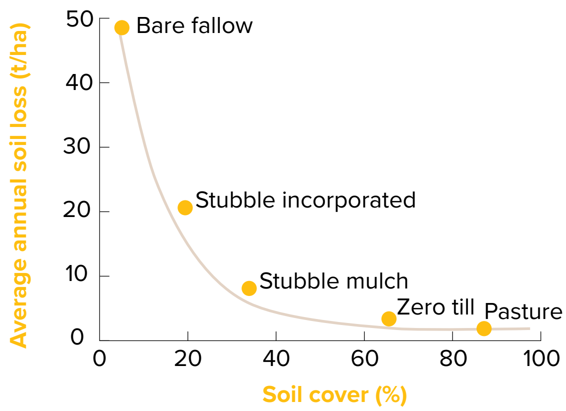

Figure 3: *Soil loss observed depending on the percentage of surface cover from sites on the eastern Darling Downs (from Freebairn 2004).*

Source: Soil Quality Pty Ltd

Increased soil water content

Another advantage of retaining stubble is that it increases soil water content by decreasing runoff, and increasing infiltration (Figure 4). The greater the amount of stubble cover the greater the potential benefits to soil water storage. Stubble coverage of 30% is considered the minimum level required for reducing the effect of soil water runoff. However, stubble coverage of ≥50% will provide further benefit for soil-moisture storage and erosion control.

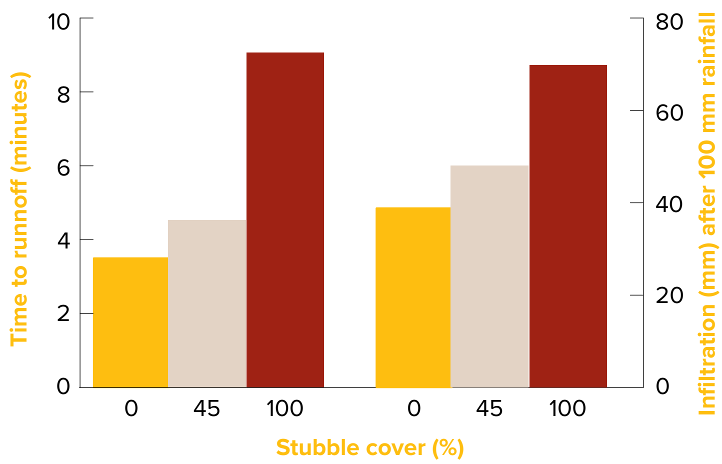

Figure 4: *Influence of different amounts of groundcover from retaining wheat stubble on time to runoff (left) and water infiltration (right) (from Thomas et al. 2008).*

Source: Soil Quality Pty Ltd

Increased biological fertility of soil

Retaining stubble increases the input of carbon to soil. Stubble is ~45% carbon by weight and therefore represents a significant carbon source. Microorganisms in soil require organic carbon to obtain energy. When stubble is retained, the greater inputs of organic carbon increase the number and activity of microorganisms in soil (see Soil

Quality Fact Sheets: Organic carbon pools—Queensland and Microbial biomass—Queensland).

Management practices affecting stubble cover

Stubble burning, grazing and cultivation are the main management practices with the potential to reduce stubble cover. A single tillage operation using a chisel plough, for example, can reduce stubble coverage by 30–40% (Table 5).

It is recommended that stubble cover be maintained as long as possible in the fallow, and that planting and fertilising machinery be adapted to minimise disturbance. Where cultivation is required to control herbicide-resistant weeds, this should be carried out as a one-off operation. [39]

VIDEOS

WATCH: Burning for weed and snail control

Burning Snails & Weed Seeds

Table 5: *Estimated reduction in wheat or barley stubble cover from different tillage operations (reproduced from Qld Government/Grains BMP: Measuring and managing stubble cover: photostandards for winter cereals).*

Implement	Residue buried by each tillage operation (%)	
	Fresh stubble	Old (brittle) stubble
Disc plough	60–80	80–90
Chisel plough	30–40	40–60
Blade plough	20–30	30–50
Boomspray	Negligible	Negligible

Source: Soil Quality Pty Ltd

For more information on weed control strategies, see Section 6: Weed control.

1.4 Fallow chemical plant-back effects

Plant-back periods are the obligatory times between the herbicide spraying date and safe planting date of a subsequent crop.

Some herbicides have a long residual. The residual is not the same as the half-life. Although the amount of chemical in the soil may break down rapidly to half the original amount, what remains can persist for long periods (e.g. sulfonylureas such as chlorsulfuron) (Table 6). Herbicides with long residuals can affect subsequent crops, especially if they are effective at low levels of active ingredient, such as the sulfonylureas. On labels, this will be shown by plant-back periods, which are usually listed under a separate heading or under the 'Protection of crops etc.' heading in the 'General instructions' section of the label.

Part of the management of herbicide resistance includes rotation of herbicide groups. Paddock history should be considered. Herbicide residues (e.g. sulfonylurea, triazines, etc.) may be an issue in some paddocks. Remember that plant-back periods begin after rainfall occurs. [40]

39 Soil Quality Pty Ltd. Benefits of retaining stubble—Queensland. http://www.soilquality.org.au/factsheets/benefits-of-retaining-stubble-in-qld

40 B Haskins (2012) Using pre-emergent herbicides in conservation farming systems. NSW Department of Primary Industries, http://www.dpi.nsw.gov.au/__data/assets/pdf_file/0003/431247/Using-pre-emergent-herbicides-in-conservation-farming-systems.pdf

Table 6: *Residual persistence of common pre-emergent herbicides, noting residual persistence in broadacre trials and paddock experiences.*

Herbicide	Half-life (days)	Residual persistence and prolonged weed control
Logran® (triasulfuron)	19	High. Persists longer in high pH soils. Weed control commonly drops off within six weeks
Glean® (chlorsulfuron)	28–42	High. Persists longer in high pH soils. Weed control longer than Logran®
Diuron	90 (range one month to one year, depending on rate)	High. Weed control will drop off within six weeks, depending on rate. Has had observed long-lasting activity on grass weeds such as black/stink grass (*Eragrostis* spp.) and to a lesser extent broadleaf weeds such as fleabane
Atrazine	60–100, up to one year if dry	High. Has had observed long lasting (more than three months) activity on broadleaf weeds such as fleabane
Simazine	60 (range 28–149)	Medium to high. One-year residual in high pH soils. Has had observed long lasting (more than three months) activity on broadleaf weeds such as fleabane
Terbyne® (terbuthylazine)	6.5–139	High. Has had observed long lasting (more than six months) activity on broadleaf weeds such as fleabane and sow thistle
Triflur® X (trifluralin)	57–126	High. Six to eight months residual. Higher rates longer. Has had observed long lasting activity on grass weeds such as black/stink grass (*Eragrostis* spp.)
Stomp® (pendimethalin)	40	Medium. Three–four months residual
Avadex® Xtra (triallate)	56–77	Medium. Three–four months residual
Balance® (isoxaflutole)	1.3 (metabolite 11.5)	High. Reactivates after each rainfall event. Has had observed long lasting (more than six months) activity on broadleaf weeds such as fleabane and sow thistle
Boxer Gold® (prosulfocarb)	12–49	Medium. Typically quicker to break down than trifluralin, but tends to reactivate after each rainfall event
Sakura® (pyroxasulfone)	10–35	High. Typically quicker breakdown than trifluralin and Boxer Gold®; however, weed control persists longer than Boxer Gold®

Source: Department of Primary Industries NSW

Conditions required for breakdown

Warm, moist soils are required to breakdown most herbicides through the processes of microbial activity. For the soil microbes to be most active, they need good moisture and a soil temperature range of 18°–30°C. Extreme temperatures above or below this range can adversely affect soil microbial activity and slow herbicide breakdown. Very dry soil also reduces breakdown. In addition, where the soil profile is very dry, a lot of rain is required to maintain topsoil moisture for the microbes to be active for any length of time.

Plant-back periods for fallow herbicides in New South Wales

Herbicide plant-back restrictions should be taken into account when spraying fallow weeds prior to sowing winter crops in NSW. Many herbicide labels place time and/or rainfall restrictions on sowing certain crops and pastures after application because of potential seedling damage. Crops such as canola, pulses and legume pastures are the most sensitive to herbicide residues, but cereal crops can also be affected (Table 7).

When treating fallow weeds, especially in late summer or autumn, consideration must be given to the planned crop or pasture for the coming year. In some cases, the crop or pasture for the following year may also have an influence on herbicide choice.

The following points are especially relevant:

- Phenoxy herbicides such as 2,4D ester, 2,4D amine and dicamba, require 15 mm of rainfall to commence the plant-back period when applied to dry soil.
- Group B herbicides such as Ally®, Logran® and Glean® break down more slowly as soil pH increases. Recently applied lime can increase the soil surface pH to a point where the plant-back period is significantly extended.
- Lontrel™, Grazon™ and Tordon™ products break down very slowly under cold or dry conditions, which can significantly extend the plant-back period.

Keeping accurate records of all herbicide treatments and early planning of crop sequences can reduce the chance of crop damage resulting from herbicide residues. [41]

Table 7: *Indicative plant-back intervals for a selection of fallow herbicides in southern New South Wales. For cereal rye, plant-back periods for wheat or barley are a reference point.*

Product	Rate	Plant-back period	Wheat	Barley	Oats	Canola	Legume Pasture	Pulse crops
2,4-D Ester 608*	0–510 ml/ha	(days)	1	1	1	14	7	7
	510–1,150 ml/ha		3	3	3	21	7	14
	1,150–1,950 ml/ha		7	7	7	28	10	21
Amicide Advance 700*	0–500 ml/ha	(days)	1	1	1	14	7	7
	500–980 ml/ha		3	3	3	21	7	14
	980–1,500 ml/ha		7	7	7	28	10	21
Kamba 500*	200 ml/ha	(days)	1	1	1	7	7	7
	280 ml/ha		7	7	7	10	14	14
	560 ml/ha		14	14	14	14	21	21
Hammer 400 EC					No residual effects			
Nail 240 EC					No residual effects			
Goal					No residual effects			
Striker					No residual effects			
Sharpen	26 g/ha	(weeks)	-	-	-	16	-	-
Lontrel	300 ml/ha	(weeks)	1	1	1	1	36	36
Garlon 600		(weeks)	1	1	NS	NS	NS	NS
Ally**		(weeks)	2	6	36	36	36	36
Logran#		(months)	-	-	-	12	12	12

41 RMS (2016). Plant-back periods for fallow herbicides in southern NSW. RMS Agricultural Consultants, http://www.rmsag.com.au/2016/plant-back-periods-for-fallow-herbicides-in-southern-nsw/

Product	Rate	Plant-back period	Wheat	Barley	Oats	Canola	Legume Pasture	Pulse crops
Glean**		(months)	-	9	6	12	12	12
Grazon Extra/Grazon DS		(months)	9	9	NS	9	24	24
Tordon 75D, Tordon 242		(months)	2	2	NS	4	9	6
Tordone Fallow Boss		(months)	9	9	NS	12	20	20

*15 mm rainfall required to commence plant-back period; **, period may extend where soil pH is >7; #, assumes 300 mm rainfall between chemical application and sowing; NS, not specified. Source: RMS Agricultural Consultants

For up-to-date plant-back periods, see the NSW Department of Primary Industries publication: Weed control in winter crops.

For more information about herbicide residues, see Section 6: Weed control.

1.5 Seedbed requirements

The rye paddock should be well prepared and relatively moist for good germination. [42]

Good seed–soil contact is necessary for proper germination and emergence. For best results, plant rye in a firm, well-prepared seedbed.

A good seedbed should be free of weeds, diseases and insects. It should be moist and warm. If rye is grown on light-textured soils that are subject to wind erosion, pre-seeding tillage should be kept to a minimum. To aid erosion control, use implements that will preserve the previous crop residue. Substituting herbicides for cultivation and seeding without pre-seeding tillage (minimum to no till) are other practical options. Under dry or firm soil conditions, seed with seeding implements that minimise soil disturbance, such as air drills with disc or narrow openers, to prevent soil drying.

When shallow seeding, the previous crop's residue will have a greater tendency to interfere with good seed–soil contact. Even spreading of the previous crop residue is essential for quick emergence. When seeding on summer fallow, take extra care to obtain a firm seedbed to facilitate shallow seed placement into moist soil and to prevent soil erosion by wind. [43]

1.5.1 Seedbed soil structural decline

Key points:

- Hard-setting or crusting soils are usually indicators of poor soil structure, which leads to poor water infiltration, poor crop or pasture growth and difficulties when cultivating.
- Where structural decline is due to sodicity, gypsum application can improve soil structure and lead to increased crop yield.
- Increasing soil organic matter and decreasing traffic by stock and machinery can improve soil structure in lighter textured soils.

Decline in surface soil structure generally results in one of two things—hardsetting or crusting (Photo 6). A surface crust is typically less than 10 mm thick and when dry can normally be lifted off the loose soil below. Crusting forces the seedling to exert more energy to break through to the surface, thus weakening it. A surface crust can also reduce water infiltration and increase runoff.

42 UVM (2011) Cereal rye. University of Vermont Extension Crops and Soils Team, April 2011, http://northerngraingrowers.org/wp-content/uploads/RYE.pdf

43 M McLelland, H Brook (2016) Fall rye production. Alberta Government, http://www1.agric.gov.ab.ca/$department/deptdocs.nsf/all/agdex1269/$file/117_20-1.pdf

Breakdown of soil structure caused by rapid wetting can lead to hardsetting. Once soils with an unstable soil structure become wet, they can collapse and then shrink as they dry. This leads to a 'massive' soil layer with little or no cracking and greatly reduced pore space. This hardset, massive structure is associated with poor infiltration, low water-holding capacity and a high soil strength. In many instances, this causes patchy establishment and poor crop and pasture growth. [44]

Photo 6: *Soil crusting (left) and cloddy seedbed (right) associated with high concentrations of exchangeable sodium.*

Source: Soil Quality Pty Ltd

Vertosols in the Northern grains region have good soil structure in their native state. When these soils are brought under cultivation and cropping, soil structure declines because of loss of organic matter, which is the main binding agent for large aggregates (macroaggregates) that provide large pores. If the soil under native state is also sodic, loss of organic matter under cropping and cultivation exacerbates the soil structure decline. [45]

In NSW, soil structure decline is considered an issue for the Tablelands and Western Slopes. [46]

1.5.2 Improving seedbed soil structure

To decrease crusting or hardsetting in soils, it is necessary to stabilise soil structure. On lighter textured soils, this is best achieved by increasing soil organic matter and surface cover and reducing soil traffic (see Soil Quality Fact Sheets: How much carbon can soil store? and Controlled traffic farming—Queensland). Removing or reducing stock when the soil is saturated also helps avoid compaction, smearing and 'pugging' of the soil surface.

Where soils are sodic, the addition of gypsum may help to ameliorate soil dispersion. Gypsum replaces the excess sodium in the soil with calcium, causing clay particles to flocculate and bind together and helping to create stable soil aggregates. In soils with moderate surface sodicity (exchangeable sodium percentage 12), gypsum application at 2.5–5.0 t/ha has been found to improve wheat grain yield significantly in Queensland (Photo 7). [47]

44 Soil Quality Pty Ltd. Seedbed soil structure decline—Queensland, http://www.soilquality.org.au/factsheets/seedbed-soil-structure-decline-queensland

45 R Dalal (2104) Soil structural decline and organic matter in the northern grains region. GRDC Update Papers, August 2014, https://grdc.com.au/Research-and-Development/GRDC-Update-Papers/2014/08/Soil-structural-decline-and-organic-matter-in-the-northern-grains-region

46 NSW EPA (2009) Land. Ch. 5. In New South Wales state of the Environment 2009. NSW Environment Protection Agency

47 Soil Quality Pty Ltd. Seedbed soil structure decline—Queensland, http://www.soilquality.org.au/factsheets/seedbed-soil-structure-decline-queensland

Photo 7: *Gypsum application (right) can help treat surface sodicity and improve grain yield under Queensland conditions.*

Source: Soil Quality Pty Ltd

1.6 Soil moisture

1.6.1 Dryland

Water availability is a key limiting factor for crop production in the Northern grains region of Australia.

Rye enhances water penetration and retention. [48]

IN FOCUS

Rye cover crop management influences on soil water, soil nitrate and corn development

Rye can be managed as a cover crop by chemical termination or harvested for forage. A field study was conducted in the United States in 2008 and 2009 to determine the impact of killed *v.* harvested rye cover crops on soil moisture and nitrate-N, and to monitor the impact of the rye on subsequent corn yield. Corn for silage was seeded after winter fallow (control), after a rye cover crop terminated three to four weeks before corn planting (killed rye), or after a rye forage crop harvested no more than two days before corn planting (harvested rye). Soil moisture after killed rye was similar to the control, but after harvested rye was 16% lower. Available soil nitrate-N was decreased after both killed rye (35%) and harvested rye (59%) compared with the control. Corn biomass yield after killed rye was similar to the control, but yield following harvested rye was reduced by 4.5 Mg/ha. Total forage biomass yield (silage + rye) was similar for all treatments. This work demonstrates that the environmental benefits of a winter rye cover crop can be achieved without impacting on corn yield, but the later termination required for rye forage production resulted in soil resource depletion and negatively affected corn silage yield. [49]

48 EA Oelke, ES Oplinger, H Bahri, BR Durgan, DH Putnam, JD Doll, KA Kelling (1990) Rye. In Alternative field crops manual. University of Wisconsin and University of Minnesota, https://hort.purdue.edu/newcrop/afcm/rye.html

49 ES Krueger, TE Ochsner, PM Porter, JM Baker (2011) Winter rye cover crop management influences on soil water, soil nitrate, and corn development. Agronomy Journal 103, 316–323, https://dl.sciencesocieties.org/publications/aj/abstracts/103/2/316?access=0&view=pdf

Tillage practices

Research shows that one-time tillage with chisel or offset disc in long-term no-till helped to control winter weeds and slightly improved grain yields and profitability while retaining many of the soil quality benefits of no-till farming systems. Tillage reduced soil moisture at most sites; however, this decrease in soil moisture did not adversely affect productivity. This could be due to good rainfall received after tillage and prior to seeding and during the crop of that year. The occurrence of rain between the tillage and sowing or immediately after sowing is necessary to replenish soil water lost from the seed-zone. This suggests the importance of timing of tillage and of considering the seasonal forecast. These results are from one season and impacts are likely to vary with subsequent seasonal conditions. [50]

Limited and strategically timed tillage could have a tactical role as part of a productive, sustainable system. Short-term detrimental effects include reduced protective cover, soil loss, increased runoff, loss of soil carbon and moisture, and reduced microbial; the impacts vary depending on the tillage implement used (Photo 8). In the long term, these effects on soil health and environment are negligible. One-off tillage is potentially a useful management tactic for difficult-to-control and herbicide-resistant weeds (Photo 9). [51]

Photo 8: *Inversion tillage using a mouldboard plough, as pictured here, has more impact than use of a chisel or disc plough.*

Source: Grains Research and Development Corporation, Strategic Tillage Fact Sheet

50 Y Dang, V Rincon-Florez, C Ng, S Argent, M Bell, R Dalal, P Moody, P Schenk (2013) Tillage impact in long term no-till. GRDC Update Papers, February 2013, https://grdc.com.au/Research-and-Development/GRDC-Update-Papers/2013/02/Tillage-impact-in-long-term-no-till

51 GRDC (2014) Is there room for strategic tillage in a no-till system? GRDC Strategic Tillage Fact Sheet—Northern and Southern Regions, July 2014, https://grdc.com.au/Resources/Factsheets/2014/07/Strategic-tillage

Photo 9: *Strategic tillage used for control of barnyard grass in fallow.*

Source: Grains Research and Development Corporation, Strategic Tillage Fact Sheet

In general, pre-plant tillage to prepare the seedbed, control weeds, and disrupt insect and disease life cycles improves crop establishment. However, with cereal rye or other small grains, no-till establishment is an effective option that allows maintenance of the no-till system. Conventional seedbeds are prepared by ploughing, discing and harrowing the soil prior to seeding. Seeding depth depends upon the species being sown. No-till seeding is suitable for highly erodible soils and for late-season establishment. [52]

IN FOCUS

Tillage, microbial biomass and soil biological fertility

Key points:

- An experiment tested the observation by farmers that low-disturbance tillage increases total organic carbon (OC) in soil.
- Rotary tillage decreased total OC and labile OC. Such losses could lead to degradation of soil structure and ultimately to a decline in productivity.
- No-till and conservation tillage increased microbial biomass carbon and microbial activity. This indicates that less intensive cultivation may favour sustained microbial function in soil.
- Although no-till and conservation tillage were similar, they may become different in the longer term.

In the mid-1990s, no-till farmers called for an experiment to test anecdotal reports that low-disturbance tillage increased total OC in soil. A seven-year experiment was conducted on a deep sand property in Western Australia using lupin–wheat rotation. The experiment compared the effect of three tillage types on total OC, soil microorganisms and crop yields:

- no-till—no soil disturbance other than seeding
- conservation tillage—a single pass before seeding with 13-cm-wide tines to a depth of ~7.5 cm

52 W Curran, DD Lingenfelter, L Garling, P Wagoner (2006) Cover crops for conservation tillage systems. Conservation Tillage Series Number Five. Pennsylvania State University, http://extension.psu.edu/plants/crops/soil-management/conservation-tillage/cover-crops-for-conservation-tillage-systems

- rotary tillage—a single intense cultivation, before seeding, to a depth of 8 cm using a rotary hoe.

Total organic carbon

Total OC is a measure of the carbon contained within soil organic matter. Low levels can indicate problems with unstable soil structure, low cation exchange capacity and nutrient turnover (see Soil Quality Fact Sheet : Total organic carbon).

After seven years, total OC had increased by 4.4 t/ha under no-till and 2.6 t/ha under conservation tillage (Figure 5), but had decreased by 0.5 t/ha under rotary tillage.

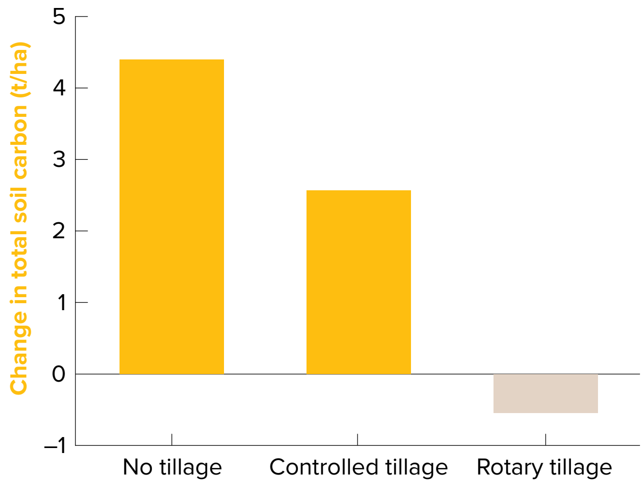

Figure 5: *Change in total soil carbon content at 0–10 cm soil depth between 1998 and 2004 in crops under three tillage regimes. Treatments with different-coloured shading are significantly different (at P = 0.05).*

Source: Soil Quality Pty Ltd

Light-fraction organic carbon

Light fraction OC consists of more recent inputs of organic matter. It responds more quickly to management than total OC and better reflects changes in soil microbiology.

Light fraction OC decreased as tillage became more intensive. By the end of the experiment, light fraction OC in the top 10 cm was 0.83 t/ha under no-till, 0.73 t/ha under conservation tillage and 0.46 t/ha under rotary tillage.

This may indicate that less intensively tilled soils are more biologically active and have higher potential for nutrient turnover and that total OC will increase further in the future.

Soil microorganisms

Soil microbial biomass carbon (see Soil Quality Fact Sheet: Microbial biomass) at 0–5 cm soil depth decreased under rotary tillage compared with no-tillage and conservation tillage (Figure 6).

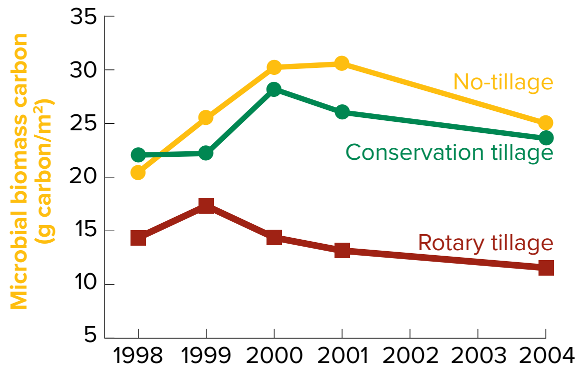

Figure 6: *Microbial biomass carbon in 0–5 cm depth of cropped soil under three tillage regimes.*

Source: Soil Quality Pty Ltd

Microbial biomass N was also higher under no-till and conservation tillage than under rotary tillage. By the end of the experiment, microbial biomass N under no-till and conservation tillage was 31% higher than under rotary tillage.

Tillage decreased microbial activity in soil. The activity of the microbial enzyme cellulase in 0–5 cm soil depth was higher under no-till and conservation tillage than rotary tillage (Figure 7).

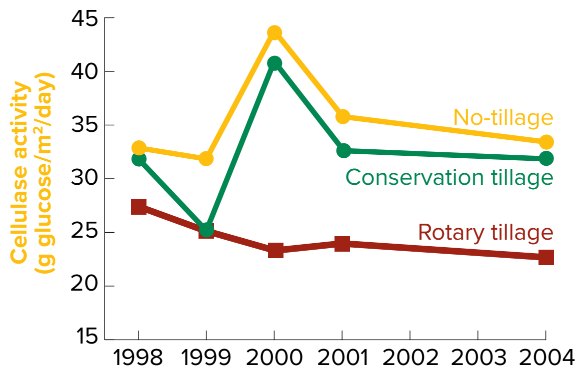

Figure 7: *Activity of the microbial cellulase in 0–5 cm depth of cropped soil under three tillage regimes.*

Source: Soil Quality Pty Ltd

Crop yields

Tillage practice affected crop yields in only one year of the trial, 2003, when lupin grain yields were higher under no-till (2 t/ha) and conservation tillage (1.9 t/ha) than under rotary tillage (1.6 t/ha).

Although tillage did not affect wheat grain yield, it did affect the incidence of Rhizoctonia bare patch. Wheat plants grown under both no-tillage and conventional tillage were more visibly affected by Rhizoctonia bare patch than wheat plants grown under rotary tillage. [53]

53 M Roper, J Carson, D Murphy Tillage, microbial biomass and soil biological fertility. Soil Quality Pty Ltd, http://www.soilquality.org.au/factsheets/tillage-microbial-biomass-and-soil-biological-fertility

1.6.2 Irrigation

Even in areas of relatively high and reliable rainfall such as the north coast of NSW, rainfall patterns do not match the water requirements of many of our commercial crops.

North-coast spring tends to be dry, but this is when many crops need water to guarantee yield and quality. Light rainfall is not effective because most of the water evaporates quickly from the soil surface.

Efficient irrigation reduces operating costs because less water has to be pumped for a given yield. It also means that on-farm dams can be smaller because less water is needed, an important consideration with restricted access to rivers.

Inefficient irrigation can lead to water and nutrients draining through the root-zone, which is a waste of water and fertilisers and leads to rising and contaminated water tables. Inefficient water use can also mean unnecessary pumping from rivers. [54]

MORE INFORMATION

NSW DPI publication: Irrigation essentials for North Coast farmers in NSW.

Irrigating winter cereals in the Northern region

Research and extension projects were undertaken between 2007 and 2011 in partnership between: NSW Department of Primary Industries (NSW DPI), Cotton Catchment Communities CRC, DAFF Queensland, Grains Research & Development Corporation (GRDC), CSIRO, the Foundation for Arable Research (NZ) and Griffiths Agriculture. Before 2007, very little research had been done to develop management guidelines for irrigated cereal crops in the northern region. The following recommendations have been made to optimize irrigated cereal crops in the Northern region.

Soil-N Level

It is essential to conduct a nitrogen soil test in April/May before sowing. Long fallow paddocks with high soil-N require careful management of canopy growth from establishment to avoid lodging.

Row spacing

30 cm row spacing is ideal (6 rows on a 1.8 metre bed). 15 cm or 45 cm row spacing (4 or 12 rows on a 1.8m bed) have, in small plot trials, yielded significantly less than 30 cm spacing.

Plant population

A population of 100-150 plants per square metre of bed or hill area is ideal in the northern region. Low plant populations of 50-100 plants per square metre of bed can achieve high yield levels but plants do not establish evenly.

Seedbed preparation

Seedbed preparation has a significant impact on seedling emergence and therefore yield potential. Planting into adequate soil tilth is critical. Tillage is required to prepare a new seedbed that is free from clods and stubble. The type of machinery used and the number of cultivations depends on the soil type and its structure. Prepare a seedbed that is in optimum condition for seed placement and emergence.

Plant establishment

Once bed preparation has been completed the best establishment scenario is a rain event that will provide sowing moisture, initiate seed germination and seedling. This scenario is ideal in that it provides the best opportunity to achieve high yields (particularly if starting soil N levels are low). In this situation, a uniform plant stand can be achieved; and the grower can then manage early season canopy growth and allow an irrigation to ensure secondary root development.

54 R Swinton, G Creighton (2009). Irrigation essentials for North Coast farmers in NSW. NSW Department of Primary Industries, http://www.dpi.nsw.gov.au/__data/assets/pdf_file/0010/349705/Irrigation-essentials-for-North-Coast-farmers-in-NSW.pdf

Pre-irrigation is risky due to the need to delay sowing if rain occurs. However, establishment may be better in a pre-irrigated paddock than a paddock that is dry-sown and watered-up. If the profile is completely dry at sowing the only option is to plant shallow and water-up. This is the least desirable option, particularly if starting soil-N levels are very high. Often, in the water-up situation, plants still do not achieve secondary root growth and require further irrigation during tillering, which may create excessive early season biomass. This can create a crop that is predisposed to lodging, particularly if the starting nitrogen levels are in excess of the plant's requirements.

Water budgeting

When undertaking a water budget; determine plant available water to a soil depth of 90 cm. To maximise yield the wheat crop (from stem elongation stage) should access its entire soil water requirement from a soil depth of 90 cm only. Depending upon in-crop rainfall, maximum yield may require between 3-5 subsequent spring irrigations.

Secondary root growth

The largest early season issue in the northern growing region is achieving adequate secondary root growth, post-sowing. Soil moisture status should be assessed at 25-30 days after emergence, and if necessary, a winter irrigation applied to ensure healthy secondary root development. However, this is a management technique only to be used in low soil-N paddocks. Early secondary root development will enhance water and nutrient uptake. Dry soil moisture below the sowing depth of seed will prevent the growth of secondary roots.

Spring irrigation

Identify the fields' refill point to schedule irrigations and minimise water stress. Use of soil moisture monitoring equipment is recommended. Soil moisture data will help identify the refill point (usually when 50% of plant's available water has been depleted) and allow irrigations to be timed between stem elongation (GS31) and the mid-dough stage (GS80) to minimise crop stress. At the mid-dough stage, soil moisture needs to be re-assessed to determine if a further irrigation is required. Correct timing of the last irrigation will ensure adequate grain fill and reduce the risk of lodging and harvesting delays.

MORE INFORMATION

Irrigated wheat

Limited water availability

The best timing for a single in-crop irrigation of around 1 ML/ha is at early to mid-stem elongation. Head emergence is the most sensitive growth stage to a short severe water stress, the best timing for a single irrigation is one that spreads available water across 2-3 plant growth stages. [55]

1.7 Yield and targets

Climate, in particular rainfall, in Australia tends to be highly variable; consequently, crop yields vary from season to season. In order to remain profitable, crop producers must manage their agronomy, crop inputs, marketing and finance to match each season's yield potential.

In cereal rye, 53–58% of total grain yield has been found to be produced by lateral shoots, depending on the cultivar and the growing conditions. [56]

Cereal rye is adapted to all soils; however, its major fit is on the lighter acid soils where yields are usually 70–100% of wheat and triticale when sown between May and June.

On the more traditional wheat soils, cereal rye yields are ~50–70% those of wheat. When sown late (in July) and in dry springs, yields are often less than 50% those of

55 Sykes J. (2012). Irrigated Wheat: Best practices guidelines in cotton farming systems. https://grdc.com.au/resources-and-publications/all-publications/publications/2016/04/irrigatedwheatbestpracticeguidelines

56 K Hakala, K Pahkala (2003) Comparison of central and northern European winter rye cultivars grown at high latitudes. The Journal of Agricultural Science, 141, 169–178.

wheat. Although it heads early, its longer grain-filling period and later maturity limit its performance in the western areas of the NSW grainbelt. [57]

Some characteristics of cereal rye are presented in Table 8.

Table 8: *Typical values for characteristics of cereal rye compared with wheat. Note: The number of seeds per kg will vary according to variety and growing conditions. To check grain bulk density, weight one litre, and this value in kilograms is its density in tonnes per m³.*

	No. of seeds per kg	Volumetric grain weight (kg/hL)	Bulk density		Angle of repose (°)
			(kg/m³)	(t/m³)	
Cereal rye	40,000	71	710	0.71	26
Wheat	34,800	75	750	0.75	27

Source: Department of Primary Industries NSW

Low yields are an issue with cereal rye, and there are several contributing factors. First, spring rainfall can be a limiting factor because rye is generally planted on sandy soils with low water-holding capacity. Second, unlike other cereals, rye needs to be cross-pollinated; this can result in low yields as the often hot temperatures result in the pollen drying out before it can fertilise neighbouring plants. When the plants remain unfertilised, the grain is unable to set properly. A third reason for low yields is that most rye varieties require a long time for grain formation, which means that the grain is often small and shrivelled. [58]

Before planting, identify the target yield required to be profitable:

- Do a simple calculation to see how much water is needed to achieve this yield. [59]
- Know how much soil water is available (treat this water like money in the bank).
- Think about how much risk your farm can carry.
- Consider how this crop fits into your cropping plan: will the longer term benefits to the system outweigh any short-term losses?
- Avoiding a failed crop saves money now and saves stored water for future crops. [60]

Estimating crop yields

Accurate, early estimation of grain yield is important. Farmers require accurate yield estimates for a number of reasons:

- crop insurance purposes
- delivery estimates
- planning harvest and storage requirements
- cash-flow budgeting.

Extensive personal experience is the best asset for estimating yield at early stages of growth. As crops near maturity, it becomes easier to estimate yield with greater accuracy.

Estimation methods

Many methods are available for farmers and others to estimate yield of various crops. The method presented here can be undertaken relatively quickly and easily. Steps are as follows:

57 P Matthews, D McCaffery, L Jenkins (2016) Winter crop variety sowing guide 2016. NSW Department of Primary Industries, https://www.dpi.nsw.gov.au/agriculture/broadacre-crops/guides/publications/winter-crop-variety-sowing-guide

58 L Martin (2015) Growing cereal rye to increase carbon and prevent wind erosion. Liebe Group, March 2015, http://www.liebegroup.org.au/wp-content/uploads/2015/03/Case-Study-Jeff-Pearse-March-2015.pdf

59 J Whish (2013) Sorghum yield risk vs starting soil moisture. GRDC Update Papers, August 2014, https://grdc.com.au/Research-and-Development/GRDC-Update-Papers/2014/08/Sorghum-yield-risk-vs-starting-soil-moisture

60 J Whish (2013) Impact of stored water on risk and sowing decisions in western NSW. GRDC Update Papers, July 2013, https://grdc.com.au/Research-and-Development/GRDC-Update-Papers/2013/07/Impact-of-stored-water-on-risk-and-sowing-decisions-in-western-NSW

1. Select an area that is representative of the paddock. Using a measuring rod or tape, measure out an area 1 m^2 and count the number of heads.
2. Do this five times to get an average for the crop: no. of heads per m^2 (e.g. 200).
3. Count the number of grains in at least 20 heads and work out the average: no. of grains per head (e.g. 24).
4. Determine the 100-grain weight for the crop (in grams) by referring to table 1 in: Estimating crop yields—a brief guide. Or in this case for cereal rye, assume 40,000 seeds per kg, from Matthews and McCaffery (2016, Table 14, p. 27) [61]. Then (1000/40,000) × 100 = 2.5 g.
5. No. of grains per m^2 = no. of heads per m^2 × no. of grains per head; e.g. 200 × 24 = 4800.
6. Yield per m^2 (g) = (no. of grains per m^2/100) × 100-grain weight; e.g. 4800/100 × 2.5 = 120 g
7. Yield (t/ha) = numeric value of yield per m^2/100; e.g. 120/100 = 1.2 t/ha

Accuracy of yield estimates depends upon an adequate number of counts being taken to get a representative average of the paddock. The yield estimate determined will be a guide only.

This type of yield estimation should be able to be used in a number of situations on a grain-growing property. Grain losses both before and during harvest can be significant and an allowance for 5–10% loss should be included in final calculations. [62]

Yield Prophet®

Scientists at the Agricultural Production Systems Research Unit (APRSU) have aimed to support farmers' capacity to achieve yield potential by developing the Agricultural Production Systems Simulator (APSIM). APSIM is a farming systems model that simulates the effects of environmental variables and management decisions on crop yield, profits and ecological outcomes.

Yield Prophet® delivers information from APSIM to farmers (and consultants) to aid their decision-making. Yield Prophet® has enjoyed a measure of acceptance and adoption amongst innovative farmers and has had valuable impacts in terms of assisting farmers to manage climate variability at a paddock level.

Yield Prophet® is an online crop production model designed to present grain growers and consultants with real-time information about their crops. This tool provides growers with integrated production risk advice and monitoring decision-support relevant to farm management.

Operated as a web interface for APSIM, Yield Prophet® generates crop simulations and reports to assist decision-making. By matching crop inputs with potential yield in a given season, Yield Prophet® subscribers may avoid over-investing or under-investing in their crop.

The simulations provide a framework for farmers and advisers to:

- forecast yield
- manage climate and soil water risk
- make informed decisions about N and irrigation applications
- match inputs with the yield potential of their crop
- assess the effect of changed sowing dates or varieties
- assess the possible effects of climate change.

Farmers and consultants use Yield Prophet® to match crop inputs with potential yield in a given season. This is achieved primarily by conducting scenario analyses in which the effects of alternative management options on crop yield and potential profitability can be assessed and applied, and can thereby influence decision-making.

61 P Matthews, D McCaffery, L Jenkins (2016) Winter crop variety sowing guide 2016. NSW Department of Primary Industries, https://www.dpi.nsw.gov.au/agriculture/broadacre-crops/guides/publications/winter-crop-variety-sowing-guide

62 Agriculture Victoria (2013) Estimating crop yields: a brief guide. Agriculture Victoria, http://agriculture.vic.gov.au/agriculture/grains-and-other-crops/crop-production/estimating-crop-yields-a-brief-guide

MORE INFORMATION

Yield Prophet®

GRDC Update Paper: Optimising performance of current northern cropping farming systems.

How does it work?

Yield Prophet® generates crop simulations that combine the essential components of growing a crop including:

- a soil test sampled prior to planting;
- a soil classification selected from the Yield Prophet® library of ~1000 soils, chosen as representative of the production area;
- historical and active climate data taken from the nearest Bureau of Meteorology weather station;
- paddock-specific rainfall data recorded by the user (optional);
- individual crop details; and
- fertiliser and irrigation applications during the growing season.

1.7.1 Seasonal outlook

Queensland

The Monthly climate statement, which interprets seasonal climate outlook information for Queensland, is produced by the Science Delivery Division of the Queensland Department of Science, Information Technology and Innovation (QDSITI). The statement is based on QDSITI's own information and draws on information from national and international climate agencies.

The QDSITI assessment of rainfall probabilities is based on the current state of the ocean and atmosphere and its similarity with previous years. In particular, QDSITI monitors the current and projected state of El Niño–Southern Oscillation (ENSO), referring to information such as Variation of sea-surface temperature from average and the Southern Oscillation Index (SOI). Based on this information, QDSITI uses two systems to calculate rainfall probabilities for Queensland:

- QDSITI's SOI-Phase system produces seasonal rainfall probabilities based on phases of the SOI.
- QDSITI's experimental SPOTA-1 (Seasonal Pacific Ocean Temperature Analysis version 1) monitors Pacific Ocean sea-surface temperatures from March to October each year to provide long-lead outlooks for Queensland summer (November–March) rainfall.

Outlooks based on both the SOI-Phase system and SPOTA-1 are freely available, although a password is required to access the experimental SPOTA-1 information (email: rouseabout@dsiti.qld.gov.au). [63]

Queensland Alliance for Agriculture & Food Innovation produces regular, seasonal outlooks for wheat producers in Queensland. These high-value reports are written in an easy-to-read style and are free.

New South Wales

The Seasonal Conditions Report is issued each month by NSW Department of Primary Industries. It contains information on rainfall, water storages, crops, livestock and other issues. It is available to landholders to help them make informed decisions on how they manage operations, and prepare for seasonal conditions and drought.

Seasonal Conditions Reports are also used by the Regional Assistance Advisory Committee in making recommendations to the NSW Government on potential support for farm businesses, families and communities. [64]

63 QDSITI (2016) Seasonal climate outlook. Queensland Department of Science, Information Technology and Innovation, https://www.longpaddock.qld.gov.au/seasonalclimateoutlook/

64 NSW DPI. Seasonal conditions reports. NSW Department of Primary Industries, http://www.dpi.nsw.gov.au/climate-and-emergencies/droughthub/information-and-resources/regional-seasonal-conditions-reports

CliMate

Australian CliMate is a suite of climate analysis tools delivered on the web, iPhone, iPad and iPod Touch devices. CliMate allows you to interrogate climate records to ask questions relating to rainfall, temperature, radiation, and derived variables such as heat sums, soil water and soil nitrate, and well as ENSO status. It is designed for decision makers such as farmers whose businesses rely on the weather.

Download from the Apple iTunes store or visit the CliMate website.

One of the CliMate tools, *Season's progress?*, uses long-term (1949 to present) weather records to assess progress of the current season (rainfall, temperature, heat sums and radiation) compared with the average and with all years.

It explores the readily available weather data, compares the current season with the long-term average, and graphically presents the spread of experience from previous seasons.

Crop progress and expectations are influenced by rainfall, temperature and radiation since planting. *Season's progress?* provides an objective assessment based on long-term records:

- How is the crop developing compared to previous seasons, based on heat sum?
- Is there any reason why my crop is not doing as well as usual because of below average rainfall or radiation?
- Based on the season's progress (and starting conditions from *HowWet/N?*), should I adjust inputs?

For inputs, *Season's progress?* asks for the weather variable to be explored (rainfall, average daily temperature, radiation, heat sum with base temperatures of 0, 5, 10, 15 and 20°C), a start month and a duration.

As outputs, text and two graphical presentations are used to show the current season in the context of the average and all years. Departures from the average are shown in a fire-risk chart as the departure from the average in units of standard deviation. [65]

1.7.2 Fallow moisture

For a growing crop, there are two sources of water: the water stored in the soil during the fallow, and the water that falls as rain while the crop is growing. As a farmer, you have some control over the stored soil water; you can measure how much you have before planting the crop. Long-range forecasts and tools such as the SOI can indicate the likelihood of the season being wet or dry; however, they cannot guarantee that rain will fall when it is needed. [66]

HowWet?

HowWet? is a program developed by APSRU that uses records from a nearby weather station to estimate how much plant available water has accumulated in the soil and the amount of organic N that has been converted to an available nitrate during a fallow. *HowWet?* tracks soil moisture, evaporation, runoff and drainage on a daily time-step. Accumulation of available N in the soil is calculated based on surface soil moisture, temperature and soil organic carbon.

HowWet?:

- estimates how much rain has been stored as plant-available soil water during the most recent fallow period;
- estimates the N mineralised as nitrate-N in soil; and
- provides a comparison with previous seasons.

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65 MCV (2014) Australian CliMate—climate tools for decision makers. Managing Climate Variability R & D Program, https://climateapp.net.au/

66 J Whish (2013) Impact of stored water on risk and sowing decisions in western NSW. GRDC Update Papers, July 2013, https://grdc.com.au/Research-and-Development/GRDC-Update-Papers/2013/07/Impact-of-stored-water-on-risk-and-sowing-decisions-in-western-NSW

This information aids in the decision about what crop to plant and how much N fertiliser to apply. Many grain growers are in regions where stored soil water and nitrate at planting are important in crop management decisions. This is of particular importance to northern Australian grain growers with clay soils where stored soil water at planting can constitute a large part of a crop's water supply.

Questions this tool answers:

- How much longer should I fallow? If the soil is near full, maybe the fallow can be shortened.
- Given the soil type on my farm and local rainfall to date, what is the relative soil moisture and nitrate-N accumulation over the fallow period compared with most years? Relative changes are more reliable than absolute values.
- Based on estimates of soil water and nitrate-N accumulation over the fallow, what adjustments are needed to the N supply?

Inputs:

- a selected soil type and weather station
- an estimate of soil cover and starting soil moisture
- rainfall data input by the user for the stand-alone version of *HowOften?*

Outputs:

- a graph showing plant-available soil water for the current year and all other years and a table summarising the recent fallow water balance
- a graph showing nitrate accumulation for the current year and all other years.

Reliability

HowWet? uses standard water-balance algorithms from *HowLeaky*? and a simplified nitrate mineralisation based on the original version of *HowWet?* Further calibration is needed before accepting with confidence absolute value estimates.

Soil descriptions are based on generic soil types with standard OC and C/N ratios, and as such should be regarded as indicative only and best used as a measure of relative water accumulation and nitrate mineralisation. [67]

1.7.3 Water Use Efficiency

Water Use Efficiency (WUE) is the measure of a cropping system's capacity to convert water into plant biomass or grain. It includes the use of water stored in the soil and rainfall during the growing season.

WUE relies on:

- the soil's ability to capture and store water;
- the crop's ability to access water stored in the soil and rainfall during the season;
- the crop's ability to convert water into biomass; and
- the crop's ability to convert biomass into grain (harvest index).

One study showed ~30 mm more water use on acidic soils by acid-tolerant cereal rye than wheat from ~70 cm deeper root penetration. [68]

Water is the principal limiting factor in rainfed cropping systems in northern Australia. The objective of rainfed cropping systems is to maximise the proportion of rainfall that crops use, and minimise water lost through runoff, drainage and evaporation from the soil surface and to weeds.

In the north of the Northern grains region, rainfall is more summer-dominant and both summer and winter crops are grown. However, rainfall is highly variable and can range, during each cropping season, from little or no rain to major rain

67 MCV (2012) How Wet/N? Managing Climate Variability R & D Program, https://climateapp.net.au/

68 D Tennant, D Hall (2001) Improving water use of annual crops and pastures—limitations and opportunities in Western Australia. Australian Journal of Agricultural Research 52, 171–182, http://www.publish.csiro.au/cp/AR00005

events that result in waterlogging or flooding. In the south of the region, rainfall is winter-dominant.

Storing water in fallows between crops is the grower's most effective tool to manage the risk of rainfall variability, as in-season rainfall alone, in either summer or winter, is rarely enough to produce a profitable crop, especially with high levels of plant transpiration and evaporation.

Fortunately, many cropping soils in the northern grains region have the capacity to store large amounts of water during the fallow. [69]

Definitions and calculation of aspects of WUE are as follows:

- Fallow efficiency (%): the efficiency with which rainfall (mm) during a fallow period is stored for use by the following crop. Calculated as: Fallow efficiency = (change in plant-available water during fallow × 100)/fallow rainfall.
- Crop WUE (kg/ha/mm): the efficiency with which an individual crop converts water transpired (or used) (mm) to grain (kg/ha). Calculated as: Crop WUE = grain yield/(crop water supply – soil evaporation).
- Systems WUE (kg/mm): the efficiency with which rainfall (mm) is converted to grain (kg) over multiple crop and fallow phases. Calculated as: SWUE = total grain yield/total rainfall.

Strategies to increase yield

In environments such as western NSW where yield is limited by water availability, there are four ways of increasing yield:

1. Increase the amount of water available to a crop (e.g. good summer weed control, stubble retention, long fallow, sowing early to increase rooting depth).
2. Increase the proportion of water that is transpired by crops rather than lost to evaporation or weeds (e.g. early sowing, early N, vigorous crops and varieties, narrow row spacing, high plant densities, stubble retention, good weed management).
3. Increase the efficiency with which crops exchange water for carbon dioxide to grow dry matter, i.e. transpiration efficiency (e.g. early sowing, good nutrition, high transpiration-efficiency varieties).
4. Increase the total proportion of dry matter that is grain, i.e. improve harvest index (e.g. early-flowering varieties, delayed N, wider row spacing, low plant densities, minimising losses to disease, high harvest index).

The last three of these all improve WUE. [70]

VIDEOS

WATCH: GCTV12: Water Use Efficiency initiative.

69 GRDC (2009) Water Use Efficiency fact sheet. Grains Research and Development Corporation, https://grdc.com.au/__data/assets/pdf_file/0029/225686/water-use-efficiency-north.pdf.pdf

70 J Hunt, R Brill (2012) Strategies for improving Water Use Efficiency in western regions through increasing harvest index. GRDC Update Papers, April 2012, https://www.dpi.nsw.gov.au/__data/assets/pdf_file/0018/431280/Strategies-for-improving-water-use-efficiency-in-western-regions-through-increasing-harvest-index.pdf

IN FOCUS

Grain yield and water use: relative performance of winter v. spring cereals in Canada

Changing economic conditions have provided strong incentives for grain producers to choose the most profitable cereal crops to grow. Grain yield and WUE were determined for winter wheat, cereal rye, hard red spring (HRS) wheat, Canada prairie spring (CPS) wheat, amber durum and barley under no-till systems. Over 60% of yield variability existing among site/years was due to water use or evapotranspiration (ET) in semi-arid Canada. Mean grain yield increased by 16.3 kg/ha with each millimetre of increase in ET. Barley produced 3748 kg/ha of grain on average, or 21% more than winter wheat, 27% more than CPS wheat, 39% more than rye or durum and 50% more than HRS wheat. Average yields differed <5% between winter wheat and CPS wheat, but in water-stressed environments, CPS wheat had 19–34% lower grain yield than winter wheat. In one of the five cases where winter wheat was seeded much later than the recommended seeding date, CPS wheat yields were 16% higher than winter wheat. With every millimetre of increased ET, CPS or barley increased grain yield by 22 kg/ha, while winter wheat increased yield by 17 kg/ha. Winter wheat and rye had no yield differences in general, but in more moist environments, winter wheat produced higher (up to 28%) grain yield than autumn rye, and in the year when winter wheat was seeded late, winter wheat yielded 11% lower than rye. As fertiliser N increased from 50 to 100 kg/ha, barley grain yield increased by 347 kg/ha, and durum grain yield increased by only 5 kg/ha. Winter wheat, autumn rye and barley had greater WUE than the other spring cereals, but soil profile (0–120 cm) water in the spring did not differ among crops. [71]

MORE INFORMATION

Water Use Efficiency of grain crops in Australia: principles, benchmarks and management

Making the most of available water in wheat production.

1.7.4 Nitrogen-use efficiency

Soil type, rainfall intensity and the timing of fertiliser application largely determine N losses from dryland cropping soils.

In cracking clay soils of the northern grains region, saturated soil conditions between fertiliser application and crop growth can lead to significant losses of N from the soil through denitrification. The gases lost in this case are nitric oxide (NO), nitrous oxide (N_2O) and di-nitrogen (N_2). Isotope studies have found these losses can be >30% of the N applied. Direct measurements of nitrous oxide highlight the rapidity of loss in this process.

Insufficient rainfall after surface application of N fertilisers can result in losses from the soil through volatilisation. The gas lost in this case is ammonia. Direct measurements of ammonia losses have found that they were generally <15% of the N applied, even less in in-crop situations. An exception occurred with the application of ammonium sulfate to soils with free lime at the surface, where losses were >25% of the N applied. Recovery of N applied in-crop requires sufficient in-crop rainfall for plant uptake from otherwise dry surface soil. [72]

71 YT Gan, GP Lafond, WE May (2000) Grain yield and water use: relative performance of winter vs. spring cereals in east-central Saskatchewan. Canadian *Journal of Plant Science* 80, 533-541, https://www.researchgate.net/publication/276030513_Grain_yield_and_water_use_Relative_performance_of_winter_vs_spring_cereals_in_east-central_Saskatchewan

72 G Schwenke, P Grace, M Bell (2013) Nitrogen-use efficiency. GRDC Update Papers, July 2013, https://grdc.com.au/Research-and-Development/GRDC-Update-Papers/2013/07/Nitrogen-use-efficiency

In southern NSW, experiments showed that banding of anhydrous ammonia or urea fertiliser provided a slow-release form of N to wheat crops, thereby reducing excessive seedling growth and the risks of haying-off. Yield responses to applied N were small or negative in a drought year but larger (17 kg grain/kg N fertiliser) in favourable seasons. Gaseous loss of ammonia to the atmosphere was negligible. [73]

IN FOCUS

Environment and genotype influence on grain protein concentration of wheat and rye

Protein is a primary quality component of cereal grains. Protein concentration is influenced by both environmental and genotypic factors that are difficult to separate. Cultivar and agronomic trials were conducted on several Saskatchewan (Canada) soil types with the objective of characterising the influence of genotype and environment on wheat (*Triticum aestivum* L.) and rye (*Secale cereale* L.) grain protein concentration and N-use efficiency (NUE) for grain protein production. Minimum protein concentration of 95.4 g protein per kg dry grain was expressed when cultivars were produced under high productivity conditions on soils with low total plant available N. Minimum protein concentration was maintained until N was no longer the factor most limiting grain yield. At this point, the protein concentration–N response curve of a cultivar entered an increased phase. Any environmental (e.g. water or time of N availability) or genotypic factor that increased yield potential also increased the amount of N required to initiate the increase phase of the grain protein concentration N–response curve. Asymptotic maximum protein concentration was determined by both environmental and genotypic factors. Maximum protein concentration at high levels of N varied from 130 to 231 and 107 to 177 g protein per kg dry grain for winter wheat and rye, respectively. At low levels of total available N, the NUE for grain protein production approached 80%. The NUE for grain protein production dropped off rapidly for subsequent increments of N fertiliser, approaching zero for maximum grain yield and reaching zero when maximum grain protein yield was achieved. The end of the increase phase of the protein concentration-N response curve occurred at approximately the same available N level as maximum grain yield. These observations indicate that management systems designed for the production of cereals with high grain protein concentrations will have a very low NUE for grain and grain protein production. [74]

Optimising nitrogen-use efficiency

Nitrogen fertilisers are a significant expense for broadacre farmers, so optimising use of fertiliser inputs can reduce this cost. There are three main stores of N within the soil with the potential to supply N to crops: soil organic matter, plant residues, and mineral N (ammonium and nitrate) present in the soil. To optimise the ability of plants to use soil N, growers should be aware of how much there is in each store, and soil testing is the best method of measuring these N sources. The results can then be used to determine fertiliser rates with models such as CropARM (previously known as

73 JF Angus, VVSR Gupta, GD Pitson, AJ Good (2014) Effect of banded ammonia and urea fertiliser on soil properties and the growth and yield of wheat. *Crop & Pasture Science* 65, 337–352, http://www.publish.csiro.au/cp/CP13337

74 DB Fowler, J Brydon, BA Darroch, MH Entz, AM Johnston (1990) Environment and genotype influence on grain protein concentration of wheat and rye. Agronomy Journal, 82(4), 655–664, https://dl.sciencesocieties.org/publications/aj/abstracts/82/4/AJ0820040655?access=0&view=pdf

WhopperCropper) and The Nitrogen Books (see Soil Quality Fact Sheet: Nitrogen—Queensland). [75]

1.8 Disease status of paddock

Fewer diseases affect rye than other cereals. [76]

1.8.1 Soil testing for disease

In addition to visual symptoms, the DNA-based soil test PreDicta B can be used to assess the disease status in the paddock. Soil samples that include plant residues should be tested early in late summer to allow results to be returned before seeding. This test is particularly useful when sowing susceptible wheat varieties, and for assessing the risk after a non-cereal crop.

PreDicta B

Cereal root diseases cost grain growers in excess of $200 million a year in lost production. Much of this can be prevented.

PreDicta B is a DNA-based soil testing service that identifies which soilborne pathogens pose a significant risk to broadacre crops prior to seeding.

PreDicta B includes tests for:

- take-all (*Gaeumannomyces graminis var. tritici* and *G. graminis var. avenae*
- Rhizoctonia barepatch (*Rhizoctonia solani AG8*)
- crown rot (*Fusarium pseudograminearum and F. culmorum*)
- blackspot of field peas (*Mycosphaerella pinodes, Phoma medicaginis var. pinodella* and *P. koolunga*).

Access PreDicta B testing service

Growers can access PreDicta B diagnostic testing services through an agronomist accredited by the South Australian Research and Development Institute (SARDI). They will interpret the results and provide advice on management options to reduce the risk of yield loss.

SARDI processes PreDicta B samples weekly from February to mid-May (prior to crops being sown) every year.

PreDicta B is not intended for in-crop diagnosis. See SARDI's Crop diagnostics webpage for other services.

The Queensland Government also has a service: Test your farm for nematodes.

PreDicta B certification courses

SARDI runs one-day courses to:

- certify agronomists in use of the PreDicta B testing service run by SARDI; and
- educate new and experienced agronomists about how better to manage soilborne diseases.

Completing the course will give agronomists:

- access to the PreDicta B service;
- access to the e-version of the Root Disease Risk Management Resource Manual; and
- a PreDicta B soil corer valued at over $100.

Courses focus on the three main diseases in each region, selecting from:

- Rhizoctonia barepatch,

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75 Soil Quality Pty Ltd. Optimising soil nutrition—Queensland. http://www.soilquality.org.au/factsheets/optimising-soil-nutrition-queensland

76 SARE (2007) Cereal rye. In Managing Cover Crops Profitably, 3rd Edition. Sustainable Agriculture Research and Education, http://www.sare.org/Learning-Center/Books/Managing-Cover-Crops-Profitably-3rd-Edition/Text-Version/Nonlegume-Cover-Crops/Cereal-Rye

- RLN,
- crown rot, and
- take-all. [77]

1.8.2 Effects of cropping history

The previous crop will influence levels of both soil- and residue-borne diseases. Important diseases to consider include take-all, crown rot, yellow leaf spot, stripe rust and Wheat streak mosaic virus. Transmission from neighbouring paddocks and volunteers are key concerns with some diseases. Controlling the 'green bridge' of over-summering cereals and weeds is an important strategy.

For diseases, the focus in the northern grains region has been on management of crown rot and RLN, yellow leaf spot in winter cereals, and the roles that rotational crops play, particularly the winter pulses. Crop sequences also affect the incidence and severity of major diseases of summer crops, especially those diseases that have several summer, and in some instances winter, crop hosts.

Crop sequencing is only a part of the integrated management of diseases. Other practices include maintaining sufficient distance from last year's paddock of the same crop or from a paddock with residue infected with a pathogen of the intended crop; the use of high quality, fungicide-treated seed; planting within the planting window; variety selection; and in-crop fungicide treatments. [78]

For more information, see Section 9: Diseases.

1.8.3 Nematode status of paddock

Pratylenchus thornei and *Pratylenchus neglectus* (RLN) are migratory root endoparasites that are widely distributed in the wheat-growing regions of Australia and can reduce grain yield by up to 50% in many current wheat varieties (Photo 10). *P. thornei* is the most damaging species and occurs commonly in the northern grain region; *P. neglectus* occurs less frequently than *P. thornei* but is still quite common. A third nematode, *Merlinius brevidens* (stunt nematode), is the most commonly identified plant-parasitic species in this region. [79]

Photo 10: *Paddock showing patches caused by root-lesion nematodes.*

Source: Department of Agriculture and Food WA

77 PIRSA (2016) PreDicta B. Primary Industries and Regions South Australia, September 2016, http://pir.sa.gov.au/research/services/molecular_diagnostics/predicta_b

78 M Ryley (2011) Diseases shared by different crops and issues for crop sequencing. GRDC Update Papers, September 2011, http://elibrary.grdc.com.au/ark!!33517/vhnf54 t/a9ft5hf

79 QDAF (2010) Test your farm for nematodes. Queensland Department of Agriculture and Fisheries, July 2010, https://www.daf.qld.gov.au/plants/field-crops-and-pastures/broadacre-field-crops/crop-diseases/root-lesion-nematodes/test-your-farm-for-nematodes

MORE INFORMATION

GRDC Fact Sheet: Plant parasitic nematodes, northern region.

Rye can help reduce root-knot nematodes (*Meloidogyne* spp.) and other harmful nematodes. [80]

Effects of cropping history on nematode status

- Well-managed rotations are vital. Avoid consecutive host crops to limit populations.
- Choose varieties with high tolerance ratings to maximise yields in fields where RLN is present.
- Choose rotation crops with high resistance ratings, so that fewer nematodes remain in the soil to infect subsequent crops.

For more information, see Section 8: Nematode control

1.9 Insect status of paddock

Rye in the paddock is generally free from insect pests. Where problems arise, growers should contact their local agronomist or state government department of primary industries for advice.

Although rye is susceptible to the same insects that attack other cereals, serious infestations are rare. Rye reduces insect pest problems in rotations and attracts significant numbers of beneficials such as ladybird beetles. [81]

Pests such as redlegged earth mites, blue oat mites, nematodes and, in some seasons, cutworms may pose a risk in some paddocks. Risk should be assessed based on paddock history (including recent control) and crop susceptibility. Controlling weeds in summer fallows and around paddocks can also minimise some of these pests.

Soil-dwelling insect pests can seriously reduce plant establishment and populations, and subsequent yield potential.

Soil insects include:

- cockroaches
- crickets
- earwigs
- black scarab beetles
- cutworms
- false wireworm
- true wireworm

1.9.1 Insect sampling of soil

Recent seasons have seen seemingly new pests and unusual damage in pulse and grain crops in the Northern grains region. Growers are advised to:

- Monitor crops frequently so as not to be caught out by new or existing pests.
- Look for and report any unusual pests or damage symptoms—photographs are useful.
- Just because a pest is present in large numbers in one year does not mean it will be so the next year. Another spasmodic pest, e.g. soybean moth, may make its presence felt.
- However, be aware of cultural practices that favour pests and rotate crops each year to minimise the build-up of pests and plant diseases. [82]

80 SARE (2007) Cereal rye. In Managing Cover Crops Profitably, 3rd Edition. Sustainable Agriculture Research and Education, http://www.sare.org/Learning-Center/Books/Managing-Cover-Crops-Profitably-3rd-Edition/Text-Version/Nonlegume-Cover-Crops/Cereal-Rye

81 SARE (2007) Cereal rye. In Managing Cover Crops Profitably, 3rd Edition. Sustainable Agriculture Research and Education, http://www.sare.org/Learning-Center/Books/Managing-Cover-Crops-Profitably-3rd-Edition/Text-Version/Nonlegume-Cover-Crops/Cereal-Rye

82 H Brier, M Miles (2015) Emerging insect threats in northern grain crops. GRDC Update Papers, July 2015, https://grdc.com.au/Research-and-Development/GRDC-Update-Papers/2015/07/Emerging-insect-threats-in-northern-grain-crops

Sampling methods

Sampling methods should be applied in a consistent manner between paddocks and sampling occasions. Any differences can then be confidently attributed to changes in the insect populations, and not to different sampling techniques.

Sweep net

The majority of crop monitoring for insect pests is done with a sweep net, or visually. Use of a shake/beating tray is another technique. Sampling pastures mostly relies on visual assessment of the sward or the soil below it. The sweep net is the most convenient sampling technique for many insects. The net should be about 38 cm in diameter, and swept in a 180 arc from one side of the sweeper's body to the other. The net should pass through the crop at such an angle that the lower lip travels through the crop marginally before the upper lip. The standard sample is 10 sweeps, taken over 10 paces. This sampling 'set' should be repeated as many times as practicable across the crop, and at no less than five locations. After completing the sets of sweeps, counts should be averaged to give an overall estimate of abundance. Sweep nets tend to underestimate the size of the pest population. Sweep-net efficiency is significantly affected by temperature, relative humidity, crop height, wind speed, plant density and the operator's vigour. [83]

Soil sampling by spade

Method:

1. Take a number of spade samples from random locations across the field.
2. Check that all spade samples are deep enough to take in the moist soil layer (this is essential).
3. Hand-sort samples to determine type and number of soil insects.

Germinating seed bait technique

Immediately following planting rain:

1. Soak insecticide-free crop seed in water for at least two hours to initiate germination.
2. Bury a dessertspoon of the seed under 1 cm of soil at each corner of a square 5 m × 5 m at five widely spaced sites per 100 ha.
3. Mark the position of the seed baits, because large populations of soil insects can destroy the baits.
4. One day after seedling emergence, dig up the plants and count the insects.

Trials have shown no difference in the type of seed used for attracting soil-dwelling insects. However, use of the type of seed that is to be sown as a crop is likely to indicate the species of pests that could damage that crop. The major disadvantage of the germinating-grain bait method is the delay between the seed placement and assessment. [84]

1.9.2 Identification

The SARDI Entomology Unit provides an insect identification and advisory service. The Unit identifies insects to the highest taxonomic level for species where possible and can give farmers biological information and guidelines for control. [85]

83 QDAF (2000) Sampling methods for insects and mites. Queensland Department of Agriculture and Fisheries, https://ipmguidelinesforgrains.com.au/ipm-information/making-informed-control-decisions/monitoring/monitoring-tools-and-techniques/

84 QDAF (2011) How to recognise and monitor soil insects. Queensland Department of Agriculture and Fisheries, April 2011, https://www.daf.qld.gov.au/plants/field-crops-and-pastures/broadacre-field-crops/integrated-pest-management/help-pages/recognising-and-monitoring-soil-insects

85 PIRSA (2015) Insect diagnostic service. Primary Industries and Regions South Australia, June 2015, http://pir.sa.gov.au/research/research_specialties/sustainable_systems/entomology/insect_diagnostic_service

Insect ID: The Ute Guide

The Insect ID Ute Guide, available on Android and iPhone, is a comprehensive reference guide for insect pests commonly affecting broadacre crops and growers across Australia, and includes the beneficial insects that may help to control them. Photos have been provided for multiple lifecycle stages, and each insect is described in detail, with information on the crops they attack, how they can be monitored, and other pests with which they may be confused. Use of this app should result in better management of pests, increased farm profitability and improved chemical usage. [86]

App features:

- region selection
- predictive search by common and scientific names
- ability to compare photos of insects side-by-side with insects in the app
- identification of beneficial predators and parasites of insect pests
- option to download content updates in-app with the latest pests affecting crops for each region
- ensures awareness of international biosecurity pests.

1.9.3 Effect of cropping history

It is important to consider paddock history when planning for pest management. Resident pests can be easier to predict by using paddock history and agronomic and weather data to determine the likely presence (and numbers) of certain pests within a paddock. This will point to the likely pest issues and allow growers to implement preventive options. [87] Reduced tillage and increased stubble retention have changed the cropping landscape with respect to soil moisture retention, groundcover and soil biology and this has also affected the abundance and types of invertebrate species being seen in crops. These systems increase invertebrate biodiversity but also create more favourable conditions for many pests such as slugs, earwigs, weevils, beetles and many caterpillars. In turn, they have also influenced beneficial species such as carabid and ladybird beetles, hoverflies and parasitic wasps. [88]

For more information, see Section 7: Insect control.

Where paddock history, paddock conditions or pest numbers indicate a high risk of pest damage, a grower might decide to use pre-seeding control measures to reduce pest pressure, apply a seed dressing to protect the crop during the seedling stage, and plan to apply a foliar insecticide if pest numbers reach a particular level. [89]

Different soil insects occur under different cultivation systems and farm management can directly influence the type and number of these pests:

MORE INFORMATION

Pest Genie Australia

APVMA.

86 GRDC (2016) Apps. Grains Research and Development Corporation, https://grdc.com.au/Resources/Apps

87 R Jennings (2015) Growers chase pest-control answers. GRDC Ground Cover Issue 117, June 2015, https://grdc.com.au/Media-Centre/Ground-Cover/Ground-Cover-Issue-117-July-August-2015/Growers-chase-pest-control-answers

88 P Bowden, P Umina, G McDonald (2014) Emerging insect pests. GRDC Update Papers, July 2014, https://grdc.com.au/Research-and-Development/GRDC-Update-Papers/2014/07/Emerging-insect-pests

89 G Jennings (2012) Integrating pest management. South Australian No-Till Farmers Association, Spring 2012, http://www.santfa.com.au/wp-content/uploads/Santfa-TCE-Spring-12-Integrating-pest-management.pdf

- Weedy fallows and volunteer crops encourage soil insect buildup.
- Insect numbers decline during a clean long fallow due to lack of food.
- Summer cereals followed by volunteer winter crops promote the buildup of earwigs and crickets.
- High levels of stubble on the soil surface can promote some soil insects due to a food source, but this can also mean that pests continue feeding on the stubble instead of germinating crops.
- No-till encourages beneficial predatory insects and earthworms.
- Incorporating stubble promotes black field earwig populations.
- False wireworms are found under all intensities of cultivation but numbers decline if stubble levels are very low.

Soil insect control measures are normally applied at sowing. Because different insects require different control measures, the species of soil insects must be identified before planting. Soil insects are often difficult to detect as they hide under trash or in the soil. Immature insects such as false wireworm larvae are usually found at the moist–dry soil interface. [90]

See Section 7: Insect control, for more information.

90 QDAF (2011) How to recognise and monitor soil insects. Queensland Department of Agriculture and Fisheries, April 2011, https://www.daf.qld.gov.au/plants/field-crops-and-pastures/broadacre-field-crops/integrated-pest-management/help-pages/recognising-and-monitoring-soil-insects

Pre-planting

Key messages:

- Although cereal rye has been grown in Australia for more than 150 years, its agronomic development and breeding has been neglected compared to other winter-grown cereals.
- A Grains Research and Development Corporation project was funded to produce higher yielding rye varieties with new end uses. These include a rye with higher soluble pentosan, a white rye suitable for New South Wales.
- Varieties include Bevy, Southern Green Forage Rye, Ryesun, Westwood and Vampire.
- Ensure that seed quality is of a high standard. Check for damage and discoloration because affected seeds may have poor germination and emergence.
- Rye seed deteriorates quickly after one year of storage.
- Rye can be susceptible to lodging.
- Ensure that the seed is pure and has come from safe seed storage conditions.

2.1 Cereal rye for forage

Key points:

- Alternative forage cereal and legume pastures offer opportunities for grazing at different times during the season.
- Choose varieties according to your needs: ability to fill feed gaps; what benefits to rotation in terms of nutrition, root and foliar disease management, weed control; and suitability for hay production.

Forage cereal rye produces rapid winter feed because it does not have a vernalisation (cold temperature) requirement and goes into reproductive mode almost immediately. Cereal rye plants should be grazed early, before Zadoks growth stage Z31 (stem elongation), to ensure two to three grazings. After Z31, grazed rye plants will not recover well and will lose palatability and feed quality, and are therefore not a good silage or hay option. Cereal rye is best sown in combination with another forage, either as a mix or followed by a spring-sown summer forage. It can be grown in all rainfall areas, but as rainfall decreases, its ability to produce biomass and recover from grazing declines.

In one trial, forage cereal rye showed outstanding early dry matter (DM) production, reaching 416 kg DM per hectare (DM/ha) at Z14/21 (four-leaf stage, one tiller) only two weeks after sowing (Table 1) on 5 July. Ten days later on July 15, forage cereal rye had increased production by 469 kg/ha, to reach 885 kg DM/ha—exceptional production at this time of year. [1]

1 A Frischke, K Drever (2010). Alternative winter pastures. Online Farm Trials, Grains Research and Development Corporation,, http://www.farmtrials.com.au/trial/14012

Table 1: *Alternative pasture dry matter production (kg/ha), Culgoa 2010.*

Pasture	5 July	15 July	14 October		Grain yield grazed (t/ha)
	Ungrazed	Ungrazed	Grazed	Ungrazed	
Forage cereal rye	416	885	8759	6962	Not intended for harvest
Forage wheat	142	287	4602	4389	2.5
Oats–medic mix	160	255	4952	3262	1.44
Eastern star clover	41	56	4799	1569	Not harvested

Source: http://www.farmtrials.com.au/trial/14012

2.1.1 Cereals for grazing

The total amount of feed available will be influenced by the type of crop, variety, disease resistance and sowing time. For overall forage production, oats will generally produce more forage than cereal rye, wheat, barley or triticale.

Cereals that produce large awns can cause mouth injuries to livestock, and they should be avoided for hay production or where head emergence under grazing cannot be controlled. These cereals include cereal rye, barley, triticale and some wheats, although awnless varieties of barley and wheat and reduced-awn triticale are available.

Selection of crop types or varieties tolerant to root and/or leaf diseases will lessen the disease impact in susceptible situations. Cereal rye variety Bevy was developed with improved leaf and stem rust disease resistance. Southern Green has excellent resistance to cereal cyst-nematode (CCN), a significant problem in lighter soils around Australia. It is also resistant to take-all (caused by *Gaeumannomyces graminis* spp.). Where annual grass control (e.g. *Vulpia* spp., soft brome, barley grass and ryegrass) has been poor in the winter–spring prior to sowing, cereal root diseases are likely to cause serious production losses, particularly on non-acid soils. Highly susceptible crops such as wheat and barley should be avoided; cereal rye has good tolerance, with oats the next best, followed by triticale. Barley yellow dwarf virus (BYDV) is a serious disease on the Slopes and Tablelands. Large losses of both DM and grain production can occur when susceptible crops (especially oats and barley) are sown early. Tolerance of BYDV will therefore influence crop and variety choice. Control of aphids will also play a role.

Quality tests on the forage of cereal rye, oats, wheat, barley and triticale, when grown under similar conditions, show no significant differences in levels of protein, energy and digestibility. Therefore, a cereal with higher grain returns may be chosen as an alternative to oats. [2]

Ideally, only one type of cereal should be sown in a paddock because stock will preferentially graze one cereal over another.

2.1.2 Dual-purpose crops

Dual-purpose crops can be a vital part of a mixed business farming operation. Reliable dual-purpose crops require a high standard of agronomy including timely sowing, careful choice of variety, good subsoil moisture and high soil fertility.

Dual-purpose winter crops, or grazing-only crops, can regularly gross $1000–$1500/ha with typical costs of $300–$350/ha. In addition, they take pressure off the

2 G Hennessy, B Clements (2009) Cereals for grazing. Primefact 720. Department of Primary Industries New South Wales, June 2009, http://www.dpi.nsw.gov.au/__data/assets/pdf_file/0011/288191/Cereals-for-grazing.pdf

remaining grazing base (pastures) so it is in an improved position to provide good feed when the dual-purpose crop is locked up for grain.

Dual-purpose crops supply quality feed in good quantities when other pastures are growing at a slow rate, especially in years with dry autumns. [3]

IN FOCUS

New South Wales dual-purpose cereal cropping trials

With the support of the GRDC, the NSW Department of Primary Industries has managed a series of dual-purpose cereal cropping trials across New South Wales, at Somerton, Purlewaugh, Cowra and Culcairn.

The trials included the newest grazing varieties of wheat, triticale, cereal rye, oats and barley. Sown in mid-April, the crops in the northern areas had a difficult start with the drier conditions at sowing, but still produced some excellent results. All trials were assessed for DM production and then grazed. A second DM assessment was taken later in the season. The crops were then allowed to develop through to harvest.

Once grazing of the crop is finished and it is locked up for grain recovery, it is important to treat it as a grain crop, with the necessary nutritional (i.e. N), weed and disease management undertaken to maximise possible grain yields.

A highlight of the trial was the high early DM production from two new cereal ryes. It is the first time for several years that newly available cereal ryes are suited to both grazing and grain recovery. These included the varieties Southern Green and Vampire. Both varieties provided strong early growth and DM production, outperforming the traditional early feed producer, oats, at many of the sites. When looking for quick early DM production, the popular option has been oats, but now suitable cereal ryes are also available.

However, although the cereal ryes were quick to produce feed, their palatability dropped later in the season compared with the other cereals, so they should make up only a part of an overall forage production system.

After the first grazing, the difference in production between the crops (i.e. oats, rye, barley, triticale and wheat) narrowed significantly.

The trials also showed that grazing periods and rest periods were important for DM recovery. Generally, grazing too hard slows regrowth. If possible, farmers should leave some DM in the paddock to aid recovery from grazing. In this way, stock can be returned to the paddock faster. This could affect gross margins, because DM production and grain recovery are both important to the overall profitability of dual-purpose crops.

These DM figures add up to a bonus for producers, with excellent returns from livestock enterprises as well as a profitable grain yield. [4]

VIDEOS

WATCH: Over the Fence: Grazing Crops: reaping big rewards and returns.

MORE INFORMATION

GRDC Factsheets: Dual-purpose crops.

GRDC Update Papers: Dual purpose crops: do they have a fit in your system and how can they be managed to optimise forage and grain potential?

GRDC Update Papers: Profitable dual purpose cereals in the north and central west (a Purlewaugh case study).

3 R Freebairn (2016) Profitable dual purpose cereals in the north and central west (a Purlewaugh case study). GRDC Update Papers. Grains Research and Development Corporation, February 2016, https://grdc.com.au/Research-and-Development/GRDC-Update-Papers/2016/02/Profitable-dual-purpose-cereals-in-the-north-west

4 A Norris (2012) Dual purpose cereals shine. The Land, February 2012, http://www.theland.com.au/story/3611427/dual-purpose-cereals-shine/

2.1.3 Cover cropping

Cover crops are crops that are planted primarily for the benefits they provide to the soil. Interest in cover crops is increasing in Australia, driven by groups such as the Victorian No-Till Farmers Association.

Cover cropping has the potential to reduce herbicide reliance and minimise tillage while improving soil fertility, reducing soil erosion, sequestering soil carbon, increasing soil water infiltration and storage, and suppressing weeds. [5]

Cover cropping to prevent wind erosion

Cereal rye can establish well on poor, windblown sand. It has four primary roots that originate from the seed and can send out roots and tillers from the second, third and fourth node. This extensive root system within the first 30 cm of soil is more developed than in other cereals. It can withstand greater sowing depths, which is useful when sowing over eroded or disturbed sites or where depth is hard to control, and it makes the plant more drought-resistant. [6]

IN FOCUS

Growing cereal rye to Increase carbon and prevent wind erosion

The owners of a farm in Western Australia had long-term problems with areas in paddocks that were consistently producing very low yields. They decided that these areas would perform better if they were sown to a lower input crop such as cereal rye. In addition, they could reduce their inputs by as much as 50%, because rye is cheaper to sow than most cereals.

In the second and third years, the rye was left to self-sow. Then it was run over with the seeder bar to topdress some additional seed. Having grown rye for three successive seasons, the owners believe it has accomplished what they set out to do. The groundcover produced by the cereal rye is significantly 'better than wheat has been able to provide and it will outperform both wheat and barley on poor acid soils'.

In the third year, however, they believe they should have been more proactive on their weed control within the cereal rye crop because a weed-control issue developed.

Soil sample results show that the soil organic carbon (SOC) improved in the affected areas. Since 2012, the SOC increased in the topsoil, by 27.8% in 2013 and 16.7% in 2014. This represents a total improvement of 47% since 2012.

Conclusions

- Cereal rye has established well on poor windblown sand.
- It has been successful in preventing further erosion.
- Approximately 80% of land cropped to rye has recovered sufficiently to return to normal rotation.
- Weeds became an issue after three years of continuous rye. [7]

5 SB Mirsky, WS Curran, DA Mortensen, MR Ryan, DL Shumway (2009). Control of cereal rye with a roller/crimper as influenced by cover crop phenology. Agronomy Journal, 101(6), 1589–1596, https://dl.sciencesocieties.org/publications/aj/pdfs/101/6/1589

6 L Martin (2015) Growing cereal rye to increase carbon and prevent wind erosion. Liebe Group, March 2015, http://www.liebegroup.org.au/wp-content/uploads/2015/03/Case-Study-Jeff-Pearse-March-2015.pdf

7 L Martin (2015) Growing cereal rye to increase carbon and prevent wind erosion. Liebe Group, March 2015, http://www.liebegroup.org.au/wp-content/uploads/2015/03/Case-Study-Jeff-Pearse-March-2015.pdf

Cereal rye is the plant commonly used for reclamation on the solonised brown soils, which lie largely in a zone of low rainfall, ~23–38 cm per annum of unreliable, winter incidence. Soils are deep sandy to shallow loamy overlying deep rubbly and powdery calcareous clay subsoils, and are neutral to alkaline at the surface, becoming more alkaline with depth. Their landscape is frequently characterised by a parallel east–west dune system. These soils make up a large part of the low-yielding wheat lands of southern Australia. They are farmed on a wide rotation, comprising volunteer pasture–fallow–wheat, in which superphosphate is used solely with the wheat. Sheep graze the pastures. These soils, especially the sands, are very susceptible to wind erosion, and much effort is now devoted to the stabilisation of the once-cleared and cultivated dunes. [8]

Control of cover crops

Cover crops that interfere with growth of primary crops defeat their purpose. Effective control or suppression of the cover crop is generally necessary before emergence of the main crop. Commonly used methods include tillage, mowing, herbicides, or selection of species that winterkill or have a short life cycle. [9] In the absence of herbicides, cereal rye cover crops are typically terminated with tillage, or with mowing in no-till situations.

Do not use rye as a cover crop just before growing other cereal grains. Volunteer rye may contaminate wheat, oats and barley. [10]

Under stressful conditions, such as those found in tilled and chemical fallow fields, grassy field edges and roadsides, rye plants can still grow and produce seed despite attaining heights of only 25 cm or less (Photo 1). [11]

Photo 1: *Shorter stands of cereal rye can still produce seed heads.*

Source: University of Nebraska)

VIDEOS

WATCH: Over the Fence: cover crop ensures soil moisture

MORE INFORMATION

University of Manitoba article: Fall rye cover crops for PFP and organic pulse crop production

Research paper: Cover crop impact on nitrogen availability and dry bean in an organic system

USDA study report: Effects of mixed species crop cover on soil health

8 ABS (2012) The soils of Australia. Australian Bureau of Statistics, November 2012, http://www.abs.gov.au/ausstats/abs@.nsf/Previousproducts/1301.0Feature%20Article801966

9 W Curran, DD Lingenfelter, L Garling, P Wagoner (2006) Cover crops for conservation tillage systems. Conservation Tillage Series Number Five. Pennsylvania State University, http://extension.psu.edu/plants/crops/soil-management/conservation-tillage/cover-crops-for-conservation-tillage-systems

10 N Rector, T Harrigan, DR Mutch, S Snapp (2009). Cereal rye: manure and livestock's new best friend. Manure $ense. Michigan State University Extension, February 2009

11 D Lyon, R Klein (2007) Rye control in winter wheat. NebGuide G1483. University of Nebraska, https://web.archive.org/web/20140413144910/http://www.ianrpubs.unl.edu/pages/publicationD.jsp?publicationId=106

2.2 Varietal performance and ratings

2.2.1 Identifying products for industry

Low amylose or sticky ryes were perceived to be of benefit to the feed industry in that high amylopectin is relevant to growth of both ruminants and monogastrics. They were also seen as potentially useful as products for the human food industry including snack foods, breakfast cereals and crispbreads. None of these uses has been realised as the Winter Cereals Committee rated this objective of low priority in the second cycle of funding. Options to develop these ryes for the above purposes are still available, and the low amylose materials developed for this project have been kept in storage. The low amylose selections will be crossed with waxy wheats with a view to developing waxy or low amylose triticales for the food and feed industries.

High amylose ryes were also isolated and crosses made to high amylose durums in 2004 with a view to developing high amylose triticales.

Low and high pentosan ryes were developed for the food and feed industries. Both were evaluated for their roles in bread making (George Weston Foods). The line for commercial increase will be tested by industry in 2005 (George Weston Foods, Byron Agricultural Company) and released to growers at the same time. The low and high pentosan ryes were seen of zero and high priority, respectively by the Winter Cereals Committee, therefore the low pentosan ryes were placed into storage, although they may be relevant to bread making and as feed for monogastrics in the future.

White rye is being commercially developed and will be tested by George Weston Foods in 2005, at the same time as it will be released to growers. It was seen as relevant for use in breads and crispbreads. However, with the shutdown of the Weston crispbread factory in Australia, its only relevance is now in the development of white rye breads.

High molecular weight (HMW) glutenin rye was seen as important to the bread making industry i.e. high loaf volume. However, there has been a shift to high baking triticale in recent years. Although this material had commenced development, high molecular weight rye from Professor Adam Lukaszewski (University of California, Riverside) was made available, but to date has not been tested under Australian rye baking technology. Yield was approximately 30% lower than conventional rye, and until it is improved, it is unlikely that this project will have a high priority.

Low- and high-amylose rye

It was anticipated that low amylose ryes would be useful for food products such as breakfast cereals, as well as feed for ruminants and monogastrics.

Both high- and low-amylose ryes were identified. The low-amylose lines had amylose contents of 6–10%. Nine high-amylose lines were identified with a range in amylose of 33–37%.

In 2004, the high amylose ryes were used in crosses with high-amylose durums with a view to developing high-amylose triticales.

Low-pentosan rye

Low-viscosity rye was seen as a priority for the feed industry, whereby a significant reduction in pentosans was perceived to be of value for monogastric nutrition.

Twelve very low-pentosan lines gave rise to a population of 100–200 low-viscosity lines, which were selected for field testing.

George Weston Foods tested the baking of some low pentosan lines. Low-pentosan lines gave a better baking response using local technology (30% rye flour, 70% wheat flour) than the normal or high-pentosan rye lines.

High-pentosan rye

Industry expressed an interest in high pentosan rye, believing that this would be of benefit to bread volume and quality parameters such as reduced staling and dietary considerations.

High-viscosity lines were identified and sown in the field in 1998. A high pentosan population (HP) was identified and built up but it did not have expected improvements in bread volume. This population was also tested in 2004 as a rye for grazing for the Queensland cattle industry.

White rye

White rye was intended for a niche market, and consideration was given to the preference for white breads for the human food industry and to the development of a white crispbread from cereal rye.

From a population that was originally very tall, several good agronomic types of normal height were selected following identification of fixed white lines and both selfing and inter-mating.

Following further selection and yield trials, a white-seeded population was increased for commercial release. The white rye could also be used in crosses with white durum with a view to developing additional sources of white triticale.

High-molecular-weight glutenin rye

A high-molecular-weight (HMW) glutenin was seen as a priority by the rye industry, which sought a better baking rye.

A rye line with a wheat–rye chromosome translocation was supplied by Professor Lukaszewski, and this line showed some improvement in baking quality. However, the translocation had also been shown to reduce the yield by 30%. This HMW glutenin rye line was crossed with the best local rye germplasm, and the material grown for a further cycle before being put into storage.

Long-season dual-purpose rye

Numerous rye lines were developed that had the dual-purpose (graze and grain) capacity of the earlier variety, Ryesun. Dual-purpose trials were conducted at the Cowra Research Station, NSW, and several promising lines were identified.

The development of dual-purpose ryes and the high-yielding variety, Westwood, was the result of ongoing breeding, trialing and selection for quality traits. Westwood was released commercially in 2003, being at least 10% higher yielding than Ryesun in NSW, and with improved lodging resistance. [12]

2.2.2 Developing products for industry

The aim of a follow-up GRDC project was to produce higher yielding rye varieties with new end uses.

Cereal rye is suited to the acid soils of central and southern NSW and to the sandy soils of the South Australian Mallee. Its main use is for rye breads (30–50% rye flour) or kibble in multigrain bread. Rye is very high in soluble fibre and is therefore of benefit to human health.

The new varieties to be developed included a higher soluble-pentosan rye and a white rye suitable for NSW, and a rye suitable for the South Australian Mallee.

A high-yielding open-pollinated rye with improved levels of soluble pentosans was developed. A white-seeded rye line was also produced. The new rye line for SA was not as high yielding as Bevy.

12 GRDC (1998) Cereal rye—new products for industry. GRDC Project US200, Final Report, http://finalreports.grdc.com.au/US200

High-pentosan rye for NSW

The high-pentosan rye developed for central NSW was coded HP Rye. This was a combination of 11 high-pentosan lines that had been allowed to randomly cross (rye is a cross-pollinating species). Selection of lines for the mixture (synthetic) was based on adjusted yield results from Cowra in 2002 and subsequent tests for soluble pentosans. In yield trials, this line proved higher yielding than the control, Ryesun, by 5–10% and had better lodging resistance. Subsequent quality testing by Westons found that this synthetic produced an excellent rye bread, and that the variation in seed colour was suitable for making kibble. The new rye variety is a good grazing-and-grain line for NSW growers and has the potential for southern Queensland as a grazing variety for the cattle industry.

White rye suitable for NSW

Thirteen white-seeded selections were combined to produce a white rye synthetic. The population from which it was developed was 20% lower yielding than Ryesun. Based on yield trials in 2001 and 2002, the best lines were combined to make the synthetic variety. This line was 10–15% lower yielding than Ryesun, and taller. Quality analysis by Westons revealed that the white rye synthetic produced a poor rye loaf due to underlying quality problems and the method used to produce rye bread in Australia.

Opportunities

The outstanding yields of new hybrid ryes offer opportunities for the development of new and improved products for:

1. Biofuel (hybrid rye now out-yields most other cereals and can be grown on marginal land which does not affect the current food and feed requirements of other cereal grains).
2. White bread making rye. The rye industry would benefit substantially from a high baking rye that would reduce the need for the addition of wheat flour (70%) in rye loaves. This option is possible using white grain triticales with excellent bread making characteristics that can be crossed with new and existing sources of white rye. [13]

Growers should be aware that cereal rye is a cross-pollinating species and it will out-cross. To maintain pure seed and varietal type, growers should regularly source new seed. The availability of seed of the older cereal rye varieties is limited and some could no longer be under commercial seed production.

2.2.3 Varieties

Bevy

Bevy is higher yielding than SA Commercial (SAC) rye and a direct replacement.

Bevy is a composite variety of mainly semi-dwarf rye lines. Most plants (80%) are semi-dwarf, with 15% as tall as SAC and 5% very short. When mature, heads also range in length.

Bevy has excellent resistance to CCN and is superior to SAC for stem and leaf rust resistance.

Bevy is up to two weeks later maturing than SAC, which may assist in avoiding effects of frost. The yield of SAC is frequently frost-affected whereas Bevy may escape.

Grain quality is similar to SAC for milling and baking, although seed size is slightly smaller.

Compared with SAC, Bevy shows increased seedling vigour and superior tillering ability and is the most suitable cereal for fragile, sandy soils. Bevy appears better

13 GRDC (2004) Rye—new products for industry. GRDC Project US00022, Final Report, http://finalreports.grdc.com.au/US00022

adapted than SAC in most situations where rye is grown, and this benefit appears greater in longer growing seasons.

The milling yield of Bevy is slightly improved over SAC and baking quality is similar for the two varieties. Bevy has slightly smaller seed, marginally lower 1000-grain weight and a smaller proportion of very dark grains than SAC. [14]

Southern Green

Southern Green is a forage rye that was developed for very rapid growth to first grazing. It has high tiller density and leaf development, and strong tiller survival after initial grazing. It has a spring habit, but is likely to lodge under good conditions. It is marketed by PGG Wrightson Seeds. [15]

Key points:

- Southern Green forage cereal rye is for quick winter feed—ready to graze in 30–55 days. Some brassicas may be quicker with a March break but Southern Green grows quickly even if the break is late.
- It can produce twice the DM of oats 45 days after sowing (Photo 2).
- In a trial, by late July (90–100 days after sowing) oat growth rates increased but cereal rye was still 30% ahead in DM yield.

Southern Green is a much more uniform and leafy crop than common cereal rye. It is also early maturing and earlier to reach stem elongation than most other cereals. It will bolt to head in autumn if planted early and not grazed. It is for quick feed and must be used.

Because of its lack of vernalisation requirement, Southern Green will go into reproductive mode almost immediately. This habit is the driver of quick winter feed production, but means it can be damaged easily by overgrazing.

Cereal rye has resistance and tolerance to CCN, making it a valuable rotation option on lighter soils where CCN is often severe. [16]

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14 R Saunders, R Wheeler. Bevy. Teague Australia Seed and Grain Brokers, http://www.teague.com.au/members/pdf/9749370EA20CA886DBF1899.pdf

15 P Matthews, D McCaffery, L Jenkins (2016) Winter crop variety sowing guide 2016. NSW Department of Primary Industries, https://www.dpi.nsw.gov.au/agriculture/broadacre-crops/guides/publications/winter-crop-variety-sowing-guide

16 Wrightson Seeds. Forage focus—southern green ryecorn. http://www.pggwrightsonseeds.com.au/assets/FTP-Uploads/Forage_Focus/Cereals/FF_Southern-Green-Forage-Ryecorn.pdf

Photo 2: *Winter feed trial (sown 21 April 2008) of Southern Green forage cereal rye (left) and Wintaroo Oats (right) at Ballarat. Photo was taken 45 days after planting. Southern Green was ready for grazing whereas Wintaroo would have been damaged by grazing at this early development stage.*

Source: Wrightson Seeds

Vampireⓓ

Vampireⓓ cereal rye is recommended for extremely vigorous growth and early grazing. It is suited to very poor soils and revegetation projects.

Key characteristics:

- main season variety
- rapid early growth
- good tolerance to acid soils and high aluminium
- improved lodging resistance and grain yield compared to Ryesun
- suitable for grazing and grain recovery
- good rotation for suppression of root-lesion nematode. [17]

Ryesun

Ryesun is a main season variety with adequate stem rust resistance. It is likely to lodge under good conditions. Ryesun is an early variety with dual-purpose capacity.

Westwood

Westwood is a main season variety with similar maturity to Ryesun. It has adequate stem and leaf rust resistance, is at least 10% higher yielding than Ryesun in NSW, and has improved lodging. Westwood was released commercially in 2003. [18 19]

17 Hart Bros Seeds. Vampire ryecorn. http://www.hartbrosseeds.com.au/all-products/vampire-ryecorn.aspx

18 P Matthews, D McCaffery, L Jenkins (2016) Winter crop variety sowing guide 2016. NSW Department of Primary Industries, https://www.dpi.nsw.gov.au/agriculture/broadacre-crops/guides/publications/winter-crop-variety-sowing-guide

19 GRDC (1998) Cereal rye—new products for industry. GRDC Project US200, Final Report, http://finalreports.grdc.com.au/US200

2.3 Planting seed quality

Seed should be free of weeds and ergot bodies, and have at least 85% germination. Stored rye seed loses its ability to germinate more rapidly than seed of other cereals. It is recommended to buy certified seed that has proven adaptation to local conditions. Fungicide seed treatments used for other small grains are suitable for use on rye, and can often improve stands. [20]

Rye seed should be cleaned thoroughly to remove weed seeds, foreign material (including ergot) and cracked kernels. Ergot bodies must be removed to prevent re-infestation of fields. Use of pedigreed seed ensures high quality. There are no ergot-resistant rye varieties. The only practical control is to sow clean, year-old seed on land that has not grown rye for at least one year. [21]

Heat damage causes slower germination, delayed emergence of the primary leaf, stunted growth or termination of the germination process. In severe cases, seed death may occur (Photo 3). During bulk storage, areas of excessive moisture can lead to microbial-induced 'hot spots' and since moisture moves from hot to cooler areas, further local heating is caused, setting off a chain reaction. [22]

Photo 3: *Normal cereal seed (left) compared to heat-damaged seed (right). Note the distinct colour difference.*

Source: Grain South Africa

For information about grower-retained seed, see the GRDC Fact Sheet: Retaining seed: Saving weather damaged grain for seed.

2.3.1 Seed germination and vigour

Seed germination and vigour greatly influence establishment and yield potential.

Germination begins when the seed absorbs water, and ends with the appearance of the radicle. It has three phases:

- water absorption (imbibition)
- activation
- visible germination. [23]

Seed germination drops rapidly when cereal rye is stored for longer than one year. [24]

Seed vigour affects the level of activity and performance of the seed or seedlot during germination and seedling emergence. Loss of seed vigour is related to a

20 EA Oelke, ES Oplinger, H Bahri, BR Durgan, DH Putnam, JD Doll, KA Kelling (1990) Rye. In Alternative field crops manual. University of Wisconsin and University of Minnesota, https://hort.purdue.edu/newcrop/afcm/rye.html

21 Alberta Government (2016) Fall rye production. http://www1.agric.gov.ab.ca/$department/deptdocs.nsf/all/agdex1269/$file/117_20-1.pdf

22 H Hatting (2102) Factors affecting wheat seed germination. Grain South Africa, http://www.grainsa.co.za/factors-affecting-wheat-seed-germination

23 DPI NSW (2007) Wheat growth and development. PROCROP Series. Department of Primary Industries New South Wales, https://www.dpi.nsw.gov.au/__data/assets/pdf_file/0006/449367/Procrop-wheat-growth-and-development.pdf

24 Alberta Government (2016) Fall rye production. http://www1.agric.gov.ab.ca/$department/deptdocs.nsf/all/agdex1269/$file/117_20-1.pdf

reduction in the ability of the seeds to carry out all of the physiological functions that allow them to perform.

This process, called physiological ageing (or deterioration), starts before harvest and continues during harvest, processing and storage. It progressively reduces performance capabilities due to changes in cell membrane integrity, enzyme activity and protein synthesis. These biochemical changes can occur very quickly (a few days) or more slowly (years), depending on genetic, production and environmental factors not fully understood. The end-point of this deterioration is death of the seed (i.e. complete loss of germination).

However, seeds lose vigour before they lose the ability to germinate. That is why seedlots that have similar, high germination values can differ in their physiological age (the extent of deterioration) and so differ in seed vigour and therefore the ability to perform. [25]

For more information on factors affecting germination, see Section 4: Plant growth and physiology.

Request a copy of the germination and vigour analysis certificate for purchased seed from your supplier. For seed stored on-farm, you can send a sample to a laboratory for analysis (see Australian Seeds Authority website).

Although a laboratory seed test for germination should be carried out before seeding to calculate seeding rates, a simple on-farm test can be done in soil at harvest and during storage:

- Use a flat, shallow, seeding tray (about 5 cm deep). Place a sheet of newspaper on the base to cover drainage holes, and fill with clean sand, potting mix or freely draining soil. Ideally, the test should be done indoors at a temperature of ~20°C or lower.
- Alternatively, lay a well-rinsed plastic milk container on its side and cut a window in it, place unbleached paper towels or cotton wool in the container, and lay out the seeds. Moisten and place on a window-sill. Keep moist, and count the seeds as outlined below.
- Randomly count out 100 seeds—do not discard damaged ones—and sow 10 rows of 10 seeds at the correct seeding depth. This can be achieved by placing the seed on the smoothed soil surface and pushing in with a pencil marked to the required depth. Cover with a little more sand or soil and water gently.
- Keep soil moist but not wet, as overwatering will result in fungal growth and possible rotting.
- After 7–10 days, the majority of viable seeds will have emerged.
- Count only normal, healthy seedlings. If you count 78 normal vigorous seedlings, the germination percentage is 78%.
- Germination of 80% is considered acceptable for cereals.
- The results from a laboratory seed-germination test should be used for calculating seeding rates. [26]

Seed purity

Seed impurity can occur from contamination through harvest, storage and machinery. This measurement will be included in a seed purity certificate. Varieties that have been retained for multiple generations have an increased risk of seed impurity due to multiple chances for contamination events and build-up. Ensure that seed comes from clean, pure and even crops; seed-purity tests should be carried out. Growers should conduct paddock audits prior to harvest to establish which paddocks best meet these criteria.

25 ISTA (1995) Understanding seed vigour. International Seed Testing Association, http://www.seedtest.org/upload/prj/product/UnderstandingSeedVigourPamphlet.pdf

26 GRDC (2011) Retaining seed. Saving weather damaged grain for seed, northern and southern regions. GRDC Fact Sheet, January 2011, http://storedgrain.com.au/wp-content/uploads/2013/06/GRDC_FS_RetainingSeed2.pdf

With dramatic increases in herbicide resistance, growers need to take seed purity into account when selecting paddocks for seed. Ryegrass and black oats frequently appear in harvested grain samples and have the potential to infest otherwise clean paddocks. [27]

2.3.2 Seed storage

The aim of storage is to preserve the viability of the seed for future sowing and maintain its quality for market. A seed is a living organism that releases moisture as it respires.

VIDEOS

WATCH: Over the Fence: ensure seed viability with aerated storage.

The ideal storage conditions:

- Temperature <15°C. High temperatures can quickly reduce seed germination and quality. This is why germination and vigour testing prior to planting is so important in the northern grains region.
- Moisture control. Temperature changes cause air movements inside the silo, carrying moisture to the coolest parts of the seed. Moisture is carried upwards by convection currents in the air; these are created by the temperature difference between the warm seed in the centre of the silo and the cool silo walls, or *vice versa*. Moisture carried into the silo head-space may condense and fall back as free water, causing a ring of seed to germinate against the silo wall.
- Aeration slows the rate of deterioration of seed with 12.5–14% moisture. Aeration markedly reduces grain temperature and evens out temperature differences that cause moisture movement.
- No pests. Temperature <15°C stops all major grain insect pests from breeding, slowing their activity and reducing damage. [28]

For more information, see Section 13: Storage.

2.3.3 Safe rates of fertiliser sown with the seed

Most varieties of cereal rye do not require any additional fertiliser over requirements of other cereals. However, given its ability to produce winter feed very quickly, strong economic responses can be gained by supplying the crop with a good amount of starter fertiliser (e.g. >100 kg/ha of di-ammonium phosphate). Follow up with a topdressing of N (30–50 kg N/ha) when the crop is at early tillering stages, perhaps three weeks after emergence. Additional fertiliser and lime can be applied according to a soil test. [29]

Crop species differ in tolerance to N fertiliser when applied with the seed at sowing. Research funded by Incitec Pivot Fertilisers has shown that the tolerance of crop species to ammonium fertilisers placed with the seed at sowing is related to fertiliser product (ammonia potential and osmotic potential), application rate, row spacing and equipment used (such as a disc or tyne), and soil characteristics such as moisture content and texture.

The safest application method for high rates of high ammonium-content fertilisers is to place them away from the seed by physical separation (combined N-phosphorus products) or by pre- or post-plant application (straight N products). For the lower ammonium-content fertilisers, e.g. mono-ammonium phosphate, adhere closely to the safe rate limits set for the crop species and the soil type. [30]

High rates of N fertiliser applied at planting in contact with, or close to, the seed may severely reduce seedling emergence. If a high rate of N is required, it should be applied pre-planting or applied at planting but not in contact with the seed (i.e.

27 S Simpfendorfer, A Martin, M Sutherland (2012) Seed impurity undermines stripe rust resistance. In 16th Australian Agronomy Conference, Australian Society of Agronomy and The Regional Institute Ltd, http://www.regional.org.au/au/asa/2012/disease/8325_simpfendorfer.htm

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

29 Wrightson Seeds. Forage focus—southern green ryecorn. Wrightson Seeds , http://www.pggwrightsonseeds.com.au/products/cereals/southerngreenryecorn/

30 Incitec Pivot Fertilisers (2014) Nitrogen fertiliser placement and crop establishment. Incitec Pivot Fertiliser Ltd, http://bign.com.au/Big%20N%20Benefits/Nitrogen%20Fertiliser%20Placement%20and%20Crop%20Establishment

banded between and below sowing rows). Rates should be reduced by 50% for very sandy soil and increased by 30% for heavy-textured soils or if soil moisture conditions at planting are excellent. [31]

If the same fertiliser rate is used with different row spacings, then the amount distributed along each seeding row will increase as row spacing becomes wider. To avoid this increased fertiliser concentration in wide-row systems, the safe rate of in-furrow fertiliser decreases as row spacing increases (Table 2). Seedbed utilisation percentage is a term that has been developed to describe the effect of row spacing and opener type on seed-furrow fertiliser concentration, and thereby quantify safe fertiliser rates (Table 3). Higher seedbed utilisation can optimise crop grain-yield potential, as well as minimising fertiliser toxicity risk. [32] [33]

Nitrogen rates should be significantly reduced when using narrow points and press-wheels or disc seeders. When moisture conditions are marginal for germination, growers need to reduce N rates if fertiliser is to be placed with, or close to, the seed.

Table 2: *Approximate safe rates (kg/ha) of nitrogen as urea, mono-ammonium phosphate or di-ammonium phosphate with the seed of cereal grains if the seedbed has good soil moisture (at or near field capacity).*
SBU, Seedbed utilisation = (width of seed row/row spacing) × 100..

Soil texture	25-mm seed spread			50-mm seed spread		
Row spacing:	**180 mm**	**229 mm**	**305 mm**	**180 mm**	**229 mm**	**305 mm**
SBU	**14%**	**11%**	**8%**	**29%**	**22%**	**17%**
Light (sandy loam)	20	15	11	40	30	22
Medium–heavy (loam–clay)	25	20	15	50	40	30

Source: RW Rainbow and DV Slee (2004), The essential guide to no-till farming (South Australian No-Till Farmers Association), reproduced in GRDC Fertiliser Toxicity Fact Sheet

Table 3: *Urea rates (kg/ha) for wheat and barley at different levels of seedbed utilisation (SBU = width of seed row/row spacing) × 100) and on different soil types, with good soil moisture.*

SBU	5%	10%	15%	20%	25%	30%	40%	50%
Heavy soil	55	60	65	70	75	80	95	105
Medium soil	45	50	55	60	65	70	80	90
Light soil	25	30	35	40	45	50	60	65

Source: Incitec Pivot Fertfact

For more information, see Section 5: Nutrition and fertiliser.

31 QDAF (2102) Wheat —nutrition. Queensland Department of Agriculture and Fisheries, https://www.daf.qld.gov.au/plants/field-crops-and-pastures/broadacre-field-crops/wheat/nutrition

32 GRDC (2011) Care with fertiliser and seed placement. GRDC Fertiliser Toxicity Fact Sheet, May 2011, https://grdc.com.au/resources-and-publications/all-publications/factsheets/2011/05/fertiliser-toxicity

33 J Laycock (2013) Seedbed utilisation. Fertfact—Guidelines for suggested maximum rates of fertiliser applied with the seed in winter crops. Incitec Pivot Fertilisers, http://farmercommunity.incitecpivotfertilisers.com.au/Guides%20and%20Publications/Agronomic%20Insights/Seed%20bed%20utilisation

Planting

Key messages:

- The use of seed treatments is now routine, but it is important to check the product registration before use.
- A permit (APVMA Permit 82304) has been issued for imidacloprid seed treatment to control Russian wheat aphid in winter cereals. However, rye is less susceptible than wheat or barley to Russian wheat aphid. [1]
- Cereal rye compares favourably with other cereals for grazing when sown early.
- Depending on the crop purpose, soil type and climate, cereal rye can be sown from February until August.
- Sowing depth for cereal rye should not exceed five centimetres.
- Seeder calibration is important for precise seed placement and seeders need to be checked regularly during sowing.

3.1 Inoculation

Not applicable to this crop.

3.2 Seed treatments

Seed treatments are applied to seed to control diseases such as smuts, bunts or rust, and insects. When applying seed treatments always read the chemical label and calibrate the applicator. Seed treatments are best used in conjunction with other disease-management options such as crop and paddock rotation, clean seed and resistant varieties, especially when managing weeds such as stripe rust. Major losses from these diseases are now rare; however, this is due to the routine use of seed treatments. Seed not treated prior to sowing may result in yield losses as high as 85%.

Some risks are associated with using seed treatments. Research shows that some seed treatments can delay emergence by:

- slowing the rate of germination, and
- shortening the length of the coleoptile, the first leaf and the sub-crown internode.

If there is a delay in emergence due to decreased vigour, it increases exposure to pre-emergent attack by pests and pathogens, or to soil crusting. This may lead to a failure to emerge. The risk of emergence failure increases when seed is sown too deeply or into a poor seedbed, especially in varieties with shorter coleoptiles. Some seed treatments contain azole fungicides (triadimenol and triadimefon). Research has found that these seed treatments can reduce coleoptile length, and that the reduction increases as the rate of application increases. [2]

Seed treatments provide targeted control of insect pests. They offer protection from low–moderate attack by insects at the establishment phase. They can delay or remove the need to apply foliar sprays and therefore in some instances can preserve beneficial populations. Seed treatments work by forming a chemical barrier over the surface of the germinating seed, which protects it from chewing insects (e.g. wireworms). Systemic seed treatments result in insecticide being translocated to the aboveground parts of germinating plants, deterring or killing pests such as aphids and mites. Although the duration of protection may be limited, a delay in crop damage and pest establishment can reduce crop losses.

1 G Baker, K Perry, M Nash, G McDonald, J Severi, P Umina (2106) Working with natural enemies and living with Russian wheat aphid a new pest of Australian cereal crops. GRDC Update Papers, August 2016, https://grdc.com.au/Research-and-Development/GRDC-Update-Papers/2016/08/Working-with-natural-enemies-and-living-with-Russian-wheat-aphid

2 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

Seed treatments for insect control can be used for:

- planting in conditions that make the seedlings more susceptible to insect damage, such as dry or cold and wet conditions
- sowing into fields where pests are known to be present and are difficult to control or detect before crop damage occurs (e.g. soil insects, earth mites)
- where crop losses cannot be tolerated, such as if seed is expensive or sown at a low rate per hectare. [3]

Seed treatments to control insect pests now include imidacloprid for Russian wheat aphid. [4]

Product registrations change over time and may differ between states and between products containing the same active ingredient. Prior to use, it is critical to check the registration status on the current product label for the intended use pattern in your state.

MORE INFORMATION

GRDC Fact Sheet: Targeted nutrition at sowing.

3.2.1 Fertiliser at seeding

The amount of nitrogen (N) that can be safely placed with the seed will vary depending on soil texture, amount of seedbed utilisation and moisture conditions. Higher amounts of N can be safely applied with the seed if it is a polymerised form of urea, where the N is released over the period of several weeks. If soil moisture is marginal for germination, high rates of fertiliser should not be placed with the seed. Nitrogen can be banded prior to seeding, but take care to avoid loss of seedbed moisture and protective crop residue. Place phosphorus with or near the seed at seeding time. [5]

3.3 Time of sowing

Rye for grain is sown at the same time as wheat, oats or barley (May or June). However, it is often sown first because rapid groundcover is usually desirable on the soils where it is sown.

Cereal rye is adapted to all soils. Its major fit is on the lighter acid soils where yields are usually 70–100% those of wheat and triticale when sown between May and June.

On the more traditional wheat soils, cereal rye yields are about 50–70% those of wheat. When sown late (in July) and in dry springs, yields are often less than 50% of comparable wheat yields. Although it heads early, its longer grainfilling period and later maturity limit its performance in the western areas of the northern grain belt.

When sown early, cereal rye compares very favourably with other cereals for grazing in terms of quick feed and total dry matter production. Crops for grazing can be sown in March or April. [6]

For the purposes of green manure, cereal rye can be sown February or March or as late as August in high-rainfall areas. [7]

3 QDAF (2016) Seed dressings or treatments. IPM guidelines for grains. Queensland Department of Agriculture and Fisheries/GRDC, http://ipmguidelinesforgrains.com.au/ipm-information/chemical-control/seed-dressings-treatments/

4 Agriculture Victoria (2016) Russian wheat aphid. Victorian Government EDJTR, http://agriculture.vic.gov.au/agriculture/pests-diseases-and-weeds/plant-diseases/grains-pulses-and-cereals/russian-wheat-aphid

5 Alberta Government (2016) Fall rye production. Alberta Agriculture and Forestry Agdex 117/20-1, http://www1.agric.gov.ab.ca/$department/deptdocs.nsf/all/agdex1269/$file/117_20-1.pdf

6 P Matthews, D McCaffery, L Jenkins (2016) Winter crop variety sowing guide 2016. NSW Department of Primary Industries, https://www.dpi.nsw.gov.au/agriculture/broadacre-crops/guides/publications/winter-crop-variety-sowing-guide

7 R Sonogan (2013) Growing cereal rye. Agriculture Victoria, May 2013, http://agriculture.vic.gov.au/agriculture/grains-and-other-crops/crop-production/growing-cereal-rye

3.4 Targeted plant population

Target 120–150 plants per m^2 for grazing and grain crops, or a seeding rate of ~60–70 kg per hectare (kg/ha) depending on seed size. Higher populations are needed for green manure crops. [8]

IN FOCUS

Effect of seeding rate and planting arrangement on rye cover crop and weed growth in the US.

Weed growth in winter cover crops in warm climates may contribute to weed management costs in subsequent crops. A two-year experiment was conducted on an organic farm in the United States to determine the impact of seeding rate and planting arrangement on rye cover crop growth and weed suppression. Each year, rye was planted at three rates (90, 180, and 270 kg/ha) and two planting arrangements (one-way *v.* grid pattern). Averaged across years, rye population densities were 322, 572, and 857 plants/m^2 at the 90, 180, and 270 kg/ha seeding rates, respectively. Early-season rye groundcover increased with seeding rate and was higher in the grid than one-way arrangement in Year 1; however, rye groundcover was not affected by rate and was higher in the one-way arrangement in Year 2. Aboveground dry matter (DM) of rye increased with seeding rate at the first two harvests but not at the final one. Planting arrangement did not affect rye aboveground DM in Year 1, but rye DM was higher in the grid pattern at the first and final harvests in Year 2. Weed emergence was not affected by seeding rate or planting arrangement. Weed biomass decreased with increased seeding rate and was lower in the grid than in the one-way arrangement in Year 2. A grid planting pattern provided no consistent benefit but planting rye at higher seeding rates maximises early season rye DM production and minimises weed growth. [9]

3.5 Calculating seed requirements

Sowing rates vary with seed size, target plant populations and establishment percentage. As a guide, comparative seed rates for grazing and grain crops are 60–70 kg/ha and green manure 80–100 kg/ha. [10]

Cereals can lodge under good conditions or if sown at too high a density. [11] Rye is tall and lodging is an issue, with some varieties more prone to lodging. [12]

The formula in Figure 1 can be used to calculate sowing rates, taking into account:

- target plant density
- germination percentage
- seed size

8 P Matthews, D McCaffery, L Jenkins (2016) Winter crop variety sowing guide 2016. NSW Department of Primary Industries, https://www.dpi.nsw.gov.au/agriculture/broadacre-crops/guides/publications/winter-crop-variety-sowing-guide

9 NS Boyd, EB Brennan, RF Smith, R Yokota (2009) Effect of seeding rate and planting arrangement on rye cover crop and weed growth. AgronomyJournal, 101(1), 47–51, https://dl.sciencesocieties.org/publications/aj/abstracts/101/1/47?access=0&view=pdf

10 P Matthews, D McCaffery, L Jenkins (2016) Winter crop variety sowing guide 2016. NSW Department of Primary Industries , https://www.dpi.nsw.gov.au/agriculture/broadacre-crops/guides/publications/winter-crop-variety-sowing-guide

11 L Forsythe, K McKee (2013) Moddus Evo: Controlling plant growth for reduced lodging and improved yields. GRDC Update Papers, February 2013, https://grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2013/02/controlling-plant-growth-for-reduced-lodging-and-improved-yields

12 P Matthews, D McCaffery, L Jenkins (2016) Winter crop variety sowing guide 2016. NSW Department of Primary Industries, https://www.dpi.nsw.gov.au/agriculture/broadacre-crops/guides/publications/winter-crop-variety-sowing-guide

- establishment, usually 80%, unless sowing into adverse conditions.

To calculate 1000-seed weight:

- count out 200 seeds
- weigh to at least 0.1 g
- multiply weight (g) by 5. [13]

Example

1000 seed weight (grams)		target plant population (/m^2)			establishment % X germination %
35	X	140	X 100	÷	80 X 90

= Your seedling rate 68 kg/ha

Your calculation

1000 seed weight (grams)		target plant population (/m^2)			establishment % X germination %
______	X	______	X 100	÷	______

= Your seedling rate ______ kg/ha

Figure 1: *Seeding rate calculator.*

Source: NSW DPI Winter crop variety guide

TOPCROP Victoria investigated sowing rates for wheat to achieve target plant densities using large-scale paddock demonstrations during the 2000 season. TOPCROP farmer groups established 30 sites across Victoria comparing 75%, 100%, 150% and 200% of the district practice for sowing rate. Findings indicated that poor seeder calibration and a lack of understanding of the influence of grain size has led to target plant densities not being reached (Figure 2). This highlights the need for sowing recommendations to be based on target plant densities rather than sowing rates. [14]

3.6 Sowing depth

Optimum planting depth varies with planting moisture, soil type, seasonal conditions, climatic conditions and the rate at which the seedbed dries. The general rule is to plant as shallow as possible, provided the seed is placed in the moisture zone, but deep enough that the drying front will not reach the seedling roots before leaf emergence, and so that the seed is separated from any pre-emergent herbicides used. Deeper seed placement slows emergence; this is equivalent to sowing later. Seedlings emerging from greater depth are also weaker, more prone to seedling diseases, and tiller poorly. [15]

13 P Matthews, D McCaffery, L Jenkins (2016) Winter crop variety sowing guide 2016. NSW Department of Primary Industries, https://www.dpi.nsw.gov.au/agriculture/broadacre-crops/guides/publications/winter-crop-variety-sowing-guide

14 A Johnson, M Evans, K Wansink (2001) Challenging sowing rates for wheat to achieve target plant densities. 10th Australian Agronomy Conference, Australian Society of Agronomy/The Regional Institute Ltd, http://www.agronomyaustraliaproceedings.org/images/sampledata/2001/p/10/johnson.pdf

15 NSW DPI (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

Research in Canada has shown that rye sown at 2.5 cm depth had twice the emergence of that sown at ~5 cm and that shallow-seeded rye had greater winter hardiness. [16]

Sowing depth for cereal rye should not exceed 5 cm. Bevy rye has a smaller seed size than wheat and it should be sown shallower, at 2–2.5 cm depth in heavy soils and 3.5–4.5 cm in sands. [17]

Research has confirmed the importance of avoiding smaller sized seed if deep sowing. Crop emergence is reduced with deeper sowing because the coleoptile may stop growing before it reaches the soil surface, with the first leaf emerging from the coleoptile while it is still below the soil surface. The leaf usually buckles and crumples, failing to emerge and eventually dying. This is exacerbated in smaller seeded varieties with reduced coleoptile length. [18 19]

The rye plant has four primary roots that originate from the seed and it can send out roots and tillers from the second, third and fourth node. This extensive root system within the first 30 cm of soil is more developed than other cereals, and is useful when sowing over eroded or disturbed sites where depth is hard to control. [20]

3.7 Sowing equipment

As much as 60% of the final yield potential for a crop is determined at planting. Seeding too thinly, using poor quality seed, and uneven stands result in end-of-season yield losses that cannot usually be overcome. [21]

Seeder calibration is important for precise seed placement and seeders need to be checked regularly during sowing (Photo 1).

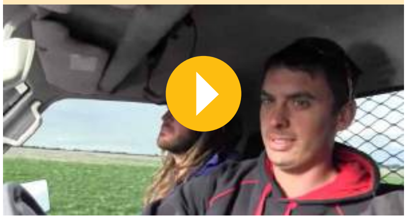
Many growers use either a knife-point/press-wheel tyne system or a single disc. Disc seeders can handle greater quantities of stubble but experience crop damage issues with pre-emergent herbicide use. Tyne seeding systems do not have the same herbicide safety issues but usually require some form of post-harvest stubble treatment, such as mulching or burning.

Photo 1: *Seeder calibration is important for precise seed placement and seeders need to be checked regularly during sowing.*

Source: Rohan Rainbow

VIDEOS

WATCH: [Over the Fence north: conditions are key to accurate seed placement.]



16 Alberta Government (2016) Fall rye production. Alberta Agriculture and Forestry Agdex 117/20-1, http://www1.agric.gov.ab.ca/$department/deptdocs.nsf/all/agdex1269/$file/117_20-1.pdf

17 R Sonogan (2013) Growing cereal rye. Agriculture Victoria, May 2013, http://agriculture.vic.gov.au/agriculture/grains-and-other-crops/crop-production/growing-cereal-rye

18 N Lee (2015) Think big when deep sowing wheat. GRDC Media, May 2015, https://grdc.com.au/Media-Centre/Media-News/West/2015/05/Think-big-when-deep-sowing-wheat

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

20 L Martin (2015) Growing cereal rye to increase carbon and prevent wind erosion. Liebe Group, March 2015, http://www.liebegroup.org.au/wp-content/uploads/2015/03/Case-Study-Jeff-Pearse-March-2015.pdf

21 W Thomason (2004) Planting wheat: seeding rates and calibration. Virginia Cooperative Extension, http://www.sites.ext.vt.edu/newsletter-archive/cses/2004-10/plantingwheat.html

Plant growth and physiology

Key messages:

- Cereal rye seeds are thought to be able to remain viable and dormant in soils for around five years. [1]
- Seeds germinate from autumn to spring with a flush in autumn at temperatures of 1–5°C. [2]
- Rye needs a temperature sum of 90°C for field emergence, provided there is sufficient water. [3]
- Cereal rye is a long-day plant; that is, it requires increasing day length to induce flowering. Flowering is induced by 14 hours of daylight accompanied by temperatures of 5–10°C. [4]
- Cereal rye has a more extensive root system in the top 30 cm than both wheat and oats. This more developed root system increases soil stabilisation and allows the plant to explore more of the topsoil profile, increasing the plants tolerance to dry conditions. It also means that cereal rye potentially dries the soil profile more than wheat and oats. [5]

Key characters of cereal rye (Table 1):

- inflorescence a dense cylindrical spike and not enclosed in the leaf sheath
- spikelets, subtended by two glumes, solitary at each node of the rachis, not digitate, sessile, erect with two (rarely three) bisexual florets, breaks above the more or less persistent glumes
- two lemmas, awned, five-ribbed. [6]

Table 1: *Characteristics of rye plant.*

Plant part	Description
No. of cotyledons	One
Leaves	Emerging leaf rolled in the bud Blade: rough to touch, flat; hairless; 75–300 mm long, 10–20 mm wide Ligule: membranous rim, 1 mm long; flat on top Auricles: small Sheath: hairless; rolled and overlapping; prominent veins Collar: prominent and lighter; hairless
Stem	Erect, slender, 200–1500 mm tall; hairless or hairy below the seed head. Usually has a waxy bloom. Tillers vigorously with usually fewer than 10 stems arising from the base

1 WL Stump, P Westra (2000). The seedbank dynamics of feral rye *Secale cereale*. Weed Technology, 14(1), 7–14, https://www.jstor.org/stable/3988499?seq=1#page_scan_tab_contents

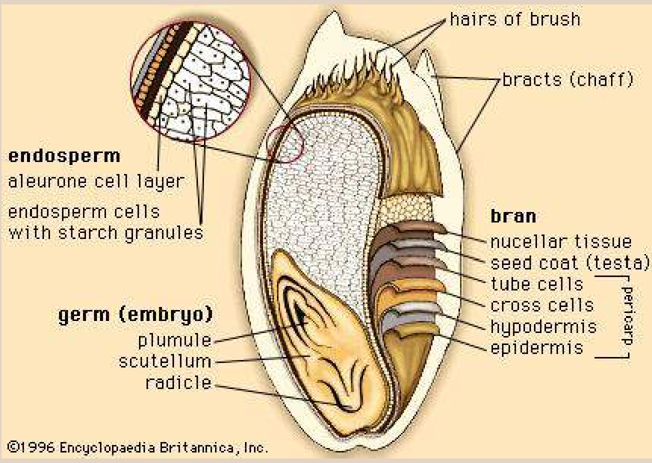
2 HerbiGuide. Rye. HerbiGuide Pty Ltd, http://www.herbiguide.com.au/Descriptions/hg_Rye.htm

3 [3] RH Schlegel (2013) Rye: genetics, breeding, and cultivation. CRC Press, https://www.crcpress.com/Rye-Genetics-Breeding-and-Cultivation/Schlegel/p/book/9781466561434

4 RH Schlegel (2013) Rye: genetics, breeding, and cultivation. CRC Press, https://www.crcpress.com/Rye-Genetics-Breeding-and-Cultivation/Schlegel/p/book/9781466561434

5 P Matthews, D McCaffery, L Jenkins (2016) Winter crop variety sowing guide 2016. Department of Primary Industries New South Wales, https://www.dpi.nsw.gov.au/agriculture/broadacre-crops/guides/publications/winter-crop-variety-sowing-guide

6 HerbiGuide. Rye. HerbiGuide Pty Ltd, http://www.herbiguide.com.au/Descriptions/hg_Rye.htm

Plant part	Description
Flower head	Bearded, dense cylindrical spike; 70–150 mm long; erect initially and drooping with age; awned (Photo 1).  **Photo 1:** *Comparison of flower heads between A, bread wheat; B, cereal rye and C: triticale.* Source: Palomar College, CA, USA
Flowers	Spikelets: no stalk, flattened; single and overlapping in a row on opposite sides and pressed against a zigzag stem; strongly attached to the stem; two fertile florets per spikelet Florets: bisexual Glumes: two the same size and shape, awl-shaped, 7–10 mm long, one rib, keeled, flattened, rough to touch Palea: 12–15 mm long, narrow, no awns, two lobes, two keels Lemma: sticks out from the glumes, oblong to narrowly egg shaped, 12–15 mm long, stiff, five ribs, flattened; hairy or finely toothed on the keel and edges. Keel tapers to a long straight awn about 20 mm long
Seeds	Light to dark brown. Oblong to oval or wedge-shaped, 5–7 mm long, 2–3 mm wide. Almost circular in cross section. Surface grooved, wrinkled and hairless. Easily rubbed from the husks (Figure 1).  **Figure 1:** *Cross-section of cereal rye seed.* Source: Encyclopaedia Britannica
Roots	Many and fibrous

Source: HerbiGuide Pty Ltd

4.1 Germination and emergence issues

4.1.1 Dormancy

Cereal rye seeds are thought to be able to remain viable and dormant in soils for around five years.

IN FOCUS

The seedbank dynamics of volunteer rye

Buried feral rye seeds were rapidly depleted in soil in the first year due to *in situ* germination. Less than 1% of the viable seeds persisted after 45 months of burial. Although after five years a small number of seedlings still emerged, soil seedbank decline was rapid when seed production was prevented. A low level of induced dormancy was detected and may explain the small populations of feral rye that persisted. Seed and seedling population shifts were large over a five-year period and were related to environmental conditions. Tillage or chemical control of feral rye in the fallow period reduced populations compared to the untreated weedy check. Moldboard plowing provided the greatest feral rye control compared to shallow tillage and chemical fallow. Feral rye seedbank populations rebounded following a wet final year of the study. These results help explain feral rye persistence in a wheat-fallow agroecosystem by the persistence of a small portion of the seedbank and by large seed inputs into the system during environmentally favorable years. Feral rye reduced wheat yield as much as 92% and represented up to 73% contamination in harvested wheat. [7]

4.1.2 Germination

Seeds germinate from autumn to spring with a flush in autumn. [8] Minimal temperatures for germinating cereal rye have been variously given as between 1°C and 5°C. [9] Rye prefers light loams or sandy soils and will germinate even in fairly dry soil. [10]

Research has shown that rye sown at a 2.5 cm depth had twice the emergence of rye sown at ~5 cm and that shallow-seeded rye had greater winter hardiness. [11]

While investigating environmental stress factors in seed germination and seedling growth, cereal rye was found to be exceptionally resistant to a wide variety of ordinarily harmful conditions:

- Germination is anaerobic, and proceeds well in the presence of carbon monoxide, nitrous oxide and hydrogen.
- Rye grains germinate readily at constant low temperatures (5°C, for example) and some can germinate on a cycle of 16 h at −30°C and 8 h at 20°C over seven days; liquid nitrogen temperatures can also be endured by dry seeds.

---

7 WL Stump, P Westra (2000). The seedbank dynamics of feral rye *Secale cereale*. *Weed Technology* 14, 7–14, https://www.jstor.org/stable/3988499?seq=1#page_scan_tab_contents

8 HerbiGuide. Rye. HerbiGuide Pty Ltd, http://www.herbiguide.com.au/Descriptions/hg_Rye.htm

9 RH Schlegel (2013) Rye: genetics, breeding, and cultivation. CRC Press, https://www.crcpress.com/Rye-Genetics-Breeding-and-Cultivation/Schlegel/p/book/9781466561434

10 A Clark (Ed.) 2007. Managing cover crops profitably. 3rd edn. Sustainable Agriculture Network, Beltsville, MD. https://www.sare.org/Learning-Center/Books/Managing-Cover-Crops-Profitably-3rd-Edition

11 Alberta Government (2016) Fall rye production. Alberta Agriculture and Forestry, http://www1.agric.gov.ab.ca/$department/deptdocs.nsf/all/agdex1269/$file/117_20-1.pdf

- In seawater and similar media, 100% germination can be effected in 10 days. [12]

Rye has been found to be more tolerant to saline conditions during germination than wheat and some triticale varieties. [13]

Optimum planting depth varies with planting moisture, soil type, seasonal conditions, climatic conditions and the rate at which the seedbed dries. The general rule is to plant as shallow as possible, provided the seed is placed in the moisture zone but deep enough that the drying front will not reach the seedling roots before leaf emergence, and to separate the seed from any pre-emergent herbicides used. [14]

When shallow seeding, the previous crop's residue will have a greater tendency to interfere with good seed–soil contact. Even spreading of the previous crop residue is essential for quick emergence. Make sure seed–soil contact occurs. [15]

For other germinating plants, rye residue that remains at the soil surface can modify the physical and chemical environment during seed germination and plant growth. [16]

4.1.3 Emergence

Rye needs a temperature sum of 90°C for field emergence, provided there is sufficient water (Photo 2). [17]

Photo 2: *Emergence of rye cover crop 11 days after planting.*

Source: Virginia Association for Biological Farming

Sowing depth influences the rate and percentage of emergence. Deeper seed placement slows emergence. Seedlings emerging from greater depth are also weaker, more prone to seedling diseases, and tiller poorly.

If deep sowing, it is important to avoid smaller sized seed because smaller seeds have shorter coleoptiles, which may stop growing before reaching the soil surface. The first leaf will then emerge from the coleoptile while still below the soil surface.

12 SM Siegal, LA Halpern, C Giumarro (1964) Germination and seedling growth of winter rye in deuterium oxide. *Nature* 201, 1244–1245, http://www.nature.com/nature/journal/v201/n4925/abs/2011244a0.html

13 UR Bishnoi, DK Pancholy (1980) Comparative salt tolerance in triticale, wheat and rye during germination. *Plant and Soil* 55, 491–493, https://www.jstor.org/stable/42935011

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

15 Alberta Government (2016) Fall rye production. http://www1.agric.gov.ab.ca/$department/deptdocs.nsf/all/agdex1269/$file/117_20-1.pdf

16 EA Oelke, ES Oplinger, H Bahri, BR Durgan, DH Putnam, JD Doll, KA Kelling (1990) Rye. In Alternative field crops manual. University of Wisconsin and University of Minnesota, https://hort.purdue.edu/newcrop/afcm/rye.html

17 RH Schlegel (2013) Rye: genetics, breeding, and cultivation. CRC Press, https://www.crcpress.com/Rye-Genetics-Breeding-and-Cultivation/Schlegel/p/book/9781466561434

Because it is not adapted to pushing through soil (it does not know which way is up), the leaf usually buckles and crumples, failing to emerge and eventually dying. [18]

Rye has been found to be slightly less salt-tolerant during plant emergence than during subsequent stages of growth. [19]

4.2 Environmental effects on plant growth and physiology

4.2.1 Photoperiod and temperature

Cereal rye is a long-day plant; that is, it requires increasing day length to induce flowering. Flowering is induced by 14 hours of daylight accompanied by temperatures of 5–10°C. Rye shows a shorter growth period than other winter and spring cereals that also differ considerably in vernalisation period (i.e. induction of a plant's flowering process by exposure to prolonged cold). Winter types of rye require 40–60 days, whereas spring types require only 10–12 days of cold temperatures to shift into the reproductive stage. [20]

Rye has been found to achieve more rapid rates of pre-anthesis dry matter accumulation, irrespective of whether it was grown at high (20–15°C) or low (10–7°C) day–night temperatures. Tiller number and leaf area per plant were greater for rye, especially at low temperatures, than triticale and wheat. [21]

4.2.2 Salinity

Cereal rye is thought to be relatively tolerant to saline soils, similar to barley, but will be affected in highly saline soils (ECe, electrical conductivity of the soil saturated paste extract, 8–16 dS/m). [22]

Relative grain yield of two rye cultivars in a field experiment in Canada was unaffected up to a soil salinity of 11.4 dS/m. Each unit increase in salinity above 11.4 dS/m reduced yield by 10.8%. These results place rye in the salt-tolerant category. Yield reduction was attributed primarily to reduced spike weight and individual seed weight rather than spike number. Bread quality decreased slightly with increasing levels of salinity. Straw yield was more sensitive to salinity than was grain yield. Rye was found to be slightly less salt tolerant during plant emergence than during subsequent stages of growth. [23]

For more information, see Section 14: Environmental issues.

4.3 Plant growth stages

The developmental cycle of rye can be divided in 12 stages. During stage one, the growing point is not differentiated. In stage two, the primordia of stems, nodes and internodes are formed in the growing point. Rye, usually planted in autumn and moderate climate, enters winter in stage two. In stage three, the growing point differentiates into further segments, which are primordia of spikelets. During this period, nitrogen supply has a positive effect on the formation of a large number of spikelets, which leads to the subsequent formation of longer spikes with a greater number of flowers and grains. A further differentiation of growing points takes place

18 DPI NSW (2007) Wheat growth and development. PROCROP Series. Department of Primary Industries New South Wales, https://www.dpi.nsw.gov.au/__data/assets/pdf_file/0006/449367/Procrop-wheat-growth-and-development.pdf

19 LE Francois, TJ Donovan, K Lorenz, EV Maas (1989) Salinity effects on rye grain yield, quality, vegetative growth, and emergence. Agronomy Journal, 81(5), 707–712, https://dl.sciencesocieties.org/publications/aj/abstracts/81/5/AJ0810050707?access=0&view=pdf

20 RH Schlegel (2013) Rye: genetics, breeding, and cultivation. CRC Press, https://www.crcpress.com/Rye-Genetics-Breeding-and-Cultivation/Schlegel/p/book/9781466561434

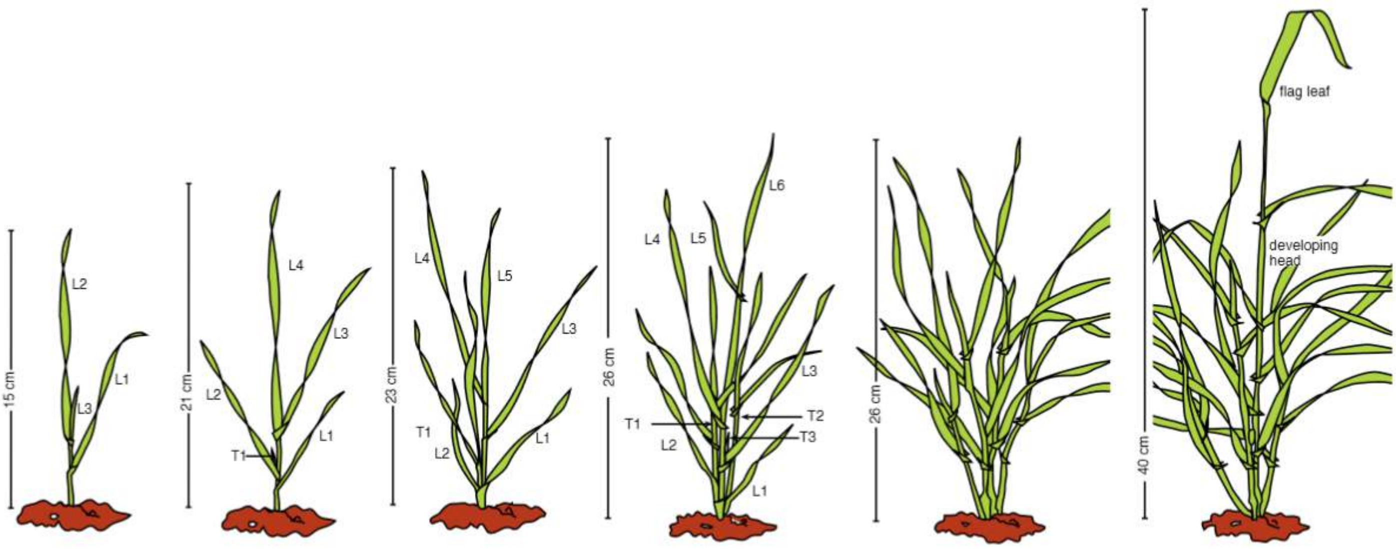
21 M Winzeler, DE McCullough, LA Hunt (1989) Leaf gas exchange and plant growth of winter rye, triticale and wheat under contrasting temperature regimes. *Crop Science* 29, 1256–1260, https://dl.sciencesocieties.org/publications/cs/abstracts/29/5/CS0290051256?access=0&view=pdf

22 C Henschke, T Herrmann (2007) Testing for soil and water salinity. PIRSA Fact Sheet No:66/00. Primary Industries and Regions South Australia, June 2007

23 LE Francois, TJ Donovan, K Lorenz, EV Maas (1989) Salinity effects on rye grain yield, quality, vegetative growth, and emergence. *Agronomy Journal* 81, 707–712, https://dl.sciencesocieties.org/publications/aj/abstracts/81/5/AJ0810050707?access=0&view=pdf

during stages three and four, in which flower primordia are formed. This process takes place in early spring. During the formation of spikelet primordia in the upper part of the spike, flowers are formed in the middle portion. The plant then enters stage five of organogenesis. Under conditions of long days and poor nitrogen supply, this process is relatively fast. Meiosis of pollen mother cells and the formation of tetrads, the embryo sac and the egg take place during stages six and seven of organogenesis. Stage seven is characterised by extensive elongation growth during which pronounced elongation of shoot internodes takes place. In stage eight, the plants ear and subsequently flower. Fertilisation and maturation of caryopses and plant then follow in the remaining four stages of development. [24]

Figure 2 presenta diagrams and descriptions of corresponding stages of rye growth.



Crop growth stage					
2-leaf stage	Start of tillering	Tillering stage	Fully tillered stage	Start of jointing	Early boot stage
Two leaves (L) have unfolded; third leaf present, yet to expand fully	First tiller (T1) appears from between a lower leaf and the main shoot. Usually 3 or 4 leaves are on the main tiller	Tillers come from the base where leaves join the stem and continue forming, usually until 5 leaves are on the main shoot. Secondary roots developing	Usually no more tillers form after the very young head starts forming in the main tiller. Tillering completed when first node detected at base of main stem	Jointing or node formation starts at the end of tillering. Small swellings (joints) form at the bottom of the main tiller. Heads continue developing and can be seen by dissecting a stem	The last leaf to form (the flag leaf) appears on top of the extended stem. The developing head can be felt as a swelling in the stem
Zadoks decimal code					
2 leaves unfolded (Z12)	4 leaves unfolded (Z14) Main shoot and 1 tiller (Z21)	5 leaves on main shoot or stem (Z15) Main shoot and 1 tiller (Z21)	6 leaves on main shoot or stem (Z16) Main shoot and three tillers (Z23)	First node formed at base of main tiller (Z31)	Z35–Z45

Figure 2: *Growth stages for cereal rye.*

Source: NSW Department of Primary Industries

24 RH Schlegel (2013) Rye: genetics, breeding, and cultivation. CRC Press, https://www.crcpress.com/Rye-Genetics-Breeding-and-Cultivation/Schlegel/p/book/9781466561434

4.3.1 Roots

Rye has four primary roots that originate from the seed and it can send out roots and tillers from the second, third and fourth node. This extensive root system within the first 30 cm of soil is more developed than in other cereals (Photo 3). This is useful when sowing over eroded or disturbed sites where depth is hard to control and it makes the plant more drought resistant. [25] This more developed root system also increases soil stabilisation and allows the plant to explore more of the topsoil profile, increasing tolerance to dry conditions (Photo 3). [26]

Figure 3: *Dense root structure of cereal rye.*

Source: Iowa Farmer Today

Despite having no taproot, its quick growing, fibrous root system can take up and hold as much as 45 kg of nitrogen, although 12–23 kg is more typical. [27]

Cereal rye roots can grow to over 1 m deep (Photo 4). This helps to recycle nutrients as well and building organic matter in the soil. [28]

25 L Martin (2015) Growing cereal rye to increase carbon and prevent wind erosion. Liebe Group, March 2015, http://www.liebegroup.org.au/wp-content/uploads/2015/03/Case-Study-Jeff-Pearse-March-2015.pdf

26 P Matthews, D McCaffery, L Jenkins (2016) Winter crop variety sowing guide 2016. NSW Department of Primary Industries, https://www.dpi.nsw.gov.au/agriculture/broadacre-crops/guides/publications/winter-crop-variety-sowing-guide

27 L Martin (2015) Growing cereal rye to increase carbon and prevent wind erosion. Liebe Group, March 2015, http://www.liebegroup.org.au/wp-content/uploads/2015/03/Case-Study-Jeff-Pearse-March-2015.pdf

28 L Betts (2012). Rye crop calendar. Farm Progress, http://farmprogress.com/story-2012-rye-cover-crop-calendar-14-94095

MORE INFORMATION

Research paper: Soil conditions and cereal root system architecture: review and considerations for linking Darwin and Weaver

Figure 4: *Deep growth of cereal rye roots.*

Source: Farm Progress

4.3.2 Plant development: photosynthesis and maturation

With the beginning of shooting, the reduction of tillers starts. This is reinforced by nutrients, especially nitrogen deficiency and/or drought. Overall, rye should not have to reduce more than 50% of the preformed tillers. The flag leaf is smaller and less important in photosynthesis. Rye has the longest stems of all cultivated small grains and these provide most of the photosynthetic area. During grain formation, stems with sheaths account for 60–80% of the total plant area. At grain-set, leaf blades provide 15–20% of the photosynthetic area, which is much lower than that for maize, wheat and oat. Stems and sheaths have lower rates of photosynthesis and export of assimilates than leaves. The most important periods of yield formation are flowering and grainfill. Successful pollination depends on sufficient spreading of husks. Cold and rainy weather at flowering hamper the opening of husks, and thus pollen distribution.

The maturation date of rye varies according to soil moisture, but vegetative growth stops once reproduction begins. In general, rye matures earlier than oat. The growth period—that is, the time from sowing to harvest—is ~295 days in rye. For rye, the photosynthetic area decreases rapidly after seedset and does not achieve a plateau near the maximum as seen with other grains. Its grain formation occurs under favourable physiological conditions for yielding.

The vegetation period lasts for ~120–150 days. [29]

4.3.3 Vegetative behaviour

Field and pot investigations of the vegetative and early reproductive growth of a winter wheat cultivar and a winter rye cultivar over three seasons showed that higher and earlier forage yields of rye are due to a combination of factors, notably more rapid rates of germination, crop emergence, leaf appearance and leaf expansion, coupled with higher leaf area ratios. Studies of net assimilation rate found no

29 RH Schlegel (2013) Rye: genetics, breeding, and cultivation. CRC Press, https://www.crcpress.com/Rye-Genetics-Breeding-and-Cultivation/Schlegel/p/book/9781466561434

evidence that the photosynthetic apparatus of rye plants is better adapted than wheat to the low temperature and light conditions of winter and early spring. However, the earlier initiation of rye stem extension was associated with significant increases in net assimilation rate, which compensated for reductions in the leaf area ratio. [30]

Rye tillers grow profusely. Individual plants can easily be split into several clones. Genotypes can differ in cloning and ability. The production of tillers can be stimulated by cutting back the plants, which helps to retard the development of spikes. Cool, moist and short-day conditions increase the tillering capacity. Continuous light prevents jointing.

Earlier than 280 degree-days after emergence, the four-leaf phase is reached and tillering starts. Once a shoot has formed six leaves and it is the vernalised enough, the formation of spikelets begins. [31]

Rye has an erect slender stem topped with a curved spike that is 7–15 cm long. The head is made up of individual spikelets, each with two florets that produce one or two kernels. The spikelets are arranged alternately along the length of the head. The leaves of the plant grow from nodes on the stem and are lance-like blades, blue-green in color. Rye can reach 1–3 m in height and it is grown either as an annual (spring rye) or as a biennial (winter rye). [32]

Rates of dry matter accumulation early in the growing season were significantly greater for rye crops than for triticale and wheat. [33]

In cereal rye, 53–58% of total grain yield has been found to be produced by lateral shoots, depending on the cultivar and the growing conditions. [34]

Winter rye generally overwinters in the tillering stage. The winter temperatures near freezing satisfy the vernalisation requirement and allow the plants to initiate reproductive development the following spring. Rye varieties are long-day plants, but they do not have an absolute requirement for a specific day length. Rye is cross-pollinated, and relies on windborne pollen. The florets remain open for some time, but if conditions are not favorable for cross-pollination, rye spikes may have several empty florets. The inflorescence is a spike with one sessile spikelet per rachis node. Spikelet initiation begins in the middle of the spike and proceeds toward the tip and base. Only the two basal florets in each spikelet produce seed. Spring rye does not require vernalisation to induce flowering. [35]

Grazing

The earliest time to start grazing is when the plants are well anchored and reaching the tillering stage (Zadoks growth stage 21–29). For most grazing cereal types under good growing conditions, this will occur 6–8 weeks from plant emergence, depending on variety.

With winter types, by deferring early grazing, more feed can be accumulated and saved for winter. For erect types, crops will usually be 20–25 cm high.

Varieties without a strong winter habit but sown in early autumn should be grazed even before tillering to retard growth and subsequent premature stem elongation and head initiation. When stem elongation occurs, immature heads are located just above the highest node (joint). If these are removed, tiller death occurs. Although the plant is usually able to produce more tillers, forage production (and grain production)

30 RKM Hay, MKA Al-Ani (1983) The physiology of forage rye (*Secale cereale*). *The Journal of Agricultural Science* 101, 63–70, https://www.cambridge.org/core/journals/journal-of-agricultural-science/article/the-physiology-of-forage-rye-secale-cereale/2E6A22C9703921F7A721CC51A2C3AB36

31 RH Schlegel (2013) Rye: genetics, breeding, and cultivation. CRC Press, https://www.crcpress.com/Rye-Genetics-Breeding-and-Cultivation/Schlegel/p/book/9781466561434

32 Plant Village. Rye *Secale cereale*. Pant Village, https://www.plantvillage.org/en/topics/rye/diseases_and_pests_description_uses_propagation

33 D McCullough, L Hunt (1993) Mature tissue and crop canopy respiratory characteristics of rye, triticale and wheat. *Annals of Botany* 72, 269–282, http://aob.oxfordjournals.org/content/72/3/269

34 K Hakala, K Pahkala (2003) Comparison of central and northern European winter rye cultivars grown at high latitudes. *The Journal of Agricultural Science* 141, 169–178, https://www.cambridge.org/core/journals/journal-of-agricultural-science/article/comparison-of-central-and-northern-european-winter-rye-cultivars-grown-at-high-latitudes/F935401E09A79882E0A9937D9BF3AEC5

35 EA Oelke, ES Oplinger, H Bahri, BR Durgan, DH Putnam, JD Doll, KA Kelling (1990) Rye. In Alternative field crops manual. University of Wisconsin and University of Minnesota, https://hort.purdue.edu/newcrop/afcm/rye.html

is severely reduced. The latest time for grazing and the severity of grazing of crops intended for grain recovery or hay production should be governed by the position of the immature head in the stem. Some growers opt to graze late and remove these heads, particularly if the crop or variety is prone to lodging. These growers choose to accept lower grain or hay yields as a trade-off for having a standing crop at harvest. [36]

4.3.4 Flowering and grain formation

Cereal rye flowers around August in southern Australia and from July to October in Western Australia. [37]

After flowering, the grain begins to form. As the grain forms and matures, it goes through a clear liquid phase prior to the commencement of starch deposition. The grain then enters the 'milky' stages, described as early, medium and late milk, followed by soft dough (Photo 3) and hard dough stages and eventually as a dry grain suitable for grain harvesting (Photo 4).

As the plant reaches maturity, sugars in the stems and leaves are translocated to the grain and converted to starch. These changes are associated with changes in colour from an all-green plant in the vegetative stages to an all-yellow plant in the fully mature plant at the hard grain stage (Photo 5). [38]

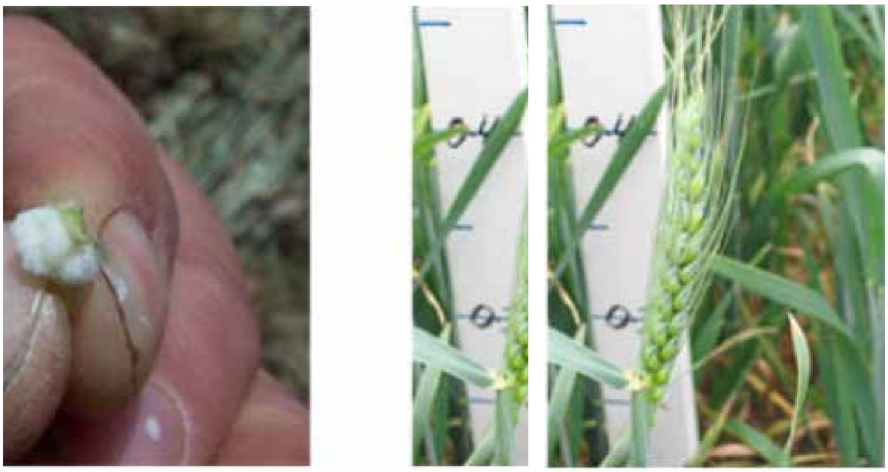


Photo 3: *Cereal grain (left) and plant (right) at the soft dough stage.*

Source: Agriculture Victoria

36 G Hennessy, D Clements (2009) Cereals for grazing. PrimeFact 270. NSW Department of Primary Industries, http://www.dpi.nsw.gov.au/__data/assets/pdf_file/0011/288191/Cereals-for-grazing.pdf

37 HerbiGuide. Rye. HerbiGuide Pty Ltd, http://www.herbiguide.com.au/Descriptions/hg_Rye.htm

38 Agriculture Victoria (2008) When to cut forage cereals. Government of Victoria EDJTR, http://agriculture.vic.gov.au/agriculture/grains-and-other-crops/crop-production/when-to-cut-forage-cereals

Photo 4: *Cereal rye grain.*

Source: Atlas of Living Australia

Photo 5: *Rye ripening.*

Source: Plant Village

Frost tolerance

Frost occurs on clear nights in early spring when the air temperature drops to ≤2°C. Damage to crops from frost may occur at any stage of development but is most damaging at and around flowering. Symptoms of frost damage can occur as sterility and stem damage. Physical damage to the plant occurs when ice forms inside the plant tissue, as expanding ice bursts membranes, resulting in mechanical damage and dehydration injury. Frost damage can reduce both grain yield and quality. After oats, cereal rye is regarded as the cereal crop least susceptible to frost damage, followed by barley, wheat and triticale. Oats are thought to be ~4°C more tolerant than wheat and barley ~2°C more tolerant, with rye therefore somewhere between 2°C and 4°C more tolerant than wheat. [39]

39 DAFWA. Frost and cropping. Department of Agriculture and Food Western Australia, https://www.agric.wa.gov.au/frost/frost-and-cropping

Frost tolerance varies between varieties of cereal rye. Bevy flowers about two weeks later than SA Commercial and is less prone to frost, which often affected yields of the SA Commercial variety. [40]

For more information on frost, see Section 14: Environmental issues.

40 Agriculture Victoria (2013) Growing cereal rye. Government of Victoria EDJTR, http://agriculture.vic.gov.au/agriculture/grains-and-other-crops/crop-production/growing-cereal-rye

Nutrition and fertiliser

Key messages:

- Only rarely are strong symptoms of nutrient deficiency shown in a cereal rye crop. If symptoms are present, they are likely to be similar to those in wheat. [1]
- Rye can be planted on land that is not fertile enough for crops like wheat.
- Rye can easily be over-fertilised; harvesting can be difficult if the rye lodges from too much nitrogen (N). [2]
- Despite having no taproot, its quick growing, fibrous root system can take up and hold as much as 45 kg of N; however, 12–23 kg is more typical. [3]
- Rye can recycle potassium (K) from deeper in the soil profile for future crop use. [4]
- The northern grain growing region has generally high soil fertility, although there is increasing evidence that this has been run down over time. [5]

5.1 Nutrient balance

Rye is generally more efficient at taking up nutrients than wheat, barley or oats, due to its extensive root system (Table 1).

Table 1: *Mean nutrient uptake of rye at different yield levels.*

	Yield (dt/ha)		
Nutrients	**40 dt/ha**	**60 dt/ha**	**80 dt/ha**
N (kg/ha)	110	150	200
P_2O_3 (kg/ha)	40	60	80
K_2O (kg/ha)	75	115	150
MgO (kg/ha)	15	22	30
CaO (kg/ha)	15	22	30
S (kg/ha)	10	15	20
B (kg/ha)	40	45	50
Cu (kg/ha)	30	40	50
Zn (kg/ha)	120	150	200
Mn (kg/ha)	350	400	600

Source: Schlegel, 2013 [6]

Trials in poor-quality soil have found that cereal rye cropping over three years increased soil organic carbon (SOC) in the topsoil by 27.8% in 2013 and 16.7% in 2014. This represents a total improvement of 47% since 2012 (Figure 1). [7]

1 M Wurst, R Brennan (2007). Winter cereal nutrition—the Ute Guide. Grains Research and Development Corporation, May 2007, https://grdc.com.au/resources-and-publications/all-publications/publications/2007/05/uteguide-wintercerealnutrition

2 UVM (2011) Cereal rye. University of Vermont, April 2011, http://northerngraingrowers.org/wp-content/uploads/RYE.pdf

3 L Martin (2015) Growing cereal rye to increase carbon and prevent wind erosion. Liebe Group, March 2015, http://www.liebegroup.org.au/wp-content/uploads/2015/03/Case-Study-Jeff-Pearse-March-2015.pdf

4 N Rector, T Harrigan, DR Mutch, S Snappe (2009) Cereal rye: manure and livestock's new best friend. Manure $ense. Michigan State University, February 2009

5 J Carson. Biological inputs—northern grain-growing region. Soil Quality Pty Ltd, http://www.soilquality.org.au/factsheets/biological-inputs-northern-grain-growing-region

6 RH Schlegel (2013) Rye: genetics, breeding, and cultivation. CRC Press, https://www.crcpress.com/Rye-Genetics-Breeding-and-Cultivation/Schlegel/p/book/9781466561434

7 L Martin (2015) Growing cereal rye to increase carbon and prevent wind erosion. Liebe Group, March 2015, http://www.liebegroup.org.au/wp-content/uploads/2015/03/Case-Study-Jeff-Pearse-March-2015.pdf

MORE INFORMATION

Liebe Group: Growing cereal rye to increase carbon and prevent wind erosion.

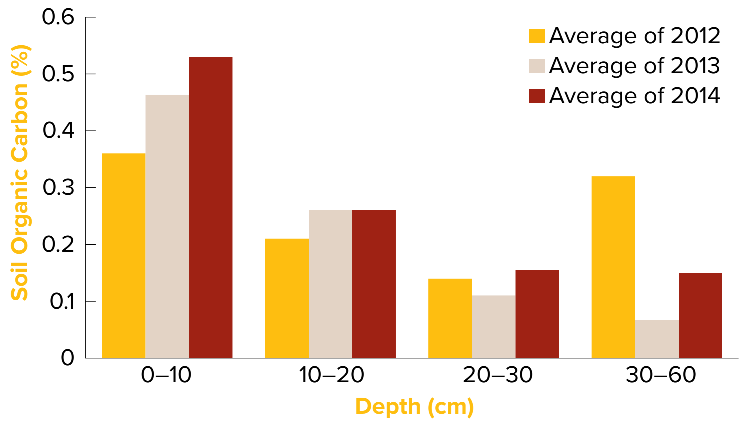


Figure 1: *Percentage average soil organic carbon sampled from four depths in three years.*

Source: Liebe Group

5.1.1 Nutrient benefits from rye

Rye improves water quality because the plant's extensive root system takes up excess soil N that would otherwise leach to contaminate groundwater or surface water bodies. This N is taken up by the plant, and then it slowly becomes available to subsequent crops as the residues gradually decompose.

Rye roots can also extract K and other nutrients from deep in the soil profile and bring them to the surface, where they become available to subsequent crops. Expect considerable fertility improvement in the topsoil when growing rye as a catch crop. [8]

According to long-term trials in the United States, cover crops on average can reduce N loading by 28% and phosphorus (P) loading by 50%. Since 2008, 46 site-years have been conducted, with farmers reporting that in 42 of 46 site-years, properly managed cover crops had little or no negative effect on maize and soybean yield (and actually increased soybean yield in four site-years). [9]

A rye cover crop and manure applications are mutually beneficial. Manure nutrients aid in decomposition of the rye, offsetting any potential yield drag, and rye captures and recycles the manure nutrients effectively to future crops, reducing commercial fertiliser needs. [10]

IN FOCUS

Winter cover crop effects on soil organic carbon in soil

Winter cover crops may increase SOC levels or reduce their rate of depletion. Selection of appropriate cover crops to increase SOC requires an adequate knowledge of the quality and quantity of plant biomass produced and its rate of decomposition in soil. This study examined the SOC and carbohydrate concentrations in soil as affected by several leguminous and non-leguminous cover crops in a temperate, humid region of the United States. The cover crops had a variable effect on SOC and soil carbohydrate concentrations due to a significant difference in total

8 H Valenzuela, J Smith (2002) Rye. Sustainable Agriculture Green Manure Crops. University of Hawai'i, August 2002, http://www.ctahr.hawaii.edu/oc/freepubs/pdf/GreenManureCrops/rye.pdf

9 S Gailans (2015). Winter cereal rye cover crop effect on cash crop yield: results from long-term, on-farm research. Synergy in Science: Partnering for Solutions Conference, Minneapolis, 15–18 November 2015, https://scisoc.confex.com/scisoc/2015am/webprogram/Paper91725.html

10 N Rector, T Harrigan, D Mutch, S Snapp (2010) Cereal rye: manure and livestock's new best friend. Michigan State University

organic C and carbohydrate produced by the cover crops. The overriding cover crop effect on SOC and carbohydrate was due to the magnitude of the C inputs from the cover crops. With more than 4 t/ha of top biomass, cereal rye and annual ryegrass were better suited as winter cover crops for building SOC levels in this study than Austrian winter pea, hairy vetch, and canola. [11]

VIDEOS

WATCH: Over the Fence North: gas and liquid fertiliser drives yield gains at Tulloona.

WATCH: Improving phosphate use efficiency.

5.1.2 Fertiliser application

Winter rye and winter wheat respond similarly to nutrient additions. Soil tests are the best guide on which to base fertiliser rates. Phosphorus should be applied in autumn although improved efficiency can be achieved by banding phosphate directly below the seed at planting, especially on high pH soils. The N application should be split, especially on lighter soils with one part applied at planting, and the rest by topdressing in the spring.

Rye should be fertilised when grown for pasture or as a cover crop. Early application of N and P increases early growth, which improves winter groundcover. A spring topdressing with N is desirable where rye is pastured. Heavy N applications promote lodging in rye grown for grain. A moderate rate of manure is a good general fertiliser. [12]

Most varieties of cereal rye do not require any more fertiliser than other cereals. However, given its ability to produce winter feed very quickly, strong economic responses can be gained from supplying the crop with a good amount of starter fertiliser (e.g. upwards of 100 kg/ha of di-ammonium phosphate). Follow up with a topdressing of N (30–50 kg/ha) when the crop is at early tillering stages, perhaps three weeks after emergence. Additional fertiliser and lime can be applied according to a soil test. [13]

Recommendations for P fertiliser and, where necessary, N fertiliser are the same as for wheat. Some current recommendations are:

- Apply P at 10–15 kg/ha and N at 10–20 kg/ha at sowing.
- Occasionally N broadcast post-sowing may be required if the crop appears deficient. [14]

5.2 Crop removal rates

Ultimately, nutrients removed from paddocks will need to be replaced to sustain production (Table 2). In irrigated cropping, large quantities of nutrients are removed and growers need to adopt a strategy of programmed nutrient replacement, but dryland growers should also consider this approach. The yield potential of a crop will be limited by any nutrient the soil cannot adequately supply. Temperature and soil moisture content will affect the availability of nutrients to plants, as will 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.

11 S Kuo, UM Sainju, EJ Jellum (1997) Winter cover crop effects on soil organic carbon and carbohydrate in soil. Soil Science Society of America Journal, 61(1), 145–152, https://dl.sciencesocieties.org/publications/sssaj/abstracts/61/1/SS0610010145?access=0&view=pdf

12 EA Oelke, ES Oplinger, H Bahri, BR Durgan, DH Putnam, JD Doll, KA Kelling (1990) Rye. In Alternative field crops manual. University of Wisconsin and University of Minnesota, https://hort.purdue.edu/newcrop/afcm/rye.html

13 Wrighton Seeds. Forage focus—southern green ryecorn. http://www.pggwrightsonseeds.com.au/products/cereals/southerngreenryecorn/

14 R Sonogan (2013) Growing cereal rye. Agriculture Victoria, May 2013, http://agriculture.vic.gov.au/agriculture/grains-and-other-crops/crop-production/growing-cereal-rye

Lack of movement of nutrients combined with current farming methods (e.g. no-till) results in stratification of nutrients, whereby nutrient concentrations build up in the surface of the soil where they are not always available to plants, depending on the seasonal conditions. On the Western Downs and in Central Queensland, cereals are often deep-sown in moisture that is below the layer where nutrients have been placed or are stratified, which has implications for management and fertiliser practices. [15]

Table 2: *Estimated nutrient removal rates (kg/ha) for cereal rye grain and straw.*

Cereal rye	Yield per ha	Nitrogen	Phosphorus pentoxide	Potassium oxide	Calcium	Magnesium	Sulfur	Copper	Manganese	Zinc
Grain	1.88 t	39	11	11	2.2	3.4	7.9	0.022	0.25	0.034
Straw	3.36 t	17	9	28	9	2.2	3.4	0.011	0.16	0.079

Source: converted from North Caroline State University

5.3 Soil testing

Key points:

- A soil test critical value is the soil test required to achieve 90% of maximum potential crop yield.
- A range of soil test values used to determine whether a nutrient is deficient or adequate is termed a critical range. The critical range reflects the degree of uncertainty around the critical value.
- Fertiliser decisions are in part based on where the soil test falls in relation to the critical range.
- Critical ranges for combinations of nutrient, crop and soil types are being established.
- Critical ranges are being established for topsoils (0–10 cm) and subsoils (10–30 cm in some cases, or to the depth of the crop root-zone in others) depending on the nutrient.
- Deeper sampling is considered essential for understanding soil nutritional status and fertiliser requirement in northern cropping systems.

In northern cropping soils, nutrient deficiencies other than N are a relatively recent development. Consequently, there has been less nutrient research conducted in these soils and on the many crop types grown in northern cropping systems. Most research has been done on N in wheat and barley.

Recent research has highlighted that N applications can be wasted, even on cropping soils that have low N availability, if the levels of other nutrients such as K, P and sulfur (S) are not adequate.

The importance of subsoil layers for nutrients such as P and K is not yet reflected in the limited soil test–crop response data available. Researchers are using rules-of-thumb to help interpret P and K soil tests in terms of likely fertiliser responsiveness on northern region Vertosols.

These figures are still 'works in progress' and will be refined as more nutrient information comes to light during this second phase of the More Profit from Crop Nutrition program. [16]

5.3.1 Why test soil?

Soil testing may be carried out for various purposes such as:

- assessment of land capability for various forms of agriculture

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

16 GRDC (2014) Crop nutrition fact sheet: soil testing crop nutrition, northern region. Grains Research and Development Corporation, January 2014, www.grdc.com.au/GRDC-FS-SoilTestingN

- identifying and quantifying soil constraints (e.g. salinity)
- monitoring of soil fertility levels
- providing guidelines as to the type and amount of fertiliser to be applied for optimum plant growth on the particular site
- as a diagnostic tool to help identify reasons for poor plant performance.

The ultimate aim is to reduce the guesswork involved in managing a specific area of a crop. However, the results and recommendations may be worthless, or even misleading, if sampling and/or analysis of submitted samples are not carried out properly or if subsequent interpretation of the data is flawed.

5.3.2 Basic requirements

Three basic steps must be followed if meaningful results are to be obtained from soil testing:

1. Take a representative sample of soil for analysis.
2. Analyse the soil by using the accepted procedures that have been calibrated against fertiliser experiments in that particular region.
3. Interpret the results using criteria derived from those calibration experiments.

Each of these steps may be under the control of a different person or entity. For example, the sample may be taken by the farmer manager or a consultant agronomist; it is then sent to an analytical laboratory; and finally the soil test results are interpreted by an agronomist to develop recommendations for the farmer. [17]

5.3.3 Types of test

Appropriate soil tests for measuring soil-extractable or plant-available nutrients are:

- bicarbonate-extractable P (Colwell P)
- bicarbonate-extractable K (Colwell K)
- KCl-40 extractable S
- 2 M KCl extractable inorganic N, which provides measurement of nitrate-N and ammonium-N.

Other measurements that aid the interpretation of soil nutrient tests include soil pH, percentage of gravel in the soil, soil carbon/organic matter content, P-absorption capacity (measured as P buffering index, PBI), electrical conductivity, chloride, and cation exchange capacity (CEC) including aluminium.

5.4 Plant and/or tissue testing for nutrition levels

5.4.1 Why measure nutrients in plant tissues?

Plant tissue testing can be used to diagnose a deficiency or monitor the general health of the crop. Plant tissue testing is most useful for monitoring crop health, because by the time symptoms appear in a crop the yield potential can already be markedly reduced.

Of the many factors affecting crop quality and yield, soil fertility is one of the most important. Producers can manage fertility by measuring the plant's nutritional status. Nutrient status is an unseen factor in plant growth, except when imbalances become so severe that visual symptoms appear on the plant. The only way to know whether a crop is adequately nourished is to have the plant tissue analysed during the growing season.

MORE INFORMATION

QDAF: Soil nutrient testing: how to get meaningful results

GRDC Fact Sheet: Soil testing for crop nutrition—northern region.

VIDEOS

WATCH: Over the Fence North: weed and nutrient research delivers at Silverton

17 D Loch. Soil nutrient testing: how to get meaningful results. Queensland Department of Agriculture and Fisheries, https://www.daf.qld.gov.au/__data/assets/pdf_file/0006/65985/Soil-Nutrient-Testing.pdf

5.4.2 What does plant tissue analysis show?

Plant tissue analysis shows the nutrient status of plants at the time of sampling. This, in turn, shows whether soil nutrient supplies are adequate. In addition, plant tissue analysis will detect unseen deficiencies and may confirm visual symptoms of deficiencies. Toxic levels also may be detected.

Although usually used as a diagnostic tool for future correction of nutrient problems, plant tissue analysis from young plants (Table 3) will allow a corrective fertiliser application that same season. A plant tissue analysis can pinpoint the cause, if it is nutritional.

A plant analysis is of little value if the plants come from fields that are infested with weeds, insects and disease organisms; if the plants are stressed for moisture; or if plants have some mechanical injury.

The most important use of plant analysis is as a monitoring tool for determining the adequacy of current fertiliser practices. Sampling a crop periodically during the season or once each year provides a record of its nutrient content that can be used through the growing season or from year to year. With soil test information and a plant analysis report, a producer can closely tailor fertiliser practices to specific soil–plant needs.

Sampling tips:

- Sample the correct plant part at the specified time or growth stage.
- Use clean plastic disposable gloves to sample to avoid contamination.
- Sample tissue (e.g. entire leaves) from vigorously growing plants unless otherwise specified in the sampling strategy.
- Take sufficiently large sample quantity (adhere to guidelines for each species provided).
- When troubleshooting, take separate samples from good and poor growth areas.
- Wash samples while fresh where necessary to remove dust and foliar sprays.
- Keep samples cool after collection.
- Refrigerate or dry if samples cannot be dispatched to the laboratory immediately to arrive before the weekend.
- Where possible sample in the morning while plants are actively transpiring.

Practices to avoid:

- sampling spoiled, damaged, dead or dying plant tissue
- sampling plants stressed by environmental conditions
- sampling plants affected by disease, insects or other organisms
- taking samples soon after applying fertiliser to the soil or foliage
- contaminating samples with dust, fertilisers or chemical sprays, or perspiration or sunscreen from hands
- sampling from atypical areas of the paddock, e.g. poorly drained areas
- sampling plants of different vigour, size and age
- combining samples from different cultivars (varieties) to make one sample
- placing samples into plastic bags, which will cause the sample to sweat and hasten its decomposition
- sampling in the heat of the day, i.e. when plants are moisture stressed
- mixing leaves of different ages. [18]

18 SoilMate (2010) Guidelines for sampling plant tissue for annual cereal, oilseed and grain legume crops. Back Paddock, http://www.backpaddock.com.au/assets/Product-Information/Back-Paddock-Sampling-Plant-Tissue-Broadacre-V2.pdf?phpMyAdmin=c59206580c88b2776783fdb796fb36f3

Table 3: *Plant tissue requirements for nutrient testing in wheat or triticale.*

Growth stage (Zadoks) to sample	Plant part	Number required
Seedling to early tillering (Z14–21)	Whole shoots cut off 1 cm above ground	40
Early tillering to 1st node (Z23–31)	Whole shoots cut off 1 cm above ground	25
Flag leaf ligule just visible to boots swollen (Z39–45)	Whole shoots cut off 1 cm above ground	25
Early tillering to 1st node (Z21–31)	Youngest expanded blade plus next two lower blades	40

Source: BackPaddock

5.5 Nitrogen

Key points:

- Rye is one of the best scavengers of N and reduces leaching losses on both sandy soils and tile-drained land.
- Nitrate is the highly mobile form of inorganic N in both the soil and the plant.
- Sandy soils in high rainfall areas are most susceptible to nitrate loss through leaching.
- Nitrogen is needed for crop growth in larger quantities than any other nutrient.
- Soil testing and N models will help determine seasonal N requirements.

The two forms of soil mineral N absorbed by most plants are nitrate and ammonium (Figure 2). In well-aerated soils during the growing season nitrate becomes the main form of N available for crops as microbial activity quickly transforms ammonium into nitrate. It is crucial to keep nitrate at adequate levels: too little can limit crop production and too much can lead to environmental pollution. The levels of soil nitrate vary over space and time. Proper agricultural management needs to consider both site-specific variations and temporal patterns in soil nitrate to supply optimum amounts from both organic and mineral sources. [19]

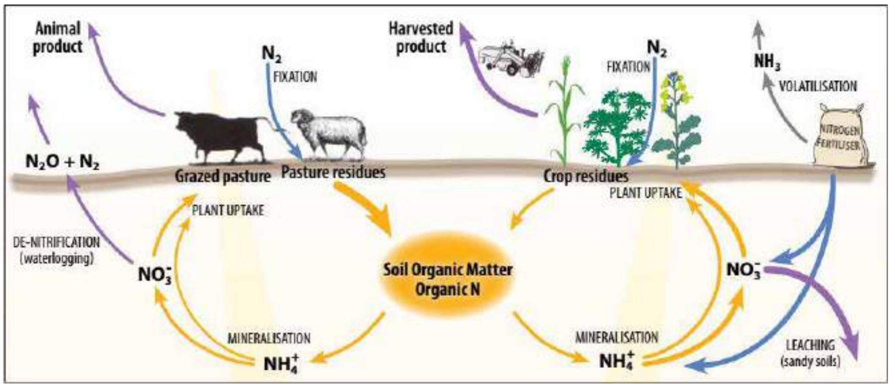


Figure 2: *Principal nitrogen cycling pathways in a mixed cropping/pasture system (adapted from Peverill et al. 1995 20).*

Source: Soil Quality Pty Ltd

The ability of rye to affect soil N levels can depend on topography. In one study, rye cover crop had a significant 15% negative effect on nitrate in topographical depressions but not in slope and summit positions. [21]

19 M Ladoni, AN Kravchenko, GP Robertson (2015) Topography mediates the influence of cover crops on soil nitrate levels in row crop agricultural systems. *PloS ONE* 10, e0143358, http://journals.plos.org/plosone/article?id=10.1371/journal.pone.0143358

20 KI Peverill, LA Sparrow, DJ Reuter (1995) Soil analysis: an interpretation manual. CSIRO Publishing.

21 M Ladoni, AN Kravchenko, GP Robertson (2015) Topography mediates the influence of cover crops on soil nitrate levels in row crop agricultural systems. *PloS ONE* 10, e0143358, http://journals.plos.org/plosone/article?id=10.1371/journal.pone.0143358

IN FOCUS

Accumulation and loss of nitrogen during growth and maturation of cereal rye

The loss of total N from herbage of cereal rye after anthesis was studied by recovering herbage, roots, and anthers of rye grown in soil (under dryland conditions), nutrient solution, and sand culture. The amount of N in herbage of dryland rye decreased an average of 7.9 kg/ha during the two weeks following anthesis. Potential loss of N from herbage through shedding of anthers and pollen was estimated at 16 kg/ha. Rye grown in sand or solution culture continued to absorb and accumulate N after anthesis which masked the N lost during anthesis. We found no evidence to suggest transport of N from herbage to roots under either dryland conditions, or sand or nutrient culture. [22]

Rye will often respond to a modest application of N fertiliser, but when it follows crops that have been well fertilised with N it seldom requires additional fertiliser. Rye has a good ability to scavenge residual soil N when it follows other crops, and it is commonly grown for this purpose. This reduces the potential for nitrate leaching into groundwater and it conserves N fertiliser inputs, which saves money. [23]

The amount of N safely placed with the seed will vary depending on soil texture, amount of seedbed utilisation and moisture conditions. Greater amounts of N can be safely applied with the seed if it is a polymerised form of urea where the N is released over a period of several weeks. If soil moisture is marginal for germination, high rates of fertiliser should not be placed with the seed. Both N and P can be banded prior to seeding, but take care to avoid loss of seedbed moisture and protective crop residue. [24]

IN FOCUS

Nitrate leaching under a cereal rye cover crop.

Winter cover crops hold potential to capture excess nitrate and reduce leaching by recycling nutrients. A study in Oregon, USA, compared winter nitrate leaching losses under winter fallow and a cover crop of winter cereal rye. Leachate was sampled with passive capillary wick samplers. This cover crop–crop rotation study, initiated in 1989, had a cropping system (winter fallow *v.* winter cereal rye) as main plots, and three N application rates, ranging from 0 to 280 kg N/ha/year, as subplots. At the recommended N rate for the summer crops, nitrate leaching losses in winter were 48 kg N/ha under sweet corn–winter fallow in 1992–93, 55 kg N/ha under broccoli–winter fallow in 1993–94, and 103 kg N/ha under sweet corn–winter fallow in 1994–95, which were reduced to 32, 21, and 69 kg N/ha, respectively, under winter cereal rye. For the first two winters, 61% of the variation in nitrate leaching was explained by N rate (29%), cereal rye N uptake (17%), and volume of leachate (15%). Seasonal, flow-

22 CB Rumburg, FA Sneva (1970) Accumulation and loss of nitrogen during growth and maturation of cereal rye (*Secale cereale*). *Agronomy Journal* 62, 311–313.

23 V Grubinger (2010). Winter rye: a reliable cover crop. University of Vermont, October 2010, https://www.uvm.edu/vtvegandberry/factsheets/winterrye.html

24 Alberta Government (2016) Fall rye production. Alberta Agriculture and Forestry, http://www1.agric.gov.ab.ca/$department/deptdocs.nsf/all/agdex1269/$file/117_20-1.pdf

weighted concentrations at the recommended N rate were 13.4 mg N/L under sweet corn–winter fallow (1992–93), 21.9 mg N/L under broccoli–winter fallow, and 17.8 mg N/L under sweet corn–winter fallow (1994–95), and these were reduced by 39%, 58%, and 22%, respectively, under winter cereal rye. [25]

5.5.1 Nitrogen deficiency symptoms in cereals

What to look for

Paddock:

- Light green to yellow plants particularly on sandy soils or unburnt header or swathe rows (Photo 1).
- Double-sown areas have less symptoms if N fertiliser was applied at seeding.

Plant:

- Plants are pale green with reduced bulk and fewer tillers.
- Symptoms first occur on oldest leaf, which becomes paler than the others with marked yellowing starting at the tip and gradually merging into light green (Photo).
- Other leaves start to yellow and oldest leaves change from yellow to almost white.
- Leaves may not die for some time.
- Stems may be pale pink.
- Nitrogen-deficient plants develop more slowly than healthy plants, but maturity is not greatly delayed.
- Reduced grain yield and protein levels.

25 FM Brandi-Dohrn, M Hess, JS Selker, RP Dick, SM Kauffman, DD Hemphill (1997) Nitrate leaching under a cereal rye cover crop. *Journal of Environmental Quality* 26, 181–188, https://dl.sciencesocieties.org/publications/jeq/abstracts/26/1/JEQ0260010181

Photo 1: *Nitrogen deficiency on unburnt header row.*

Source: Department of Agriculture and Food Western Australia

Photo 2: *Nitrogen-deficient plants are smaller with yellow leaves and fewer tillers.*

Source: Department of Agriculture and Food Western Australia

VIDEOS

WATCH: GCTV14: Nitrogen deficiency.

Deficiency symptoms can be treated with N fertiliser or foliar spray. NOTE: There is a risk of volatilisation loss from urea or ammonium sources of N on alkaline soils when topdressed on dry soils in dewy conditions. Losses rarely exceed 3% per day. [26]

What else could it be?

Condition	Similarities	Differences
Waterlogging	Pale plants with oldest leaves most affected	Root browning or lack of feeder roots and wet soil
Potassium deficiency	Pale plants with oldest leaves most affected	Differences include more marked leaf tip death and contrast between yellow and green sections of K-deficient plants. Tillering is less affected
Molybdenum deficiency	Pale poorly tillered plants	Molybdenum deficiency affects the middle leaves first and cause white heads, shrivelled grain and delayed maturity

5.6 Phosphorus

Key points:

- Phosphorus is one of the most critical and limiting nutrients in agriculture in the northern cropping region.
- Phosphorous cycling in soils is complex.
- Only 5–30% of P applied as fertiliser is taken up by the plant in the year of application.
- Phosphorus fertiliser is best applied at seeding.
- Phosphorus is the most generally used fertiliser for rye. The rate of P application varies in the range 6–18 kg/ha, lighter applications being used in drier districts. [27]

Phosphorus is essential for plant growth, but few Australian soils have enough P for sustained crop and pasture production. Complex soil processes influence the availability of P applied to the soil, with many soils able to adsorb or 'fix' P, making it less available to plants (Figure 3). A soil's ability to fix P must be measured when determining requirements for crops and pastures. [28]

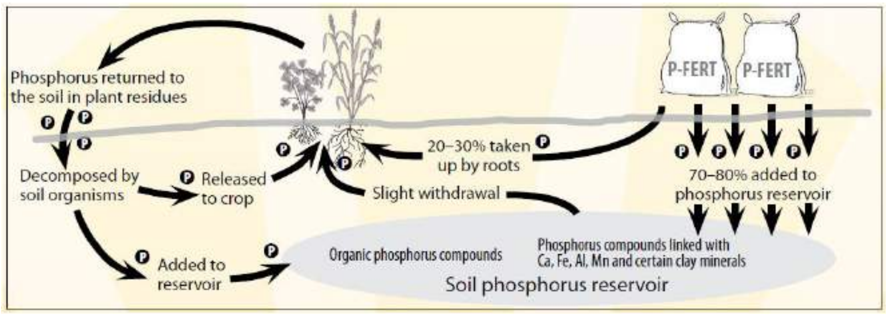


Figure 3: *The phosphorus cycle in a typical cropping system is very complex, where movement through the soil is minimal and availability to crops is severely limited (from Fertiliser Industry Federation of Australia Inc., 2000 29).*

Source: Soil Quality Pty Ltd

26 DAFWA (2015) Diagnosing nitrogen deficiency in wheat. Department of Agriculture and Food Western Australia, May 2015, https://agric.wa.gov.au/n/1995

27 RL Reid (Ed.) (2013). The manual of Australian agriculture. Elsevier, http://www.sciencedirect.com/science/book/9780409309461

28 S Alt (2013) Phosphorus NSW. Soil Quality Pty Ltd, http://www.soilquality.org.au/factsheets/phosphorus-nsw

29 Fertiliser Industry Federation of Australia Inc. (2000) Australian soil fertility manual. (Ed. JS Glendinning) CSIRO Publishing.

IN FOCUS

Uptake and utilisation of phosphate from iron phosphate—rye shows efficiency

Two glasshouse experiments were conducted to evaluate the genotypic variation amongst cereal genotypes in P uptake from relatively insoluble iron phosphate (FePO4). Two rates of iron phosphate were selected representing a deficient and sufficient supply (26 and 339 mg P/kg soil, respectively).These rates were used to screen 99 wheat, eight triticale, and four cereal rye genotypes for P-use efficiency. Phosphorus efficiency was rated by four criteria: shoot dry weight at deficient P supply, shoot weight at deficient supply relative to shoot weight at sufficient P supply, P uptake efficiency (amount of P taken up per unit of P supplied) and P-utilisation efficiency (shoot weight per unit P in plant). No genotypes were rated as efficient under all four criteria. Only two genotypes were rated efficient (rye Bevy, rye PC00361) and one inefficient (wheat Machete) under three criteria. Significant genotypic variation was identified in cereals in the ability to take up and utilise P from poorly soluble iron phosphate, although all genotypes were able to utilise this source of P to some degree. [30]

5.6.1 Managing phosphorus

Place P with or near the seed at seeding time or band prior to seeding. High application rates can lead to both salt burning of the seedlings and a thin plant stand, reducing potential yield. [31]

Rye has been found to be more efficient in taking up and utilising P than wheat at low rates of P supply. [32]

Symptoms

Paddock:

- Smaller, lighter green plants with necrotic leaf tips, generally on sandier parts of the paddock or between header or swathe rows.
- Plants look unusually water-stressed despite adequate environmental conditions (Photo 3).
- Affected areas are more susceptible to leaf diseases.

Plant:

- In early development, usually in cases of induced P deficiency, seedlings appear to be pale olive green and wilted (Photos 4 and 5).
- On older leaves, chlorosis starts at the tip and moves down the leaf on a front, while the base of the leaf and the rest of the plant remain dark green. Unlike N deficiency, necrosis (death) of these chlorotic (pale) areas is rapid, with the tip becoming orange to dark brown and shrivelling, while the remainder turns yellow. At this stage, the second leaf has taken on the early symptoms of P deficiency.

30 LD Osborne, Z Rengel (2002) Genotypic differences in wheat for uptake and utilisation of P from iron phosphate. *Australian Journal of Agricultural Research* 53, 837–844, http://www.publish.csiro.au/cp/AR01101

31 Alberta Government (2016) Fall rye production. Alberta Agriculture and Forestry, http://www1.agric.gov.ab.ca/$department/deptdocs.nsf/all/agdex1269/$file/117_20-1.pdf

32 LD Osborne, Z Rengel (2002) Genotypic differences in wheat for uptake and utilisation of P from iron phosphate. *Australian Journal of Agricultural Research* 53, 837–844, http://www.publish.csiro.au/cp/AR01101

- By tillering, uncommon symptoms of severe deficiency are dull, dark green leaves with slight mottling of the oldest leaf.

Photo 3: *Stunted early growth with reduced tillers in phosphorus-deficient crop on the left.*

Source: Department of Agriculture and Food Western Australia

Photo 4: *Phosphorus-deficient plants on the left are later maturing with fewer smaller heads.*

Source: Department of Agriculture and Food Western Australia

VIDEOS

WATCH: GCTV13: Phosphorus deficiency.

WATCH: Over the Fence North: Deep P placement delivers yield return on Darling Downs.

Photo 5: *Phosphorus-deficient plants with dark leaves and necrosis moving down from the tip of the oldest leaf.*

Source: Department of Agriculture and Food Western Australia

Plants have a high requirement for P during early growth. Because P is relatively immobile in the soil, topdressed or sprayed fertiliser cannot supply enough to correct a deficiency.

Phosphorus does leach on sands of very low PBI (a measure of P retention), particularly on coastal plains. Topdressing is effective on these soils. [33]

What else could it be?

Nitrogen deficiency, molybdenum deficiency or potassium deficiency

Similarities: Small, less tillered and light green plants.

Differences: Phosphorus-deficient plants are thinner with darker leaves and tip death of older leaves without leaf yellowing.

5.7 Sulfur

Historically, adequate S has been supplied by mineralisation from organic matter, from co-application as a nutrient in N and P fertilisers (sulfate of ammonia and superphosphate) or via the presence of calcium sulfate layers in root-accessible layers of the subsoil.

However, with the increased use of high-analysis N and P fertilisers low in S, deficiency in crops is increasing, especially in wet years due to leaching. Sulfur deficiency appears to be a complex interaction between seasonal conditions, crop

33 DAFWA (2015) Diagnosing phosphorus deficiency in wheat. Department of Agriculture and Food Western Australia, May 2015, https://agric.wa.gov.au/n/1996

species and plant availability of subsoil S. This affects the ability of the soil S test to predict plant-available S. Deficiencies may be more evident in wet years due to S leaching. [34]

Deficiency symptoms

Paddock:

- Look for areas of pale plants (Photo 6).

Plant:

- Plants grow poorly and lack vigour with reduced tillering, delayed maturity and lower yields and protein levels.
- Youngest leaves are affected first and most severely.
- Leaves on deficient plants leaves turn pale with no stripes or green veins but generally do not die and growth is retarded and maturity delayed (Photo 7).
- With extended deficiency the entire plant becomes lemon yellow and stems may become red.

Photo 6: *Areas of pale plants characterise sulfur deficiency (note, however, that many nutrient deficiencies also exhibit pale patches).*

Source: Department of Agriculture and Food Western Australia

34 GRDC (2014) Crop nutrition fact sheet: soil testing crop nutrition, northern region. Grains Research and Development Corporation, January 2014, www.grdc.com.au/GRDC-FS-SoilTestingN

Photo 7: *Leaves remain healthy despite the yellowing in a sulfur-deficient plant.*

Source: Department of Agriculture and Food Western Australia

Topdressing 10–15 kg per hectare of sulfur as gypsum or ammonium sulfate will overcome deficiency symptoms. Foliar sprays generally cannot supply enough sulfur for plant needs. [35]

What else could it be?

Condition	Similarities	Differences
Iron deficiency	Pale new growth	Iron-deficient plants have interveinal chlorosis
Group B herbicide damage	Seedlings with pale new leaves	Plants generally recover from Group B herbicide damage and leaves often have interveinal chlorosis
Waterlogging, nitrogen deficiency, molybdenum deficiency or manganese deficiency	Pale growth	The youngest leaves of S-deficient plants are affected first, whereas the middle or older leaves are affected first with waterlogging, manganese, N and molybdenum deficiency

5.8 Potassium

- Potassium deficiency is an emerging issue in northern cropping soils.
- Soil and plant testing is the most effective means of determining K requirements.

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

- It is important to maintain adequate K in soil; once deficiency symptoms emerge, costly fertiliser applications will be required. [36]
- Rye can recycle K from deeper in the soil profile for future crop use. [37]

Potassium is an essential plant nutrient. It has many functions including the regulation of the opening and closing of stomata—the 'breathing holes' on plant leaves that control moisture loss from the plant. Adequate K increases vigour and disease resistance of plants, and helps to form and move starches, sugars and oils. Available K exists as an exchangeable cation associated with clay particles and humus. Rye increases the concentration of exchangeable K near the soil surface by bringing it up from lower in the soil profile.

Potassium deficiency

Throughout Queensland's cropping regions there has been a gradual decline in soil K levels due to crop removal of K and low fertiliser application rates. In particular, grain growers on Red Ferrosol soils in the inland Burnett region have increasingly encountered K deficiency over the last 10 years due to the lower available reserves in these soils. The problem is also increasingly evident on medium–heavy cracking clay soils. Cotton, legumes and hay baling/silage systems have had a particularly large impact on K reserves in some soils.

Crops may vary in their response to K fertiliser application, and in winter cereals, responses are generally low unless large deficiencies are present. Although significant soil K reserves still exist in many Queensland cropping soils, particularly the heavier alluvial and cracking clay soils, it is important to maintain soil reserves by replacing the K removed in harvested products. If K depletion is allowed to the extent that crop productivity is affected, heavy and very costly fertiliser applications will be required. [38]

What to look for

Paddock:

- Smaller lighter green plants with necrotic leaf tips, generally on sandier parts of the paddock or between header or swathe rows (Photo 8).
- Plants look unusually water-stressed despite adequate environmental conditions.
- Affected areas are more susceptible to leaf disease.

Plant:

- Plants appear paler and weak (Photo 9).
- Older leaves are affected first with leaf tip death and progressive yellowing and death down from the leaf tip and edges. There is a marked contrast in colour between yellow leaf margins and the green centre.
- Yellowing leaf tip and leaf margins sometimes generates a characteristic green 'arrow' shape towards leaf tip.

36 Soil Quality Pty Ltd. Potassium—Queensland. Soil Quality, http://www.soilquality.org.au/factsheets/potassium-queensland

37 N Rector, T Harrigan, DR Mutch, S Snappe (2009) Cereal rye: manure and livestock's new best friend. Manure $ense. Michigan State University, February 2009

38 Soil Quality Pty Ltd. Potassium—Queensland. Soil Quality, http://www.soilquality.org.au/factsheets/potassium-queensland

Photo 8: *Header rows in potassium-deficient crops have lesser symptoms.*

Source: Department of Agriculture and Food Western Australia

Photo 9: *Potassium-deficient plants may display floppy older leaves and furled flag leaf from water stress. Affected plants are paler, weak and more susceptible to leaf disease. Discoloured leaf tissue can be bright yellow.*

Source: Department of Agriculture and Food Western Australia

Topdressing K will generally correct the deficiency. Foliar sprays generally cannot supply enough K to overcome a severe deficiency and can scorch crops. [39]

What else could it be?

Condition	Similarities	Differences
Molybdenum deficiency	Pale plants with leaf tip death	Potassium-deficient plants do not have white or rat-tail heads, and have more marked contrast between yellow and green sections of affected leaves
Nitrogen deficiency	Pale plants with oldest leaves most affected	Potassium-deficient plants have more marked leaf tip death and contrast between yellow and green sections of affected leaves, and tillering is less affected
Spring drought	Water-stressed plants with older leaves dying back from the tip, yellowing progressing down from tip and edges and often leaf death occurs	The main difference is that K deficiency is more marked in high growth plants in good seasons
Root-lesion nematode	Smaller, water-stressed pale plants	Root-lesion nematode affected plants have 'spaghetti' roots with few feeder roots

39 DAFWA (2015) Diagnosing potassium deficiency in wheat. Department of Agriculture and Food Western Australia, April 2015, https://agric.wa.gov.au/n/1997

Assessing potassium requirements

Soil and plant tissue analysis together give insight into the availability of K in the soil. Growers should not rely on soil testing alone because results are subject to many potential sources of error.

Tissue analysis of whole shoots of crop plants will determine whether a deficiency exists but this does not define a K requirement. These results are generally too late to be useful in the current season, but inform the need to assess K requirements for the next crop.

Potassium available in the soil is measured by the Colwell K or exchangeable K soil tests. The amount of K needed for plant nutrition depends on soil texture (Table 4).

Table 4: *Critical soil test thresholds for potassium (Colwell K, µg/g).*

	Deficient	Moderate	Sufficient
Cereal, canola, lupins etc. [40]	<50	50–70	>70
Pasture legumes [41]	<100 (sand) <150 (clay loam)	100–140 (sand) 150–180 (clay loam)	>140 (sand) >180 (clay loam)

Source: Soil Quality Pty Ltd

Sandy soils require less K to be present, but are more likely to show deficiencies. Clay soils require more K to be present, but are more capable of supplying replacement K through the weathering of clay minerals.

Potassium lost through product removal should be replaced once K levels in paddocks fall below sufficient levels, rather than waiting for deficiency symptoms to appear. Replacement requirements for each crop differ, and this must be accounted for when budgeting K requirements for the coming season. [42]

5.9 Micronutrients

Important micronutrients for rye are boron, copper, Fe, manganese, zinc (Zn) and molybdenum. Rye response to micronutrients is generally low, except Zn.

5.9.1 Zinc

Zinc deficiency is a nutritional constraint for crop production in Australia and is particularly widespread in cereals growing on calcareous soil. Rye has a higher Zn-use efficiency than other cereals. Rye possesses exceptional ability to grow and yield well on severely Zn-deficient calcareous soils and it is therefore regarded as Zn-efficient. [43]

Zinc is an essential component of various enzyme systems for energy production, protein synthesis and growth regulation. Zinc-deficient plants exhibit delayed maturity. The most visible Zn-deficiency symptoms are short internodes and a decrease in leaf size. Zinc shortages are mostly found in sandy soils, which tend to be low in organic matter. Deficiency occurs more often during cold, wet conditions and is related to reduced root growth and activity. Zinc uptake by plants decreases with increasing soil pH and is adversely affected by high levels of available P and Fe in soil. [44]

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40 RF Brennan, MJ Bell (2013) Soil potassium—crop response calibration relationships and criteria for field crops grown in Australia, Crop & Pasture Science 64, 514–522, http://www.publish.csiro.au/cp/CP13006

41 CJP Gourley, AR Melland, RA Waller, IM Awty, AP Smith, KI Peverill, MC Hannah (2007) Making better fertiliser decisions for grazed pastures in Australia. Department of Primary Industries Victoria, June 2007, http://www.asris.csiro.au/downloads/BFD/Making%20Better%20Fertiliser%20Decisions%20for%20Grazed%20Pastures%20in%20Australia.pdf

42 Soil Quality Pty Ltd. Potassium—NSW. Soil Quality , http://www.soilquality.org.au/factsheets/potassium-nsw

43 I Cakmak, H Ekiz, A Yilmaz, B Torun, N Köleli, I Gültekin, A Alkan, S Eker (1997). Differential response of rye, triticale, bread and durum wheats to zinc deficiency in calcareous soils. *Plant and Soil* 188, 1–10, http://link.springer.com/article/10.1023/A:1004247911381

44 RH Schlegel (2013) Rye: genetics, breeding, and cultivation. CRC Press, https://www.crcpress.com/Rye-Genetics-Breeding-and-Cultivation/Schlegel/p/book/9781466561434

Deficiency symptoms

Paddock:

- Patchy growth of stunted plants with short thin stems and usually pale green leaves.
- Heavily limed soils, sands and gravels or alkaline grey clays tend to be most affected.
- Zinc deficiency symptoms are usually seen on young seedlings early in the growing season.

Plant:

- Young to middle leaves develop yellow patches between the mid-vein and edge of the leaf and extend lengthways towards the tip and base of the leaf. This stripe may occur only on one side of the mid-vein.
- The areas eventually die turning pale grey or brown.
- The leaf changes from green to a muddy greyish-green in the central areas of middle leaves.
- Stunted plants often have 'diesel-soaked' leaves, showing dead areas about halfway along the leaves, causing them to bend and collapse in the middle section (Figure 13).
- Maturity is delayed. [45]

Photo 10: *In zinc-deficient plants, leaves yellow and die and can show a 'tramline effect'. Necrosis halfway along middle and older leaves causes them to droop.*

Source: Department of Agriculture and Food Western Australia

45 DAFWA (2015) Diagnosing zinc deficiency in wheat. Department of Agriculture and Food Western Australia, June 2015, https://agric.wa.gov.au/n/1999

What else could it be?

Condition	Similarities	Differences
Manganese deficiency	Leaf kinking, pale lesions, streaks and wilted plants	Manganese-deficient plants are very pale, are more common as patches of limp dying plants and lack the parallel necrotic tramlines adjoining the midrib
Wheat streak mosaic virus	Stunted plants with many tillers and striped leaf lesions	Zinc-deficient plants have pale linear spots or lesions that can develop into parallel tramlines and lack vivid yellow streaks towards the leaf tip
Yellow dwarf virus	Stunted plants with many tillers and striped leaf lesions	Zinc-deficient plants have pale linear spots or lesions that can develop into parallel tramlines and lack vivid yellow streaks towards the leaf tip

IN FOCUS

Differential response of rye, triticale, bread and durum wheats to zinc deficiency in calcareous soils

Field and greenhouse experiments were carried out to study the response of rye, triticale, two bread wheats, and two durum wheats to Zn deficiency and Zn fertilisation in severely Zn-deficient calcareous soils (DTPA-extractable Zn, 0.09 mg/kg soil). The first visible symptom of Zn deficiency was a reduction in shoot elongation followed by the appearance of whitish brown necrotic patches on the leaf blades. These symptoms were either absent or only slight in rye and triticale, but occurred more rapidly and severely in wheats, particularly in durum wheats. The same was true for the decrease in shoot dry matter production and grain yield. For example, in field experiments, at the milk stage, decreases in shoot dry matter production due to Zn deficiency were absent in rye, and were on average 5% in triticale, 34% in bread wheats and 70% in durum wheats. Zinc fertilisation had no effect on grain yield in rye but enhanced grain yield of the other cereals. Zinc efficiency of cereals, expressed as the ratio of yield (shoot dry matter or grain) produced under Zn deficiency compared with Zn fertilisation were, on average, 99% for rye, 74% for triticale, 59% for bread wheats and 25% for durum wheats.

These distinct differences among and within the cereal species in susceptibility to Zn deficiency were closely related to the total amount (content) of Zn per shoot, but not related to Zn concentrations in shoot dry matter. For example, the most Zn-efficient rye and the Zn-inefficient durum wheat cultivar C-1252 did not differ in shoot Zn concentration under Zn deficiency, but the total amount of Zn per whole shoot was approximately six-fold higher in rye than the durum wheat. When Zn was applied, rye and triticale accumulated markedly more Zn both per whole shoot and per unit shoot dry matter than wheats.

The results demonstrate an exceptionally high Zn efficiency of rye and show that among the cereals studied, Zn efficiency declines in the order rye > triticale > bread wheat > durum wheat (Figure 4). The differences in expression of Zn efficiency are possibly related to a greater capacity of efficient genotypes to acquire Zn from the soil relative to inefficient genotypes. [46]

46 I Cakmak, H Ekiz, A Yilmaz, B Torun, N Köleli, I Gültekin, A Alkan, S EkerS (1997). Differential response of rye, triticale, bread and durum wheats to zinc deficiency in calcareous soils. *Plant and Soil* 188, 1–10, http://link.springer.com/article/10.1023/A:1004247911381

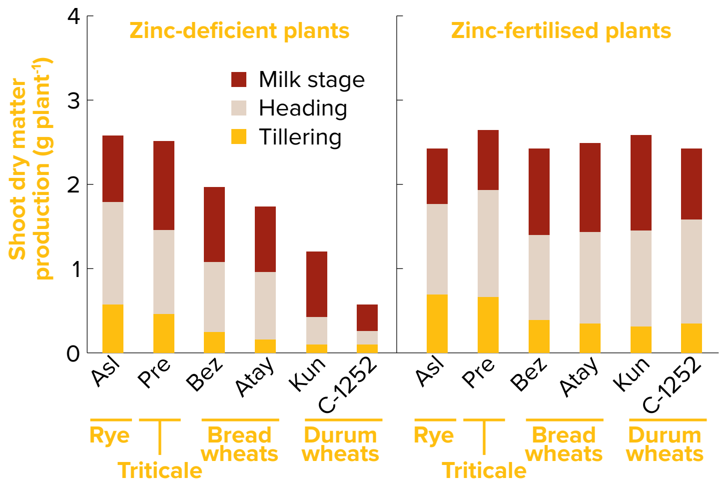

Figure 4: *Dry matter production of different cereals (ASL, Aslim; PRE, Presto; BEZ, Bezostaja-1; ATAY, Atay-85; KUN, Kunduru-1149) grown in the field experiment without and with zinc fertilisation (23 kg Zn/ha) in a Zn-deficient calcareous soil. Plants (main tillers) were sampled at the tillering, heading and milk stages, respectively 105, 144 and 168 days after 1 January.* [47]

Managing zinc deficiency:

- Foliar spray (effective only in current season) or drilled soil fertiliser.
- Zinc foliar sprays need to be applied as soon as deficiency is detected to avoid irreversible damage.
- Zinc is immobile in the soil; therefore, topdressing is ineffective, only being available to the plant when the topsoil is wet.
- Mixing Zn throughout the topsoil improves availability through more uniform nutrient distribution.
- Zinc drilled deep increases the chances of roots being able to obtain enough Zn when the topsoil is dry.
- Zinc seed treatment is used to promote early growth where root disease is a problem, but the level is lower than a plant needs in the current season.
- Zinc present in compound fertilisers often meets the current requirements of the crop. [48]

47 I Cakmak, H Ekiz, A Yilmaz, B Torun, N Köleli, I Gültekin, A Alkan, S Eker (1997). Differential response of rye, triticale, bread and durum wheats to zinc deficiency in calcareous soils. *Plant and Soil* 188, 1–10, http://link.springer.com/article/10.1023/A:1004247911381

48 DAFWA (2015) Diagnosing zinc deficiency in wheat. Department of Agriculture and Food Western Australia, June 2015, https://agric.wa.gov.au/n/1999

IN FOCUS

Role of rye chromosomes in improvement of zinc efficiency in wheat and triticale

Disomic wheat–rye addition lines (*Triticum aestivum* L., cv. Holdfast–*Secale cereale* L., cv. King-II) and an octoploid triticale line (×Triticosecale Wittmark L. Pluto × Fakon), as well as the respective wheat and rye parents, were used to study the role of rye chromosomes on the severity of Zn deficiency symptoms, shoot dry matter production, Zn efficiency, shoot Zn concentration and Zn content. Plants were grown in a greenhouse in a Zn-deficient calcareous soil with and without Zn supply at 10 mg/kg soil. Zinc efficiency was calculated as the ratio of dry weight produced under Zn deficiency to the dry weight produced under Zn fertilisation. In the experiments with addition lines, visual Zn deficiency symptoms were slight in the rye cv. King-II, but were severe in the wheat cv. Holdfast. The addition of rye chromosomes, particularly 1R, 2R and 7R, into Holdfast reduced the severity of deficiency symptoms. Holdfast showed greater decreases in shoot dry matter production through Zn deficiency and thus had a low Zn efficiency (53%). King-II was less affected by Zn deficiency and had a higher Zn efficiency (89%). With the exception of the 3R line, all addition lines had higher Zn efficiency than their wheat parent: the 1R line had the highest Zn efficiency (80%). In the experiment with the triticale cultivar and its parents, rye cv. Pluto and wheat cv. Fakon, Zn deficiency symptoms were absent in Pluto, slight in triticale and very severe in Fakon. Zinc efficiency was 88% for Pluto, 73% for triticale and 64% for Fakon. Such differences in Zn efficiency were better related to the total amount of Zn per shoot than to the amount of Zn per unit dry weight of shoot. In the rye cultivars, Zn efficiency was closely related to Zn concentration. Triticale was more similar to rye than wheat regarding Zn concentration and Zn accumulation per shoot under both Zn-deficient and Zn-sufficient conditions.

The results show that rye has an exceptionally high Zn efficiency, and the rye chromosomes, particularly 1R and 7R, carry the genes controlling Zn efficiency. [49]

5.9.2 Iron

Iron (Fe) is involved in the production of chlorophyll and is a component of many enzymes associated with energy transfer, N reduction and N_2 fixation, and lignin formation. Iron deficiencies are mainly manifested as yellow leaves due to low levels of chlorophyll. Leaf yellowing first appears on the younger upper leaves in interveinal tissues. Severe Fe deficiencies cause the leaves to turn completely yellow or almost white, and then brown as leaves die.

Iron deficiencies are found mainly in alkaline soils, although some acidic, sandy soils, low in organic matter, may also be Fe-deficient. Cool, wet weather enhances Fe deficiencies, especially in soils with marginal levels of available Fe. Poorly aerated or compacted soils also reduce iron uptake. High levels of available P, manganese and Zn in soils can also reduce Fe uptake. [50]

49 I Cakmak, R Derici, B Torun, I Tolay, HJ Braun, R Schlegel (1997) Role of rye choromosomes in improvement of zinc efficiency in wheat and triticale. *Developments in Plant and Soil Sciences* 78, 237–241, http://link.springer.com/chapter/10.1007%2F978-94-009-0047-9_65

50 RH Schlegel (2013) Rye: genetics, breeding, and cultivation. CRC Press, https://www.crcpress.com/Rye-Genetics-Breeding-and-Cultivation/Schlegel/p/book/9781466561434

Symptoms

Paddock:

- Pale plants particularly in waterlogged or limed areas (Photo 11).

Plant

- Youngest growth is affected first and most severely.
- Symptoms begin with young leaves turning pale green or yellow.
- Interveinal areas become yellow, and in severely deficient plants, the interveinal area turns almost white (Photo 12).
- New growth remains yellow for some time before leaves start to die.
- Old leaves remain pale green and apparently healthy.
- Severely affected plants are stunted with thin spindly stems.

Photo 11: *Iron-deficient plants are pale green to yellow.*

Source: Department of Agriculture and Food Western Australia. Photo: courtesy CSIRO Publishing

Photo 12: *Pale yellow, iron-deficient leaves, most showing prominent green veins (right) compared with dark green, healthy leaf (left).*

Source: Department of Agriculture and Food Western Australia

What else could it be?

Condition	Similarities	Differences
Sulfur deficiency	Pale plants with pale new growth	Sulfur-deficient plants do not have interveinal chlorosis
Group B herbicide damage	Pale seedlings with interveinal chlorosis on new leaves	Herbicide-damaged plants generally recover and are not restricted to waterlogged areas
Waterlogging, N deficiency, molybdenum deficiency or manganese deficiency	Pale growth	Middle or older leaves are affected first

Managing iron deficiency:

- No yield responses to Fe to justify soil application.
- Where symptoms occur, particularly in cold and wet conditions, they are frequently eliminated by increased soil and air temperatures.
- Foliar sprays will remove the symptoms where they occur in highly calcareous or limed soils. [51]

5.9.3 Copper

Copper (Cu) is necessary for carbohydrate and N metabolism. Inadequate Cu results in stunting. Copper is also required for lignin synthesis which is needed for cell wall strength and prevention of wilting. Deficiency symptoms of Cu are dieback of stems, yellowing of leaves, stunted growth and pale green leaves that wither easily. Deficiencies of Cu are mainly reported in sandy soils low in organic matter. Copper uptake decreases as soil pH increases. Increased P and Fe availability in soils decreases Cu uptake by plants. Rye is efficient at taking up available Cu from the soil. [52]

Deficiency symptoms

Paddock:

- Before head emergence, deficiency shows as areas of pale, wilted plants with dying new leaves in an otherwise green healthy crop (Photo 13).
- 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 on recently limed paddocks.

Plant:

- Youngest growth is affected first.
- First sign of Cu deficiency before flowering is growing point death and tip withering, and/or bleaching and twisting up to half the length of young leaves (Photo 14).
- Base of the leaf can remain green.
- Old leaves remain green, but paler than normal.
- Tiller production may increase but die prematurely.
- Mature plants are dull grey-black in colour with white or stained empty or 'rat-tail' heads.
- Grain in less severely affected plants may be shrivelled. Heads with full grain droop due to weak stems.

51 DAFWA (2015) Diagnosing iron deficiency in wheat. Department of Agriculture and Food Western Australia, May 2015, https://agric.wa.gov.au/n/1991

52 RH Schlegel (2013) Rye: genetics, breeding, and cultivation. CRC Press, https://www.crcpress.com/Rye-Genetics-Breeding-and-Cultivation/Schlegel/p/book/9781466561434

Photo 13: *Copper-deficient plants have pale necrotic flag leaves at head emergence.*

Source: Department of Agriculture and Food Western Australia

Photo 14: *A copper-deficient plant showing a partly sterile head and twisted flag leaf.*

Source: Department of Agriculture and Food Western Australia

What else could it be?

Condition	Similarities	Differences
False black chaff	Discoloration on the upper stem and glumes	False black chaff does not affect yield or grain quality
Molybdenum deficiency	White heads and shrivelled grain	Molybdenum deficiency affects middle leaves first rather than the youngest leaf
Boron deficiency	Youngest leaf death	Boron-deficient plants are dark rather than light green and affected leaves have marginal notches and split near the base
Stem and head frost damage	White heads, shrivelled grain, late tillers and delayed maturity	Spring frost does not cause death or twisting of the flag leaf and is location-specific (frost-prone areas)
Take-all	White heads and shrivelled grain	Take-all causes blackened roots and crowns and often kills the plant

Managing copper deficiency:

- Foliar spray (only effective in the current season) or drilled soil fertiliser.
- Copper foliar sprays are not effective after flowering because sufficient Cu is required pre-flowering for pollen development.

- Mixing Cu throughout the topsoil improves availability due to more uniform nutrient distribution.
- As Cu is immobile in the soil, topdressing is ineffective, only being available to the plant when the topsoil is wet.
- In long-term, no-till paddocks frequent small applications of Cu via drilled or in-furrow application reduces the risk of plant roots not being able to obtain the nutrient in dry seasons.
- Copper drilled deep increases the chances of roots being able to obtain enough Cu when the topsoil is dry.
- Copper seed treatment is insufficient to for plant requirements in the current season. [53]

5.9.4 Manganese

Rye has been found to be tolerant of manganese (Mn) deficiency in soils in South Australia, where it produced 100% relative grain yields, and did not respond to Mn fertiliser. It was therefore regarded as Mn-efficient. [54]

Deficiency symptoms

Paddock:

- Manganese deficiency often appears as patches of pale, floppy plants in an otherwise green healthy crop (Photo 15).

Plant:

- Frequently, plants are stunted and occur in distinct patches.
- Initially, middle leaves are affected, but it can be difficult to determine which leaves are most affected because symptoms rapidly spread to other leaves and the growing point (Photo 16).
- Leaves develop interveinal chlorosis and/ or white necrotic flecks and blotches.
- Leaves often kink, collapse and eventually die.
- Tillering is reduced, with extensive leaf and tiller death. With extended deficiency, the plant may die.
- Surviving plants produce fewer and smaller heads.

53 DAFWA (2015) Diagnosing copper deficiency in wheat. Department of Agriculture and Food Western Australia, May 2015, https://agric.wa.gov.au/n/1990

54 RD Graham, WJ Davies, DBH Sparrow, JS Ascher (1983). Tolerance of barley and other cereals to manganese-deficient calcareous soils of South Australia. In Genetic aspects of plant nutrition, pp. 339–345, Springer, https://link.springer.com/chapter/10.1007/978-94-009-6836-3_40

Photo 15: *Manganese-deficient plants showing as patches of pale floppy plants in otherwise healthy crop.*

Source: Department of Agriculture and Food Western Australia

Photo 16: *Middle leaves are affected first by manganese deficiency, showing as yellowing and necrosis.*

Source: Department of Agriculture and Food Western Australia

What else could it be?

Condition	Similarities	Differences
Zinc deficiency	Pale plants with interveinal chlorosis and kinked leaves	Differences include linear tramline necrosis on Zn-deficient plants. Manganese-deficient plants are more yellow and wilted
Nitrogen deficiency	Pale plants	Nitrogen-deficient plants do not show wilting, interveinal chlorosis, leaf kinking and death
Waterlogging	Pale plants	Waterlogged plants do not show wilting, interveinal chlorosis, leaf kinking and death
Iron deficiency	Pale plants	New leaves are affected first and plants do not die
Sulfur deficiency	Pale plants	New leaves are affected first and plants do not die

Managing manganese deficiency:

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

- Seed Mn coating treatments have little effect in correcting the deficiency. [55]

5.9.5 Aluminium

The ability of crops to overcome aluminium (Al) toxicity varies among species and cultivars. Among the wheat family, rye is considered the most Al-tolerant species. For example, when three cereal ryes, three durum wheats and 30 triticales were sown in a gravel bed with solutions containing 0, 5, 10, 15, 20 and 40 Al µg/g, the cereal ryes tested were found to be very tolerant of Al. [56]

IN FOCUS

Aluminium long-term stress differently affects photosynthesis in rye genotypes

Two rye genotypes differing in Al tolerance (sensitive and tolerant) were exposed to 1.11 and 1.85 mM Al over three weeks. Growth, water status and photosynthesis-related parameters were assessed. After three weeks of Al exposure, both genotypes presented similar decrease in leaf growth. Al-induced relative water content decreased in both genotypes, but was more pronounced in the Al-sensitive cultivar. Aluminium toxicity induced a decrease in net photosynthetic rate only after three weeks of exposure. RuBisCo is an enzyme involved in the first major step of carbon fixation, a process by which atmospheric carbon dioxide is converted by plants and other photosynthetic organisms to energy-rich molecules. For both Al concentration conditions, RuBisCo activity decreased, however, this decrease did not limit glucose accumulation in either of the rye cultivars. This study revealed that Al-induced damages earlier in the growth of the Al-sensitive cultivar, but both genotypes showed long term high susceptibility to Al. Furthermore, the photosynthetic parameters proved to be a good tool to monitor Al-sensitivity and long term exposure showed to be crucial to evaluating Al-sensitivity. [57]

5.10 Nutritional deficiencies

To help identify nutritional deficiencies, see the GRDC's Winter cereal nutrition: the ute guide.

Making use of the crop nutrition information available

As part of the GRDC More Profit from Crop Nutrition (MPCN) extension and training for the southern region project (BWD00021), Birchip Cropping Group (BCG), in conjunction with other grower groups, has been hosting nutrition events across the southern region since 2012.

Many key nutrition areas are being investigated through the MPCN initiative; however, a few immediate resources are available to advisers to help with understanding nutrition and giving such advice.

55 DAFWA (2015) Diagnosing manganese deficiency in wheat. Department of Agriculture and Food Western Australia, May 2015, https://www.agric.wa.gov.au/mycrop/diagnosing-manganese-deficiency-wheat

56 B Scott (1981) Species and varieties for acid soils. Riverina Outlook Conference, http://www.regional.org.au/au/roc/1981/roc198161.htm

57 S Silva, G Pinto, MC Dias, CM Correia, J Moutinho-Pereira, O Pinto-Carnide, C Santos (2012) Aluminium long-term stress differently affects photosynthesis in rye genotypes. *Plant Physiology and Biochemistry* 54, 105–112, https://www.ncbi.nlm.nih.gov/pubmed/22391128

Useful resources:

- eXtension Aus Crop Nutrition: Connecting the lab and the paddock in crop nutrition. This is a group of leading experts in crop nutrition for the Australian grains industry collaborating to provide timely, concise information on crop nutrition issues in Australia. Provides updates on the latest research and articles focusing on strategic management of crop nutrition in the current season.
- Better Fertiliser Decisions for Cropping (BFDC): Fertiliser decisions made by grain growers should all start with, and rely on, knowledge of the fertility status of paddocks. These decisions need to account for the nutrient requirements of plants for growth, nutrient availability in soils, and nutrient losses that can occur during crop growth (e.g. de-nitrification or erosion). BFDC provides the fertiliser industry, agency staff and agribusiness advisors with knowledge and resources to improve nutrient recommendations for optimising crop production. BFDC is recognised by the Fertiliser Industry Federation of Australia as the best available data for supporting the decision tools that fertiliser industry members use to formulate recommendations. [58]

58 A Elliott (2016) Making use of the crop nutrition information available to you. GRDC Update Papers, February 2016, https://grdc.com.au/Research-and-Development/GRDC-Update-Papers/2016/02/Making-use-of-the-crop-nutrition-information-available-to-you

Weed control

Key messages

- Cereal rye is extremely competitive and has an aggressive root system, so it competes well against weeds. [1]
- Because cereal rye matures earlier than other cereal crops, strict harvest and grazing management procedures are important to prevent it from becoming a weed. [2]
- Consider Integrated Weed Management (IWM) practices when controlling weeds.
- When selecting a herbicide, it is important to know the crop growth stage, weeds present and plant-back period. Herbicides must be applied at the correct stage of crop growth, or significant yield losses may occur.
- Check product labels for up-to-date registrations and application methods.
- Use practices that minimise the risk of development of herbicide resistance.

Weeds are estimated to cost Australian agriculture AU$2.5–4.5 billion per annum. For winter cropping systems alone, the cost is $1.3 billion. Consequently, any practice that can reduce the weed burden is likely to generate substantial economic benefits to growers and the grains industry (Photo 1).

Photo 1: *Annual ryegrass (Lolium rigidum) is one of the most problematic weeds in Australia.*

Source: FarmPress

6.1 Cereal rye: a weed suppressor

Rye is one of the best cool-season crops for outcompeting weeds, especially small-seeded, light-sensitive annuals. Weed biomass has been found to decrease with increasing rye residue, with weeds completely suppressed at levels of residue above 1500 g per m^2. [3] Rye can effectively suppress weeds by shading, competition and allelopathy.

Based on research from southern New South Wales (NSW), the competitiveness of crops against annual ryegrass (*Lolium rigidum*, at 300 plants per m^2) was in the order oats > cereal rye > triticale > oilseed rape > barley > wheat > field pea > lupin. [4]

1 UVM Extension Crops & Soils Team (2011) Cereal rye. Northern Grain Growers Association, http://northerngraingrowers.org/wp-content/uploads/RYE.pdf

2 Atlas of living Australia Ryecorn. http://bie.ala.org.au/species/http://id.biodiversity.org.au/node/apni/2905471

3 MR Ryan, SB Mirsky, DA Mortensen, JR Teasdale, WS Curran (2011) Potential synergistic effects of cereal rye biomass and soybean planting density on weed suppression. Weed Science 59(2), 238–246, https://pubag.nal.usda.gov/pubag/downloadPDF.xhtml?id=49636&content=PDF

4 D Lemerle, B Verbeek, N Coombes (1995) Losses in grain yield of winter crops from *Lolium rigidum* competition depend on crop species, cultivar and season. *Weed Research* 35, 503–509, http://onlinelibrary.wiley.com/doi/10.1111/j.1365-3180.1995.tb01648.x/abstract

A study in southern NSW found that, in the first year, residues of cereal rye were no more effective, and in some cases less effective, against fleabane than residues of other cereals. However, all of the residues showed greater suppression of establishment of summer annual weeds than occurred in border areas without stubble. In the second year, cereal rye residue was equal best for suppression of both fleabane and witchgrass. Some crops were clearly more suppressive of in-crop weeds, including rye, likely due to reduced light at the soil surface and competitive canopy architectures. [5]

6.1.1 Allelopathic effects

Cereal rye produces several compounds in its tissues and releases root exudates that apparently inhibit germination and growth of weed seeds. These allelopathic effects, together with cereal rye's ability to smother other plants of cool weather growth, make it a good choice for weed control.

The allelopathic effects of rye have been shown in field and laboratory studies to inhibit germination of some triazine-resistant weeds (barnyard grass, willow herb, horseweed). [6]

Rye has also been found to reduce total weed density an average of 78% when rye residue covered more than 90% of soil in a no-till study in Maryland, United States [7].

Growers can increase the weed-suppressing effect of rye by planting it with an annual legume. However, do not expect complete weed control, and complement with weed-management measures. Thick stands ensure excellent weed suppression. To extend the weed-management benefits of rye, allow its allelopathic effects to persist longer by leaving killed residue on the surface rather than incorporating it. Allelopathic effects usually taper off after about 30 days.

After harvesting or removing rye, it is best to wait three–four weeks before planting small-seeded crops. Be aware that rye seedlings have more allelopathic compounds than the mature rye residues, with allelopathic effects usually lasting about 30 days. Transplanted vegetables and larger seeded species, especially legumes, are less susceptible to the allelopathic effects of rye. In one study, use of a mechanical under-cutter to sever roots when rye was at mid–late bloom—and leaving residue intact on the soil surface (as whole plants)—increased weed suppression compared with incorporation or mowing.

If weed suppression is an important objective when planting a rye–legume mixture, plant early enough for the legume to establish well. Otherwise, a pure stand is likely to work better. [8]

Remove cereal rye early to avoid problems from its allelopathic effect

It is usually the decaying green 'ooze' from cereal rye that can create problems for germinating grasses (such as maize), rather than the herbicide used to kill the rye (Photo 2). This toxic effect of the dying rye is what makes it a good cover crop choice for organic producers. A good rye stand reduces weed problems while the rye is growing. Producers then roll down the rye to terminate it (no herbicide is used) and plant their broadleaf crop. The decaying rye affects the germinating grasses, greatly reducing the grass-weed pressure while the crop is becoming established. The cover provided by the rye also reduces weed pressure by providing a mulch and by keeping the sun off the soil surface until the crop canopy forms.

5 L Weston, R Stanton, H Wu, J Mwendwa, P Weston, J Weidenhamer, W Brown. (2015). GRDC Update Papers: Impact of crop residues on summer fallow weeds. https://grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2015/02/impact-of-crop-residues-on-summer-fallow-weeds

6 T Przepiorkowski, SF Gorski (1994) Influence of rye (Secale cereale) plant residues on germination and growth of three triazine-resistant and susceptible weeds. *Weed Technology* 8, 744–747, https://www.jstor.org/stable/3988190?seq=1#page_scan_tab_contents

7 JR Teasdale, CE Beste, WE Potts (1991) Response of weeds to tillage and cover crop residue. *Weed Science* 39, 195–199, http://www.jstor.org/stable/4044915?seq=1#page_scan_tab_contents

8 A Clark (Ed.) (2007) Cereal rye. In Managing cover crops profitably. 3rd ed. SARE Outreach Handbook Series Book 9. National Agricultural Laboratory, http://www.sare.org/Learning-Center/Books/Managing-Cover-Crops-Profitably-3rd-Edition/Text-Version/Nonlegume-Cover-Crops/Cereal-Rye

In no-till situations, when using a cereal rye cover crop, it is best to spray out the rye two–three weeks before planting subsequent crops, so that the rye is brown before planting. Rye should not be sprayed out five–ten days before planting, assuming that glyphosate is being used to kill the rye, because the rye will be decaying as following crop is germinating. For a shorter window before spraying and planting, a different herbicide should be used to kill the cereal rye more quickly so that it is dead brown sooner.

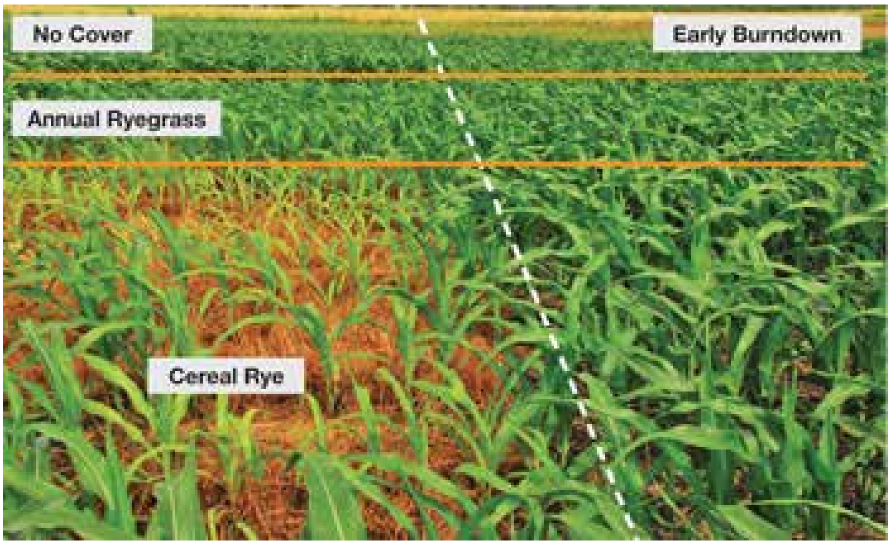

Photo 2: *Effects of a late kill of cereal rye on maize plants. The impact appears to be from a combination of the carbon penalty and allelopathy exerted by the cereal rye.*

Source: AgWeb

Some producers say that the germination problems are minimal if there is no rain to leach the 'ooze' down to the germinating seed during this establishment time. Others report that the germination problems can be reduced by planting the subsequent crop deeper so that not as much of the 'ooze' makes it down to the germinating seed. [9]

6.1.2 Managing volunteer rye

Volunteer rye may contaminate wheat, oats and barley. [10] Once the seed population of cereal rye is established in the soil, it can be a serious weed problem. Rye in wheat reduces yield by competition and reduces quality where its seed contaminates the harvested grain. Crop rotations where neither wheat nor barley is grown for two consecutive years greatly reduces the amount of cereal rye. [11]

Rye is not always a tall, robust plant; under stressful conditions, such as those found in tilled and chemical fallow fields, grassy field edges and roadsides, rye plants can still grow and produce seed despite attaining heights of less than 25 cm (Photo 3).

9 P Jasa (2012) Kill cereal rye early to avoid problems from its allelopathic effect. University of Nebraska, Cropwatch, 4 May 2012, http://cropwatch.unl.edu/kill-cereal-rye-early-avoid-problems-its-allelopathic-effect

10 Manure $ense (2009) Cereal rye: manure and livestock's new best friend. Michigan State University, February 2009

11 A Ogg, R Parker. (2000). Control of Volunteer crop plants. Washington State University. https://research.libraries.wsu.edu/xmlui/bitstream/handle/2376/5254/EB1523E.pdf?sequence=1

Photo 3: *Shorter stands of cereal rye can still produce seed heads.*

Source: NebGuide

Prevent seed source

Preventative methods are a critical part of an IWM control system for volunteer rye. Eliminating potential seed sources for rye establishment is a top priority.

To eliminate seed sources:

1. Plant clean seed. Volunteer rye seed is often found in cereal seed, especially wheat. Growers should buy only certified seed.
2. Remove any volunteer rye before it produces seed. Rye plants as short as 20 cm can produce viable seed.
3. Thoroughly clean harvesters before moving between paddocks.
4. Make sure that all rye is kept out of paddock edges, roadside ditches and other areas that may contaminate paddocks. [12]

Grazing volunteer weeds

Plants vary in their palatability and that under the 'right' stocking rate, animals will selectively graze the more palatable plants. This knowledge is useful when previously grown crops volunteer in the sown crop and herbicides are not available or their use would damage the crop.

For best results;

- introduce sheep early, before crop canopy closes
- use older sheep
- use low stocking rates
- spray weeds along fence line to concentrate sheep in crop
- remove sheep before they do much damage to crop
- remove sheep before flowering.

Observe grazing withholding periods if any chemicals are used in crop. [13]

12 D Lyon, R Klein. (2007). Rye control in winter wheat. NebGuide. http://weedscience.unl.edu/extensionPublications/nebguides/g1483.pdf

13 Grain Legume Handbook (2008). Chapter 5: Weed control. GRDC. https://grdc.com.au/resources-and-publications/all-publications/publications/2008/03/2008-grains-legume-handbook

Cultural practices

Growers can improve wheat's competitiveness with volunteer rye by using cultural practices that stimulate rapid emergence and vigorous seedling growth. For example, deep-banding N fertiliser near wheat seeds at planting, planting larger sized wheat seeds, increasing wheat seeding rates, reducing wheat-row spacing, and planting taller wheat cultivars that tiller profusely are all cultural practices that have been reported to improve wheat's competitiveness with weeds. [14]

These practices exert minimal impact on weeds when used alone, but combining several practices together greatly enhances wheat competitiveness. For example, applying N fertiliser earlier in a fallow season rather than just before planting slightly favours wheat growth over volunteer rye. Mowing can also be effective in controlling volunteer rye because of its tall growth habit and slow development. [15]

Tillage or chemical control of volunteer rye during the fallow period can reduce subsequent populations in the wheat crop similarly over a two-year period.

Chemical control

Grass control herbicides are now available which will control most grassy weeds in pulses. Volunteer cereals can also be controlled with some of these herbicides. Simazine alone and in mixtures with trifluralin in pulses can be used to control some other grasses that are not readily controlled by the specific grass herbicides. [16]

Post-emergence, non-selective herbicides such as glyphosate or paraquat can control volunteer rye and other winter annual grasses found in fallow fields. Glyphosate and paraquat do not provide residual weed control, so any volunteer rye plants that emerge after treatment will not be controlled. When coming in contact with soil, both herbicides are inactivated; therefore, all plants should be emerged prior to application. The effectiveness of both herbicides on volunteer rye decreases as plant size and maturity increase. Glyphosate is labelled for volunteer rye control in wheat as a wiper application. This technique requires at least a 25-cm height differential between the wheat and volunteer rye. Care must be taken to prevent any herbicide from contacting the wheat. Any herbicide that drops or otherwise contacts wheat will result in death. [17]

Selective chemical control of cereal rye may only be partially effective. [18]

Check the AVPMA website for up to date chemical control options.

6.2 Integrated weed management

The Grains Research and Development Corporation (GRDC) supports IWM. Download the Integrated Weed Management Manual.

Integrated weed management is a system for managing weeds over the long term, particularly the management and minimisation of herbicide resistance. There is a need to combine herbicide and non-herbicide methods into an integrated control program. Given that there are additional costs associated with implementing IWM, the main issues for growers are whether it is cost-effective to adopt the system and whether the benefits are likely to be long-term or short-term in nature.

The manual looks at these issues and breaks it down into seven clear sections, assisting the reader to make the development of an IWM plan a simple process.

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14 S Miller, C Alford, W Stump. (). Feral Rye – a serious threat to high quality wheat. University of Wyoming. http://www.wyomingextension.org/agpubs/pubs/B1157.pdf

15 R Anderson. (2004). Control strategies for jointed goatgrass, volunteer rye and downy brome. Central great plains research station. https://www.webharvest.gov/peth04/20041016034012/http://www.akron.ars.usda.gov/fs_control.html

16 Grain Legume Handbook (2008). Chapter 5: Weed control. GRDC. https://grdc.com.au/resources-and-publications/all-publications/publications/2008/03/2008-grains-legume-handbook

17 S Miller, C Alford, W Stump (2004) Feral rye: a serious threat to high quality wheat. University of Wyoming, http://www.wyoextension.org/agpubs/pubs/B1157.pdf

18 A Ogg, R Parker. (2000). Control of Volunteer crop plants. Washington State University. https://research.libraries.wsu.edu/xmlui/bitstream/handle/2376/5254/EB1523E.pdf?sequence=1

Effective strategic and tactical options are available to manage weed competition that will increase crop yields and profitability. Weeds with herbicide resistance are an increasing problem in grain-cropping enterprises. The industry and researchers advise that growers adopt IWM to reduce the damage caused by herbicide-resistant weeds.

The following five-point plan will assist in developing a management strategy in every paddock:

1. Review past actions and history
2. Assess current weed status
3. Identify weed management opportunities
4. Match opportunities and weeds with suitably effective management tactics
5. Combine ideas into a management plan. Use of a rotational plan can assist.

An integrated weed management plan should be developed for each paddock or management zone.

In an IWM plan, each target weed is attacked using tactics from several groups (see links below). Each tactic provides a key opportunity for weed control and is dependent on the management objectives and the target weed's stage of growth. Integrating tactic groups reduces weed numbers, stops replenishment of the seedbank and minimises the risk of developing herbicide-resistant weeds.

IWM tactics:

- Reduce weed seed numbers in the soil
- Control small weeds
- Stop weed seedset
- Hygiene—prevent weed seed introduction
- Agronomic practices and crop competition

Successful weed management also relies on the implementation of the best agronomic practices to optimise crop growth. Basic agronomy and fine-tuning of the crop system are the important steps towards weed management.

Several agronomic practices can improve crop environment and growth, along with the crop's ability to reduce weed competition. These include crop choice and sequence, improving crop competition, planting herbicide-tolerant crops, improving pasture competition, and using fallow phases and controlled traffic or tramlining. [19]

6.2.1 Cover cropping for weed management

The critical period for weed suppression by the cover crop is typically during the first 30 days of cover crop growth. A cover crop's ability to suppress weeds is generally correlated with its early season biomass production rather than its biomass at maturity. Cover crops such as cereal rye maximise light interception with a dense canopy early in the season are the best at suppressing weed growth and weeds seed production (Photo 4). [20]

19 S Peltzer, A Douglas (2016) Crop weeds: integrated weed management (IWM). DAFWA, https://www.agric.wa.gov.au/grains-research-development/crop-weeds-integrated-weed-management-iwm

20 R Smith, RL Bugg, M Gaskell, O Daugovish, M Van Horn, (Eds.) (2011) Cover cropping for vegetable production: A Grower's Handbook (Vol. 3517). UCANR Publications.

Photo 4: *Effect of seeding rate on weed suppression of a 90% legume and 10% cereal rye mixed cover crop. The higher seeding rate (left) was more effective in suppressing weeds than the lower seeding rate (right) which saw the emergence of weeds.* [21]

Research in NSW examined the ability of various grain crops and their residues, including cereal rye, to suppress weeds until subsequent planting the following year. Experiments were performed over three years in low-input grain production systems with moderate winter rainfall (<550 mm) without irrigation. Crops generally proved competitive with weeds during their establishment and growth. In addition, remaining crop residues were suppressive to summer annual weed establishment compared with borders without stubble. Some crops were clearly more suppressive of in-crop weeds, including rye, grazing and cereal barley, grazing and cereal wheat, and grazing and grain canola. In the third year of the study, cereal rye, oats and canola showed the greatest total weed suppression at 224 days after planting. [22]

Suppression of the grass weed annual ryegrass by rye, wheat and triticale was compared in field trials at Wagga Wagga in 1993. Cereal rye and triticale were more competitive than wheat, with a biomass of annual ryegrass at maturity of 70 g/m^2 with triticale compared with 170 g/m^2 with wheat. Early seedling vigour, superior height and broad leaves appeared to influence the greater competitive ability of the triticale and cereal rye. [23]

6.3 Weeds in Northern cropping systems

Weed management, particularly in reduced tillage fallows, has become an increasingly complex and expensive part of cropping in the Northern grains region. Heavy reliance on glyphosate has selected for species that were naturally more glyphosate tolerant or has selected for glyphosate-resistant populations. The four key weeds that are causing major cropping issues are:

- awnless barnyard grass (ABYG) (*Echinochloa colona*)
- flaxleaf fleabane (*Conyza bonariensis*)
- feathertop Rhodes grass (FTR) (*Chloris virgata*)
- windmill grass (*Chloris truncata*).

Annual ryegrass (*Lolium rigidum*) is also becoming and increasing threat to the Northern cropping region.

21 SR Smith, RL Bugg, M Gaskell, O Daugovish, M Van Horn (Eds) (2011) Cover cropping for vegetable production: A Grower's Handbook (Vol. 3517). UCANR Publications.

22 L Weston, R Stanton, H Wu, J Mwendwa, P Weston, J Weidenhamer, W Brown. (2015). GRDC Update Papers: Impact of crop residues on summer fallow weeds. https://grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2015/02/impact-of-crop-residues-on-summer-fallow-weeds

23 D Lemerle, K Cooper (1996) Comparative weed suppression by triticale, cereal rye and wheat. Triticale: Today and Tomorrow, Vol. 5. Developments in Plant Breeding, 749–750.

6.3.1 Awnless barnyard grass

Photo 5: *Large glyphosate-resistant awnless barnyard grass.*

Photo: T Cook, Source: Agronomo

Awnless barnyard grass (Photo 5) has been a key summer grass problem for many years. It is a difficult weed to manage for at least three main reasons:

1. It has multiple emergence flushes (cohorts) each season.
2. It is easily moisture-stressed, leading to inconsistent knockdown control.
3. Glyphosate-resistant populations are increasingly being found.

Key points:

- Glyphosate resistance is widespread. Tactics against this weed must change from glyphosate alone.
- Utilise residual chemistry wherever possible and aim to control 'escapes' with camera spray technology.
- Try to ensure that a double-knock of glyphosate followed by paraquat is used on one of the larger early summer flushes of ABYG.
- Restrict Group A herbicides to management of ABYG in-crop and aim for strong crop competition.
- ABYG is a potential candidate for harvest weed-seed control where it germinates in spring in winter crops. [24]

Resistance levels

Prior to summer 2011–12, there were 21 cases of glyphosate-resistant ABYG. Collaborative surveys were conducted by NSW Department of Primary Industries (DPI), Queensland Department of Agriculture and Fisheries (QDAF) and Northern Grain Alliance (NGA) in summer 2011–12 with a targeted follow-up in 2012–13. Agronomists from the Liverpool Plains to the Darling Downs and west to areas including Mungindi collected ABYG samples, which were tested at the Tamworth Agricultural Institute with Glyphosate CT at 1.6 L/ha (a.i. 450 g/L) at a mid-tillering growth stage. Total application volume was 100 L/ha.

24 T Somes (2016) Can harvest weed-seed control work in the north. GRDC Ground Cover Issue 124, https://grdc.com.au/Media-Centre/Ground-Cover/Ground-Cover-Issue-124-SeptemberOctober-2016/Can-harvest-weedseed-control-work-in-the-north

The main finding from this survey work was that the number of 'confirmed' glyphosate-resistant ABYG populations had nearly trebled. Selected populations were also evaluated in a separate glyphosate rate-response trial. The experiment showed that some of these populations were suppressed only when sprayed with 12.8 L/ha.

Growers can no longer rely on glyphosate alone for ABYG control.

Residual herbicides (fallow and in-crop)

A range of active ingredients providing useful management of ABYG is registered for use in summer crops, e.g. metolachlor (products such as Dual Gold®) and atrazine, or in fallow, e.g. imazapic (products such as Flame®). The new fallow registration of isoxaflutole (Balance®) can provide useful suppression of ABYG but has stronger activity against other problem weed species. Few (if any) residuals give consistent, complete control. However, they are important tools that need to be considered to reduce the weed population exposed to knockdown herbicides, as well as to alternate the herbicide chemistry being employed. Use of residuals together with camera spray technology (for escapes) can be a very effective strategy in fallow.

Double-knock control

This approach uses two different tactics applied sequentially. In reduced tillage situations, it is frequently glyphosate first followed by a paraquat-based spray as the second application or 'knock'. Trials have shown that glyphosate followed by paraquat gives effective control even on glyphosate-resistant ABYG. Note that most effective results will be achieved from paraquat-based sprays by using higher total application volumes (100 L/ha) and by targeting seedling weeds.

Several Group A herbicides, e.g. Verdict® and Select®, are effective on ABYG but should be used in registered summer crops. Even on glyphosate-resistant ABYG, a double-knock of glyphosate followed by paraquat is an effective tool. In the same situations, there has been little benefit from a Group A followed by paraquat application. Note that Group A herbicides appear more sensitive to ABYG moisture stress. Application on larger, mature weeds can result in very poor efficacy.

Timing of the paraquat application for ABYG control has generally proven flexible. The most consistent control is obtained from a delay of ~3–5 days, when lower rates of paraquat can also be used. Longer delays may be warranted when ABYG is still emerging at the first application timing; shorter intervals are generally required when weed size is larger or moisture stress conditions are expected. High levels of control can still be obtained with larger weeds but paraquat rates will need to be increased to 2.0 or 2.4 L/ha. [25]

Double-knock is more expensive than a single herbicide application and it may not need to be applied every year. For more information on the costing of double-knock treatment for various weeds, see: Costs of key integrated weed management tactics in the northern region. [26]

6.3.2 Flaxleaf fleabane

For more than a decade flaxleaf fleabane *(Conyza bonariensis*) has been the major weed-management issue in the Northern cropping region, particularly in reduced tillage systems (Photo 6). Fleabane is also an issue in southern NSW.

25 R Daniel (2013) Weeds and resistance—considerations for awnless barnyard grass, *Chloris* spp. and fleabane management. Northern Grower Alliance, http://www.nga.org.au/module/documents/download/225

26 F Scott, T Cook (2016) Costs of key integrated weed management tactics in the northern region. Primefact. NSW Department of Primary Industries, https://www.dpi.nsw.gov.au/biosecurity/weeds/weed-control/herbicides/costs-iwm-tactics-northern

Photo 6: *Flaxleaf fleabane is common through southern Queensland and northern NSW.*

Source: BCC

Fleabane is a wind-borne, surface-germinating weed that thrives in situations of low competition. Germination flushes typically occur in autumn and spring when surface-soil moisture levels stay high for a few days. However, emergence can occur at almost all times of the year. An important issue with fleabane is that knockdown control of large plants in the summer fallow is variable and can be expensive due to reduced control rates.

Key points:

- Utilise residual chemistry wherever possible and aim to control 'escapes' with camera-spray technology.
- This weed thrives in situations of low competition; avoid wide row cropping unless effective residual herbicides are included.
- 2,4-D is a crucial tool for consistent double-knock control.
- Successful growers have increased their focus on fleabane management in winter (crop or fallow) to avoid expensive and variable salvage control in the summer.

Resistance levels

Glyphosate resistance has been confirmed in fleabane. There is great variability in the response of fleabane to glyphosate, with many samples from non-cropping areas still well controlled by glyphosate, whereas fleabane from reduced tillage cropping situations shows increased levels of resistance. The most recent survey has focused on non-cropping situations, with a large number of resistant populations found on roadsides and railway lines where glyphosate alone has been the principal weed management tool employed.

Residual herbicides (fallow and in-crop)

One of the most effective strategies to manage fleabane is the use of residual herbicides during fallow or in-crop. Trials have consistently shown good efficacy from a range of residual herbicides commonly used in sorghum, cotton, chickpeas and winter cereals. There are at least two registrations for residual fleabane management in fallow. Additional product registrations for in-crop knockdown and residual herbicide use, particularly in winter cereals, are being sought. A range of commonly used winter cereal herbicides exists with useful knockdown and residual fleabane activity. So far, trials have indicated that increasing water volumes from 50 to 100 L/ha may help the consistency of residual control, with application timing to ensure good herbicide–soil contact also important.

Knockdown herbicides (fallow and in-crop)

Group I herbicides have been the major products for fallow management of fleabane, with 2,4-D amine the most consistent herbicide evaluated. Despite glyphosate alone generally giving poor control of fleabane, trials have consistently shown a benefit from tank mixing 2,4-D amine and glyphosate in the first application. Amicide® Advance at 0.65–1.1 L/ha mixed with Roundup® Attack at a minimum of 1.15 L/ha then followed by Nuquat® at 1.6–2.0 L/ha is a registered option for fleabane knockdown in fallow. Sharpen is a product with Group G Mode of Action (MoA). It is registered for fallow control when mixed with Roundup® Attack at a minimum of 1.15 L/ha but only on fleabane up to a maximum of six leaves. Currently, the only in-crop knockdown registration is for Amicide® Advance at 1.4 L/ha in either wheat or barley.

Double-knock control

The most consistent and effective double-knock control of fleabane has included 2,4-D in the first application followed by paraquat as the second. Glyphosate alone followed by paraquat will result in high levels of leaf desiccation but plants will nearly always recover.

Timing of the second application in fleabane is generally aimed at ~7–14 days after the first application. However, the interval to the second knock appears quite flexible. Increased efficacy is obtained when fleabane is actively growing or if rosette stages can be targeted. Although complete control can be obtained in some situations, control levels will frequently reach only ~70–80%, particularly when targeting large, flowering fleabane under moisture-stressed conditions. The high cost of fallow double-knock approaches and inconsistency in control level of large, mature plants are good reasons to focus on proactive fleabane management at other growth stages. [27]

6.3.3 Feathertop Rhodes grass

Feathertop Rhodes grass has emerged as an important weed-management issue in southern Queensland and NSW since about 2008 (Photo 7). FTR is another small-seeded weed species that germinates on, or close to, the soil surface. It has rapid early growth rates and can become moisture-stressed quickly. FTR is well established in central Queensland, and is now more common further south, and has been observed in southern NSW. Patches should be aggressively treated to avoid whole-of-paddock blow-outs.

VIDEOS

WATCH: GCTV4: Flaxleaf fleabane

27 R Daniel (2013) Weeds and resistance—considerations for awnless barnyard grass, *Chloris* spp. and fleabane management. Northern Grower Alliance, http://www.nga.org.au/module/documents/download/225

Photo 7: *Seed heads of feathertop Rhodes grass.*

Source: BCC

Key points:

- Glyphosate alone or glyphosate followed by paraquat has generally poor efficacy.
- Utilise residual chemistry wherever possible and aim to control 'escapes' with camera spray technology.
- A double-knock of Verdict™ (haloxyfop) followed by paraquat can be used in Queensland prior to planting mungbeans where large spring flushes of FTR occur.
- Treat patches aggressively, even with cultivation, to avoid paddock blow-outs.
- FTR is a potential candidate for harvest weed-seed control where it germinates in spring in winter crops. [28]

Residual herbicides (fallow and in-crop)

This weed is generally poorly controlled by glyphosate alone even when sprayed under favourable conditions at the seedling stage. Trials have shown that residual herbicides generally provide the most effective control, a similar pattern to that seen with fleabane. Currently registered residual herbicides are being screened and offer promise in both fallow and in-crop situations. The only product currently registered for FTR control is Balance® (isoxaflutole) at 100 g/ha for fallow use.

Double-knock control

A double-knock of glyphosate followed by paraquat is an effective strategy on ABYG; however, the same approach is variable and generally disappointing for FTR management. By contrast, a small number of Group A herbicides (all members of the 'fop' class) can be effective against FTR but need to be managed within a number of constraints:

- Although they can provide high levels of efficacy on fresh and seedling FTR, they need to be followed by a paraquat double-knock to get consistent high levels of final control.
- Group A herbicides have a high risk of resistance selection, again requiring follow-up with paraquat.
- Many Group A herbicides have plant-back restrictions to cereal crops.

28 T Somes (2016) Can harvest weed-seed control work in the north. GRDC Ground Cover Issue 124, https://grdc.com.au/Media-Centre/Ground-Cover/Ground-Cover-Issue-124-SeptemberOctober-2016/Can-harvest-weedseed-control-work-in-the-north

- Group A herbicides generally have a narrower range of weed growth stages for successful use than herbicides such as glyphosate; i.e. Group A herbicides will generally give unsatisfactory results on flowering and/or moisture-stressed FTR.
- Not all Group A herbicides are effective on FTR.

A permit (PER12941, for use of Verdict™ 520) has been issued for Queensland only for the control of FTR in summer fallow situations prior to planting mungbeans, see APVMA.

Timing of the second application for FTR is still being refined, but application at ~7–14 days generally provides the most consistent control. Application of paraquat at shorter intervals can be successful, when the Group A herbicide is translocated rapidly through the plant, but has resulted in more variable control in field trials. Good control can often be obtained up to 21 days after the initial application.

6.3.4 Windmill grass

While FTR has been a grass-weed threat from Queensland and moving south, windmill grass is more of a problem in central NSW and is spreading north. Windmill grass is a perennial, native species found throughout northern NSW and southern Queensland (Photo 8). The main cropping threat appears to be from the selection of glyphosate-resistant populations, with control of the tussock stage providing most management challenges.

Photo 8: *Windmill grass plant and seed head.*

Source: Native seeds

Key points:

- Glyphosate alone or glyphosate followed by paraquat has generally poor efficacy.
- Preliminary data suggest that residual chemistry may provide some benefit.
- A double-knock of quizalofop-p-ethyl (e.g. Targa®) followed by paraquat can be used in NSW.

Resistance levels

Glyphosate resistance has been confirmed in windmill grass with three cases in NSW, all west of Dubbo. Glyphosate-resistant populations of windmill grass in other states have all been collected from roadsides, but in central west NSW, two were from fallow paddock situations.

Residual herbicides (fallow and in-crop)

Preliminary trials have shown a range of residual herbicides with useful levels of efficacy against windmill grass. These herbicides have potential for both fallow and in-crop situations. Currently, no products are registered for residual control of windmill grass.

Double-knock control

Similar to FTR, a double-knock of a Group A herbicide followed by paraquat has provided clear benefits compared with the disappointing results usually achieved by glyphosate followed by paraquat. Constraints apply to double-knock for windmill grass control similar to those for FTR.

For information on a permit for NSW only for the control of windmill grass in summer fallow situations, visit APVMA.

Timing of the second application for windmill grass is still being refined, but application at ~7–14 days generally provides the most consistent control. Application of paraquat at shorter intervals can be successful, when the Group A herbicide is translocated rapidly through the plant, but has resulted in more variable control in field trials and has been clearly antagonistic when the interval is one day or less. Good control can often be obtained up to 21 days after the initial application. [29]

6.3.5 Annual ryegrass

Annual ryegrass is one of the most serious and costly weeds of cropping systems in southern Australia, including southern NSW.

Annual ryegrass is a problem for a number of reasons:

- It produces an extremely high number of seeds per plant
- It is highly competitive
- Is a host for the bacteria *Clavibacter* spp. that cause annual ryegrass toxicity (ARGT)
- It can be infected by ergot fungus
- Many populations have developed resistance to both selective and non-selective herbicides

Annual ryegrass has become a major constraint to productive and profitable cropping systems in southern NSW over recent years. This has been accelerated as a result of ineffective weed control; caused possibly by poor post emergent herbicide options, and therefore, development of herbicide resistance.

Cropping intensity has also played a role, as crop rotations have tightened and leaned more towards no-till farming systems, which rely heavily on herbicides for weed control.

The importance of pre-emergent herbicides has therefore increased, along with the necessity to undertake agronomic strategies to maximise pre-emergent herbicide effectiveness.

A trial at Barellan was established to evaluate a range of pre and post emergent herbicide options applied to control ryegrass in both a stubble retained and stubble burnt no-till system.

29 R Daniel (2013) Weeds and resistance—considerations for awnless barnyard grass, *Chloris* spp. and fleabane management. Northern Grower Alliance, http://www.nga.org.au/module/documents/download/225

The trial highlighted the value of pre-emergent herbicides in no-till farming systems, especially in the presence of stubble. However, the fact that under high pressure situations, even the best pre-emergent herbicides do not provide 100% control, unfortunately allows seed set for the following season.

In this trial, full control was only achieved by applying a pre-emergent herbicide in conjunction with a post emergent herbicide that had no resistance. In this case Atlantis was the product of choice. Unfortunately, in a commercial situation the cost of this practice is often difficult to justify.

Effect of pre-emergent herbicides on ryegrass

All pre-emergent herbicides performed extremely well and provided excellent weed control over the nil control. In most cases greater than 98% control of ryegrass was achieved when the first counts were performed in June.

As the season progressed, the residual effect of some of the herbicides was reduced. This in turn reduced the average weed control across all pre-emergent herbicides to 95.5% of the nil control.

There was a difference in the level of ryegrass control between the pre-emergent herbicides.

All products were very hard to differentiate in their control of ryegrass in the inter row, however within the plant row measurable differences were able to be identified.

Sakura® and Sakura® mixtures provided the highest level of control, followed by Boxer Gold® and then Trifluralin and Trifluralin mixtures (Figure 9).

This is most likely the result of varying residual activity between products, and their ability to wash into and provide weed control within the plant row.

Photo 9: *The ryegrass observed in the untreated control (left) compared to Sakura (right). The control was sprayed with two litres of Roundup three weeks prior to this photo aiming to minimise seed set.*

Source: GRDC.

Effect of stubble on pre-emergent herbicides

The presence of stubble increased the weed control achieved with pre-emergent herbicides. This result was unexpected, but consistent across the trial.

The reasons for this are not definite, however would likely be due to the effect that stubble may have had on surface soil moisture, where retained stubble showed wetter surface soil moisture than where the stubble was burnt. This wetter surface soil moisture may have resulted in the pre-emergent herbicides being active for a longer period of time and also more consistently during early crop growth when the ryegrass was germinating. Stubble is also known to reduce weed establishment, and this may have played a small role.

MORE INFORMATION

Managing annual ryegrass in cropping systems – pre and post emergent herbicide trial, Barrellan 2013

APVMA.

Interestingly, where the stubble was retained the crop was noticeably greener in October. This may be due to the nutrient value of the stubble becoming available at the end of the season.

Effect of post emergent herbicides on ryegrass

Post emergent herbicides were applied across the trial as a matrix at the perfect weed and crop growth stage and received favourable environmental conditions prior to and following application.

Unfortunately, this site highlighted the level of resistance to the post emergent herbicides, with only Atlantis providing a satisfactory level of control.

Boxer Gold (not registered for this purpose) only provided 30% control when used as a post emergent, and also caused slight crop damage.

The remaining herbicides provided little or no control, and would have been a waste of money in a commercial situation. [30]

6.4 Non-herbicide weed control in the Northern Region

Diversity in cropping systems and diversity in weeds in the Northern GRDC grains region calls for diversity in weed management solutions, including non-herbicide tactics.

Survey work in the region has identified more than 70 different weed species that impact on grain production and over 10% of these weed species have confirmed populations within Australia that are resistant to glyphosate and several other chemical MoAs (Table 1).

Table 1: *Confirmed herbicide resistance in weed populations found in NSW and Queensland.*

Mode of Action	Resistant weeds
A (fops, dims, dens)	Wild oats, paradoxa grass, annual ryegrass
B (SUs, imis, etc.)	Annual ryegrass, wild oats, paradoxa grass, Indian hedge mustard, charlock, wild radish, turnip weed, African turnip weed, common sowthistle, black bindweed
C (triazines, ureas, amides, etc.)	Awnless barnyard grass, liverseed grass
D (DNAs, benzamides, etc.)	Annual ryegrass
I (phenoxys, pyridines, etc.)	Wild radish
L (bipyridyls; i.e. diquat, paraquat)	Flaxleaf fleabane
M (glycines; i.e. glyphosate)	Annual ryegrass, awnless barnyard grass, liverseed grass, windmill grass, feathertop Rhodes grass, sweet summer grass, flaxleaf fleabane, common sowthistle
Z (dicarboxylic acids, etc.)	Wild oats

Source: adapted from a table prepared by M Widderick, (QDAF), WeedSmart

A survey of common sowthistle determined populations as glyphosate-resistant if treated seedlings were surviving and reshooting 21 days after glyphosate application. In this test, glyphosate was applied at the upper label rate for small sized plants (up to five-leaf).

Although the majority of common sowthistle samples collected from central Queensland through NSW were still susceptible to label rates of glyphosate applied

30 B Haskins, A MacLennan. (2014). GRDC Update Papers: Managing annual ryegrass in cropping systems – pre and post emergent herbicide trial, Barrellan 2013. https://grdc.com.au/Research-and-Development/GRDC-Update-Papers/2014/03/Managing-annual-ryegrass-in-cropping-systems-pre-and-post-emergent-herbicide-trial-Barellan-2013

to small seedlings, resistant populations were found throughout the study area, showing that this is not a localised problem but rather the inevitable result of over-reliance on a particular herbicide.

Most Northern Region weeds are self-pollinated so resistant plants will produce resistant seed. To reduce the likelihood of resistance, a key approach is to use multiple tactics to maintain low weed numbers. While weed numbers are low so too is the risk of resistance genes being present in the population.

To keep these 'difficult-to-control' weeds in check will clearly require other, non-herbicide, tactics to reduce germination and weed seedset. QDAF researchers have been studying common weeds, particularly FTR, ABYG and common sowthistle, to find weaknesses in each weed's ecology to help identify non-chemical control tactics that could be part of an effective management system.

The QDAF weed research team are investigating non-chemical options, including various cover crops, crop competition, strategic tillage, strategic burning and harvest weed seed control options. Although growers are making good use of chemical strategies such as double-knock, residual herbicides, spot spraying and weed sensing technology to preserve herbicide efficacy, there is an urgent need to investigate non-chemical options that can be added to a weed management program to target resistant weeds in the Northern Region, as outlined in the WeedSmart 10 Point Plan [31].

6.4.1 Strategic tillage

Most growers are keen to preserve their no-till or minimum-tillage farming systems that have delivered significant benefits and so are very reluctant to re-introduce cultivation for weed-control purposes.

The QDAF weed research team has been investigating ways to use cultivation that will have maximum effect on driving down weed numbers while having least impact on the minimum-tillage farming system. The research explores the impact of different tillage operations in situations where the weed population has blown out and intensive patch- or paddock-scale management is required. The key is to understand weed ecology, particularly how seed in the soil seedbank, responds to different types of cultivation.

The team used small plots to determine the effect of burial at different depths on weed-seed persistence (long-term viability) and emergence. They also conducted experiments to determine the displacement of seed (glass beads were used to represent the seed) throughout the cultivated zone using four different types of machine—harrows, Gyral, offset discs and one-way discs—compared with the no-till control treatment.

Sowthistle emergence occurs primarily from seeds close to the soil surface, with up to 30% of viable seeds emerging over five months. Seed can emerge from a depth of up to 2 cm with approximately 4% emergence after six months. Seed buried below 5 cm is unable to emerge and can persist at depth.

Seed persistence (the percentage of viable seed after burial) in fleabane was most reduced when seed was buried to a depth of 2 cm and not disturbed for at least two years. Seed buried to a depth of 10 cm remained viable for over three years. FTR seed persisted for only 12 months regardless of being left on the surface or buried to 10 cm depth. ABYG, however, persisted on the soil surface for up to two years and when buried to 10 cm depth remained viable for over three years.

The Gyral machine placed the majority of weed seed in the 0–2 and 2–5 cm zones whereas the offset discs and one-way discs achieving burial of about half the seed below 5 cm depth.

All species responded to increased tillage intensity with reduced germinations. The research suggests that infrequent but intense cultivation can be a useful weed-

31 WeedSmart (2016) Non-herbicide weed control in the Northern Region. WeedSmart, http://www.weedsmart.org.au/bulletin-board/non-herbicide-weed-control-in-the-northern-region/

management tool within an otherwise no-till farming system. Generally, once a deep cultivation has been done there should be no cultivation of that area or paddock for at least four years to avoid the risk of bringing seed back to the soil surface. [32]

6.4.2 Strategic burning

Feathertop Rhodes grass is known to colonise around mature plants and potentially spread to form distinct weedy patches. Killing the large plant at the centre of the colony is usually not possible with chemical treatments.

Strategic burning of early infestations of this weed can effectively reduce the biomass of the survivor plant and reduce the amount of viable seed present on the soil surface from 7500 seeds/m^2 to less than 500 seeds/m^2.

Growers have made effective use of a flame-thrower to burn large FTR plants during the fallow (Photo 10). [33]

Photo 10: *Strategic burning of early infestations of feathertop Rhodes grass in a fallow can reduce the biomass of the survivor plant and reduce the amount of viable seed present on the soil surface.*

Source: WeedSmart

6.4.3 Narrow windrow burning

There have been a few early adopters of narrow windrow burning (NBW) in southern NSW primarily due to the successes being achieved in Western Australia where NWB is commonly used to manage weed seeds at harvest. Although the data on weed reduction from WA was clear (99% control of annual ryegrass and wild radish seeds collected at harvest, AHRI 2007), there is still some hesitation regarding the practicalities of NWB in higher yielding systems of southern NSW.

One of the main advantages of NWB is that it is cheap to set up, requiring just a bit of thought and some welding skills. The hardest part is getting the chute design right.

Harvest height is a critical component of the NWB system. The rule of thumb is 'beer can' height, or approximately 15 cm, to ensure the majority of ryegrass or wild radish seed heads are captured.

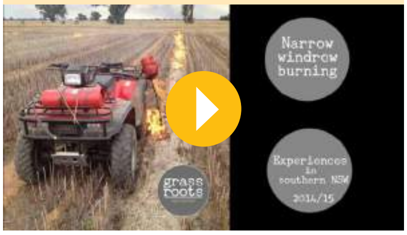
Burning efficiently and effectively is the hardest part of the NWB process. It is time consuming and the logistics need to be considered early on in the season. Choosing the right firelighter can make a big difference to the time involved, operator comfort and to the result achieved.

32 WeedSmart (2016) Non-herbicide weed control in the Northern Region. WeedSmart, http://www.weedsmart.org.au/bulletin-board/non-herbicide-weed-control-in-the-northern-region/

33 WeedSmart (2016) Non-herbicide weed control in the Northern Region. WeedSmart, http://www.weedsmart.org.au/bulletin-board/non-herbicide-weed-control-in-the-northern-region/

VIDEOS

WATCH: NWB Show and tell video 1: Paddock experiences in SNSW



MORE INFORMATION

Grassroots Agronomy: Narrow windrow burning in southern NSW

WeedSmart: Employ crop competitiveness to combat weeds

Key tips:

Lighting the windrow on the side facing downwind helps to produce a slower, hotter burn back over the top. Lighting on the upwind side can result in the fire burning too quickly across the top, leaving the middle unburnt. You can see this in the 'NWB experiences in southern NSW' video on YouTube.

For higher yielding cereal crops, burn in the morning when the straw is still damp (March/April).

If windrows get wet, wait at least two weeks before burning and make sure summer weeds have been controlled.

If possible, avoid stubble grazing in paddocks that have been narrow windrowed. Stock tend to kick the windrows around, increasing the risk of fire escape, but also creating tracks which can act as annoying firebreaks in the middle of a windrow.

With closer settlement in southern NSW, health risks associated with smoke inhalation need to be considered. [34]

6.4.4 Crop competition

Crop competition through narrower row spacing and/or increased planting density provides an effective offense against most weeds. For example, narrowing cereal rows from 50 to 25 cm spacing had the most marked effect on fleabane seedhead production with an additive advantage if the crop density is also increased from 50 to 100 plants/m^2 (Figure 1).

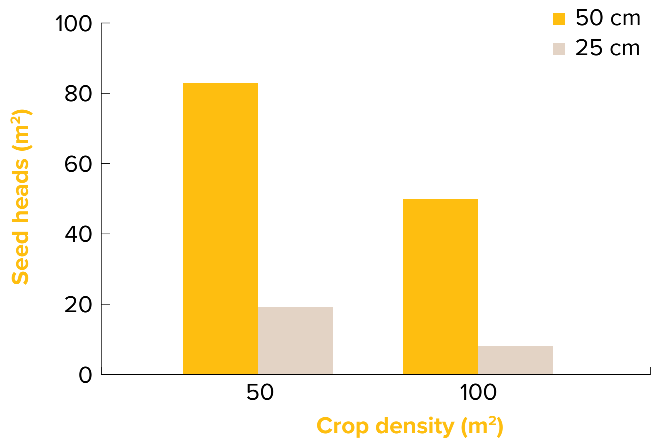


Figure 1: *Fleabane seedhead production at 25 and 50 cm row spacing and two planting densities of wheat.*

Source: M Widderick, QDAF, WeedSmart

Project work is continuing to investigate the options for increasing crop competitiveness in Northern crops (Photo 11). [35]

34 K Condon. (2015). Narrow windrow burning in southern NSW Grass roots agronomy.

35 WeedSmart (2016) Non-herbicide weed control in the Northern Region. WeedSmart, http://www.weedsmart.org.au/bulletin-board/non-herbicide-weed-control-in-the-northern-region/

Photo 11: *Crop competition through narrower row spacing and/or increased planting density provides an effective offensive against common sowthistle and flaxleaf fleabane.*

Source: WeedSmart

6.4.5 Cover crops

Summer fallow periods are heavily reliant on glyphosate for summer grass control. Preliminary research explored the potential role of cover crops in place of a chemical fallow for control of summer grass weeds. Summer cover crops such as cowpea, lablab and French millet have the potential to smother summer-growing weeds, particularly ABWG and FTR, and return large amounts of organic biomass to the soil.

French millet planted on its own, or in combination with the legumes, increased the amount of biomass produced. The higher the biomass production the greater the suppression of weeds.

Cover crops will tend to use fallow stored moisture, so the effect of two termination dates on subsequent crop yield and on weed numbers was investigated. Germination of FTR was found to be minimal after all of the cover crop treatments. The yield of the following wheat crop was comparable to the chemical fallow control and no yield differences were found between treatments. For ABYG, late termination of the cover crop reduced weed emergences before and after the following wheat crop, although there was a trend towards slightly reduced wheat yield compared with the early termination treatments, which tended to boost yield compared with the chemical fallow control.

The reduction in ABYG emergence and wheat yield are both likely due to reduced soil water following the late-terminated cover crops. Much more work is required to identify suitable cover crops and define the parameters for their use as a weed-management tactic in Australia. [36]

6.5 Herbicides explained

When selecting a herbicide, it is important to know crop growth stage, weeds present and plant-back period. For best results, weeds should be sprayed while they are small and actively growing. Herbicides must be applied at the correct stage of crop growth, or significant yield losses may occur. Check product labels for up-to-date registrations and application methods.

36 WeedSmart (2016) Non-herbicide weed control in the Northern Region. WeedSmart, http://www.weedsmart.org.au/bulletin-board/non-herbicide-weed-control-in-the-northern-region/

6.5.1 Residual and non-residual

Residual herbicides remain active in the soil for an extended period (months) and can act on successive weed germinations. Residual herbicides are absorbed through the roots or shoots, or both. Examples of residual herbicides include imazapyr, chlorsulfuron, atrazine and simazine.

The persistence of residual herbicides is determined by a range of factors including application rate, soil texture, organic matter levels, soil pH, rainfall/irrigation, temperature and the herbicide's characteristics. Persistence of herbicides will affect the sequence chosen (a rotation of crops, e.g. wheat–barley–chickpeas–canola–wheat). Non-residual herbicides, such as the non-selective paraquat and glyphosate, have little or no soil activity and they are quickly deactivated in the soil. They are either broken down or bound to soil particles, becoming less available to growing plants. They also may have little or no ability to be absorbed by roots.

6.5.2 Post-emergent and pre-emergent

These terms refer to the target and timing of herbicide application. Post-emergent refers to foliar application of the herbicide after the target weeds have emerged from the soil, whereas pre-emergent refers to application of the herbicide to the soil before the weeds have emerged. [37]

Herbicides are classified into a number of MoA groups. The group refers to the way a chemical works—their different chemical make-up and MoA (Table 2). [38]

Table 2: *Herbicide groups and examples of chemicals and proprietary products in each group.*

Group A	Hoegrass®, Nugrass®, Digrass®, Verdict®, Targa®, Fusilade®, Puma S®, Tristar®, Correct®, Sertin® Grasp®, Select®, Achieve®, Gallant®, Topik®
Group B	Glean®, chlorsulfuron, Siege®, Tackle®, Ally®, Associate®, Logran®, Nugran®, Amber Post® Londax®, Spinnaker®, Broadstrike®, Eclipse®, Renovate®
Group C	Simazine, atrazine, Bladex®, Igran®, metribuzin, diuron, linuron, Tribunil®, bromoxynil, Jaguar®, Tough®
Group D	Trifluralin, Stomp®, Yield®, Surflan®
Group E	Avadex® BW, EPTC, chlorpropham
Group F	Brodal®, Tigrex®, Jaguar®
Group H	Saturn®
Group I	2,4-D, MCPA, 2,4-DB, dicamba, Tordon®, Lontrel®, Starane®, Garlon®, Baton®, Butress®, Trifolamine®
Group K	Dual®, Kerb®, Mataven®
Group L	Reglone®, Gramoxone®, Nuquat®, Spraytop®, Sprayseed®
Group M	Glyphosate, Glyphosate CT®, Sprayseed®, Roundup CT®, Touchdown®, Pacer®, Weedmaster®

List of commonly used products only. List of products does not necessarily imply state registration. Check that product is registered in your state before use. Groups G and J not included.

Source: NSW DPI

VIDEOS

WATCH: Over the Fence North: Weed and nutrient research delivers at Silverton

6.6 Pre-emergent herbicides

Pre-emergent herbicides control weeds between radicle (embryonic root) emergence from the seed and seedling emergence through the soil. Some pre-emergent herbicides may also provide post-emergent control.

37 GRDC Integrated weed management, Section 4: Tactics for managing weed populations, https://grdc.com.au/resources-and-publications/iwmhub

38 Agriculture Victoria Monitoring Tools. http://agriculture.vic.gov.au/agriculture/farm-management/business-management/ems-in-victorian-agriculture/environmental-monitoring-tools/herbicide-resistance

Benefits and issues:

- The residual activity of pre-emergent herbicides controls the first few flushes of germinating weeds while the crop or pasture is too small to compete.
- Good planning is needed to use pre-emergent herbicides as an effective tactic. It is necessary to consider weed species and density, crop or pasture type, soil condition, and rotation of crop or pasture species.
- Soil activity and environmental conditions at the time of application play an important role in the availability, activity and persistence of pre-emergent herbicides.
- Positive and negative aspects of using pre-emergent herbicides should be considered in the planning phase. [39]

To maximise efficacy of pre-emergent herbicides while minimising crop damage, it is important to know:

- the position of the weed seeds in the soil
- the soil type (particularly amount of organic matter and crop residue on the surface)
- the solubility of the herbicide
- the herbicide's ability to be bound by the soil.

6.6.1 Understanding pre-emergent herbicides

With the increasing incidence of resistance to post-emergent herbicides across Australia, pre-emergent herbicides are becoming more important for weed control. Typically, pre-emergent herbicides have more variables that can influence efficacy than post-emergent herbicides. Post-emergent herbicides are applied when weeds are present and the main considerations usually relate to application coverage, weed size and environmental conditions that impact on performance. Pre-emergent herbicides are applied before the weeds germinate; the various herbicides behave differently in the soil and may behave differently in different soil types. It is therefore essential to know the behaviour of the herbicide, the soil type and the farming system in order to use pre-emergent herbicides in the most effective way.

Pre-emergent herbicides must be absorbed by the germinating seedling from the soil. To do so, these herbicides need to have some solubility in water and to be positioned in the soil to be absorbed by the roots or emerging shoot. The dinitroaniline herbicides, such as trifluralin, are an exception because they are absorbed by the seedlings as a gas; however, these herbicides still require water in order to be released from the soil as a gas. Therefore, weed control with pre-emergent herbicides will always be lower under dry conditions.

Visit the APVMA website for up-to-date herbicide registrations.

6.6.2 Behaviour of pre-emergent herbicides in the soil

Behaviour of pre-emergent herbicides in the soil is driven by three key factors:

1. Solubility of the herbicide
2. How tightly the herbicide is bound to soil components
3. The rate of breakdown of the herbicide in the soil.

Characteristics of some common pre-emergent herbicides are given in Table 3. Water solubility of herbicides ranges from very low for trifluralin to very high for chlorsulfuron. Water solubility influences how far the herbicide will move in the soil profile in response to rainfall events. Herbicides with high solubility are at greater risk of being moved into the crop seed row by rainfall and potentially causing crop damage. If a herbicide moves too far through the soil profile, it risks moving out of the weed root-zone and failing to control the weed species at all. Herbicides with very low water solubility are unlikely to move far from where they are applied.

39 A Douglas (2016) Herbicides. DAFWA, https://www.agric.wa.gov.au/herbicides/herbicides?page=0%2C2

Table 3: *Water solubility, binding characteristics to soil organic matter (Koc) and degradation half-life for some common pre-emergent herbicides.*

Herbicide	Water solubility (at 20°C and neutral pH)		Koc (in typical neutral soils)		Degradation half-life (days)
	(mg L)	Rating	(mL g)	Rating	
Trifluralin	0.22	Very low	15,800	Very high	181
Pendimethalin	0.33	Very low	17,800	Very high	90
Pyroxasulfone	3.9	Low	223	Medium	22
Triallate	4.1	Low	3000	High	82
Prosulfocarb	13	Low	2000	High	12
Atrazine	35	Medium	100	Medium	75
Diuron	36	Medium	813	High	75.5
S-metolachlor	480	High	200	Medium	15
Triasulfuron	815	High	60	Low	23
Chlorsulfuron	12,500	Very High	40	Low	160

Source: GRDC

Some rules-of-thumb for maximising pre-emergent herbicide efficacy while minimising crop damage are:

1. Soils with low organic matter are particularly prone to crop damage from pre-emergent herbicides (especially sandy soils) and rates should be reduced where necessary to lower the risk of crop damage.
2. The more water-soluble herbicides will move more readily through the soil profile and are better suited to post-sowing pre-emergent applications than the less water-soluble herbicides. They are also more likely to produce crop damage after heavy rain.
3. Pre-emergent herbicides need to be present at sufficient concentration at or below the weed seed (except for triallate which needs to be above the weed seed) to provide effective control. Keeping weed seeds on the soil surface will improve control by pre-emergent herbicides.
4. High crop-residue loads on the soil surface can inhibit pre-emergent herbicide action because they prevent the herbicide from contacting the seed. More water-soluble herbicides cope better with crop residue, but it is best to manage crop residue so that at least 50% of the soil surface is exposed at the time of application.
5. If the soil is dry on the surface but moist underneath there may be sufficient moisture to germinate the weed seeds but not enough to activate the herbicide. Poor weed control is likely under these circumstances. The more water-soluble herbicides are less adversely affected under these conditions.
6. Many pre-emergent herbicides can cause crop damage. Separation of the product from the crop seed is essential. In particular, care needs to be taken with disc seeding equipment in choice of product and maintaining an adequate seeding depth. [40]

Top tips for using pre-emergent herbicides

- Only use pre-emergent herbicides as part of an integrated weed-control plan including both chemical and non-chemical weed-control practices.
- Preparation starts at harvest. Minimise compaction and maximise trash spreading from the header.
- Minimise soil disturbance allowing weed seeds to remain on the soil surface.
- Leave stubble standing rather than laying it over.

40 C Preston (2014) Understanding pre-emergent cereal herbicides. GRDC Update Papers, 4 March 2014, https://grdc.com.au/Research-and-Development/GRDC-Update-Papers/2014/03/Understanding-pre-emergent-cereal-herbicides

MORE INFORMATION

GRDC Update Paper: Understanding pre-emergent cereal herbicides

NSW DPI: Using pre-emergent herbicides in conservation farming systems

WeedSmart: Gearing up to use pre-emergent herbicides

GRDC Fact Sheet: Pre-emergent herbicides

GRDC Media Centre: How pre-emergent herbicides work

- Knife-points and press-wheels allow greatest crop safety. Avoid harrows.
- If using a disc seeder understand the mechanics of your machine and the limitations it may carry relative to a knife-point and press-wheel.
- Pay attention to detail in your sowing operation and ensure soil throw on the inter-row while maintaining a seed furrow free from herbicide.
- Ensure the seed furrow is closed to prevent herbicide washing onto the seed.
- Ensure even seed placement, typically 3–5 cm of loose soil on top of seed in cereals for best crop safety.
- Use incorporation by sowing (IBS) rather than post-plant pre-emergent (PSPE) for crop safety.
- Understand herbicide chemistry. Choose the right herbicide in the right paddock at the right rate. [41]

6.6.3 Post-sowing pre-emergent (PSPE) herbicide use

Post-sowing pre-emergent herbicide use is the application of pre-emergent herbicides after sowing (but before crop emergence) to the seedbed.

Absorption of PSPE herbicide occurs primarily through the roots, but there may also be some foliar absorption (e.g. Terbyne®). When applied to soil, best control is achieved when the soil is flat and relatively free of clods and trash. Sufficient rainfall (20–30 mm) to wet the soil through the weed root-zone is necessary within 2–3 weeks of application. Assuming such conditions, best weed control is achieved from PSPE application because rainfall gives the best incorporation. Mechanical incorporation pre-sowing is less uniform, and so weed control may be less effective; however, with pre-sowing application and sowing with minimal disturbance, incorporation will essentially be by rainfall after application.

For pre-emergent herbicide controls in NSW, see Weed control in winter crops 2016 (Table 12, pp. 44–45).

6.6.4 Incorporation by sowing (IBS)

Incorporation by sowing is when a herbicide is applied just before sowing (usually in conjunction with a knockdown herbicide such as glyphosate) and then soil throw from the sowing operation incorporates the herbicide into the seedbed. IBS is the preferred method of applying pre-emergent herbicides in conservation farming systems, as crop safety is maximised, stubble remains standing to protect the seedbed, and soil disturbance is minimised.

The IBS method will often increase safety to crops because the sowing operation removes a certain amount of herbicide away from the seed row. However, this can reduce weed control, as chemical is moved out of the seed row. In this case, it is wise to include a water-soluble herbicide in the mix, aiming to have some herbicide wash into the seed furrow.

CASE STUDY

Crop safety and the use of pre-emergent residual herbicides

Two trials were conducted in 2013 evaluating the crop safety and efficacy of registered residual herbicides for the control of annual ryegrass in wheat and cereals. Most treatments were managed by the IBS approach, which specifies the use of narrow-point tynes on the planting equipment. This approach helps to ensure sufficient soil is thrown across the inter-row space to 'incorporate' the herbicide, plus it removes most of the herbicide-

41 B Haskins (2012) Using pre-emergent herbicides in conservation farming systems. DPI NSW, http://www.dpi.nsw.gov.au/__data/assets/pdf_file/0003/431247/Using-pre-emergent-herbicides-in-conservation-farming-systems.pdf

treated soil from the planting furrow to improve crop safety. Consequently, however, IBS generally provides poor weed control in the zone immediately around the planting row. PSPE was also evaluated because it provides more uniform weed efficacy but requires herbicides or rates with improved crop safety together with reduced incorporation characteristics.

Key findings

Planting method:

- The use of a disc planter for IBS of residual herbicides resulted in significantly reduced wheat emergence for all four herbicides evaluated.
- The disc planter 'set-up' increased the risk of crop damage (Figure 2).
- The results reinforce the need to use only narrow-point tynes when using residual herbicides with IBS recommendations.

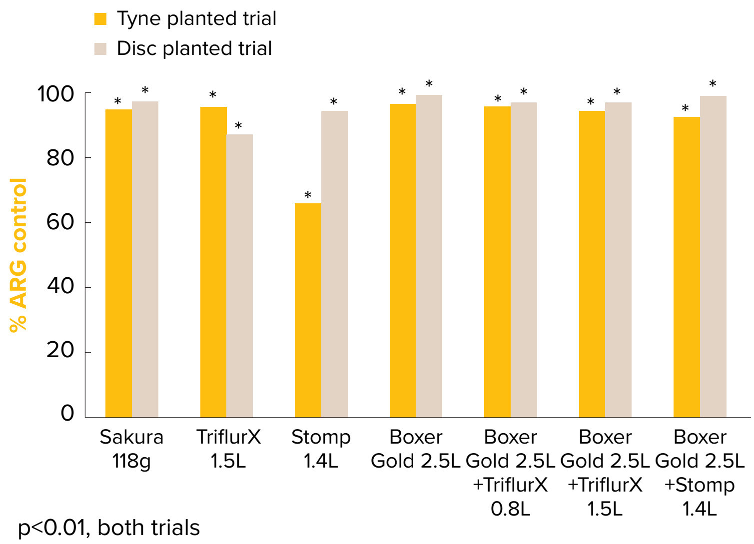


Figure 2: *Annual ryegrass (ARG) control based on counts 94 days after planting, as a percentage of the untreated control. All treatments applied in 70 L/ha total volume using AIXR110015 nozzles at 300 kPa. *Significant (P < 0.05) control compared with untreated within same trial.*

Source: GRDC

Herbicide efficacy:

- High levels of annual ryegrass control were achieved by most IBS treatments.
- The most consistent products were Boxer Gold® or Sakura®.
- Weed control from Boxer Gold® was significantly reduced in one of the two trials when applied by PSPE.

Conclusions

This work was conducted because of safety concerns for commercial crop from the use of residual herbicides at planting for annual ryegrass control. These two trials highlighted some key points:

1. Crop safety was significantly reduced when a disc planter was used for incorporation.
2. The disc set-up appears to have exaggerated crop safety issues by planting seed in an area with increased herbicide concentration.

3. Observation suggested that small differences in planting depth might have affected crop safety.

This work reinforces some of the difficulties growers and agronomists face with the use of residual herbicides. Crop safety and efficacy are influenced by a range of factors including planting equipment, planting depth, soil type, stubble load, and rainfall quantity and timing. A more thorough understanding of the impacts from these (and perhaps other) factors is needed to get the best from these important weed-management tools. [42]

6.7 In-crop herbicides: knockdowns and residuals

In-crop herbicides control weeds that have emerged since crop or pasture establishment and they can be applied with little damage to the crop or pasture plants.

Benefits:

- Post-emergent herbicides give high levels of target weed control with the additional benefit of improved crop or pasture yield.
- Observations made just prior to application allow fine-tuning of herbicide selection to match weeds present in the paddock.
- Timing of application can be flexible to suit weed size, crop growth stage and environmental conditions.
- Some post-emergent herbicides have pre-emergent activity on subsequent weed germinations.

Issues:

- Careful consideration is needed when selecting the best post-emergent herbicide to use in any one situation.
- Application of post-emergent herbicides to stressed crops and weeds can result in reduced levels of weed control and increased crop damage.
- Crop competition is important for effective weed control using selective post-emergent herbicides.
- The technique used for application must be suited for the situation in order to optimise control.
- Always use the correct adjuvant to ensure effective weed control.
- Selective post-emergent herbicides applied early and used as a stand-alone tactic have little impact on the weed seedbank.
- Choose the most suitable formulation of herbicide for each situation.
- The effectiveness of post-emergent herbicides is influenced by a range of plant and environmental factors. [43]

For post-emergence herbicide controls for cereal rye in NSW, see Weed control in winter crops 2016 (Table 20, pp 64–68).

6.7.1 Key points for in-crop herbicide application

- Knowledge of a product's translocation and formulation type is important for selecting nozzles and application volumes.
- Evenness of deposit is important for poorly or slowly translocated products.

42 R Daniel, A Mitchell (2014) Pre-emergent herbicides; part of the solution but much still to learn. GRDC Update Papers, 5 March 2014, https://grdc.com.au/Research-and-Development/GRDC-Update-Papers/2014/03/Pre-emergent-herbicides-part-of-the-solution-but-much-still-to-learn

43 A Douglas (2016) Herbicides. DAFWA, https://www.agric.wa.gov.au/herbicides/herbicides?page=0%2C2

- Crop growth stage, canopy size and stubble load should influence decisions about nozzle selection, application volume and sprayer operating parameters.
- Robust rates of products and appropriate water rates are often more important for achieving control than the nozzle type, but, correct nozzle type can widen the spray window, improve deposition and reduce drift risk.
- Travel speed and boom height can affect control and drift potential.
- Appropriate conditions for spraying are always important. [44]

In-crop herbicides will normally require a different set of nozzles from those used in summer fallow spraying and application of pre-emergent herbicides.

In-crop post-emergent herbicides should be applied as an upper-end medium to lower-end coarse droplet spectrum depending on the particular herbicide being used. This must be combined with the relevant application volume to get enough droplets per square centimetre on the target to achieve good coverage. The nozzles must also be matched to your spray rig, pump and controller, and desired travel speed.

Operate within the recommended groundspeed range and apply the product in a higher application volume. The actual recommended application volume will vary with the product and situation, so read the label and follow the directions.

6.7.2 How to get the most out of post-emergent herbicides

- Consider application timing—the younger the weeds the better. Frequent crop monitoring is critical.
- Consider the growth stage of the crop.
- Consider the crop variety being grown and applicable herbicide tolerances.
- Know which species were historically in the paddock and the resistance status of the paddock (if unsure, send plants away for a Weed Resistance Quick-Test.
- Do not spray a crop stressed by waterlogging, frost, high or low temperatures, drought or (for some chemicals) cloudy/sunny days. This is especially pertinent for frosts with grass-weed chemicals.
- Use the correct spray application:
- Consider droplet size with grass-weed herbicides, water volumes with contact chemicals and time of day.
- Observe the plant-back periods and withholding periods.
- Consider compatibility if using a mixing partner.
- Add correct adjuvant. [45]

MORE INFORMATION

GRDC Fact Sheet: In-crop herbicide use

6.8 Conditions for spraying

When applying herbicides, the aim is to maximise the amount reaching the target and to minimise the amount reaching off-target areas. This results in:

- improved herbicide effectiveness
- reduced damage and/or contamination of off-target crops and areas.

In areas where several agricultural enterprises coexist, conflicts can arise, particularly from the use of herbicides. All herbicides are capable of drift.

When spraying a herbicide, you have a moral and legal responsibility to prevent it from drifting and contaminating or damaging neighbours' crops and sensitive areas.

All grass herbicide labels emphasise the importance of spraying only when the weeds are actively growing under mild, favourable conditions (Photo 12). Any of the following stress conditions can significantly impair both uptake and

44 GRDC (2014) In-crop herbicide use. GRDC Fact Sheet July 2014, https://grdc.com.au/GRDC-FS-InCropHerbicideUse

45 WeedSmart Post-emergents, http://www.weedsmart.org.au/post-emergents/

translocation of the herbicide within the plant, likely resulting in incomplete kill or only suppression of weeds:

- moisture stress (and drought)
- waterlogging
- high temperature–low humidity conditions
- extreme cold or frosts
- nutrient deficiency, especially effects of low N
- use of pre-emergent herbicides that affect growth and root development, i.e. simazine, Balance®, trifluralin, and Stomp®
- excessively heavy dews resulting in poor spray retentions on grass leaves

Photo 12: *Boom spray on crop.*

Source: DAFWA

Ensure that grass weeds have fully recovered before applying grass herbicides.

6.8.1 Minimising spray drift

Before spraying

- Always check for susceptible crops in the area, for example broadleaf crops such as grape vines, cotton, vegetables and pulses, if you are using a broadleaf herbicide.
- Check sensitive areas such as houses, schools, waterways and riverbanks.
- Notify neighbours of your spraying intentions.

Under the Records Regulation of the Pesticides Act 1999, when spraying you must record the weather and relevant spray details.

The Cotton Field Awareness Map is provided free of charge with the purpose of minimising off-target damage from downwind pesticide application, particularly during fallow spraying. Users can also access the map to check the location of the paddock(s) they may be planning to spray to assess the proximity of the nearest cotton crop.

During spraying

- Always monitor weather conditions carefully and understand their effect on 'drift hazard'.
- Do not spray if conditions are not suitable, and stop spraying if conditions change and become unsuitable.
- Record weather conditions (especially temperature and relative humidity), wind speed and direction, herbicide and water rates, and operating details for each paddock.
- Supervise all spraying, even when a contractor is employed. Provide a map marking the areas to be sprayed, buffers to be observed and sensitive crops and areas.
- Spray when the temperature is less than 28°C.
- Maintain a downwind buffer. This may be in-crop, for example keeping a boom's width from the downwind edge of the field.
- Minimise spray release height.
- Use the largest droplets that will give adequate spray coverage.
- Always use the least-volatile formulation of herbicide available.
- If there are sensitive crops in the area, use the herbicide that is the least damaging.

6.8.2 Types of drift

Sprayed herbicides can drift as droplets, as vapours or as particles:

- *Droplet drift* is the easiest to control because, under good spraying conditions, droplets are carried down by air turbulence and gravity, to collect on plant or soil surfaces. Droplet drift is the most common cause of off-target damage caused by herbicide application. For example, spraying of fallows with glyphosate under the wrong conditions often leads to severe damage to establishing crops.
- *Particle drift* occurs when water and other herbicide carriers evaporate quickly from the droplet, leaving tiny particles of concentrated herbicide. This can occur with herbicide formulations other than esters. This form of drift has damaged susceptible crops up to 30 km from the source.
- *Vapour drift* is confined to volatile herbicides such as 2,4-D ester. Vapours may arise directly from the spray or evaporation of herbicide from sprayed surfaces. Use of 2,4-D ester in summer can lead to vapour drift damage of highly susceptible crops such as tomatoes, cotton, sunflowers, soybeans and grapes. This may occur hours after the herbicide has been applied.

In 2006, the Australian Pesticides and Veterinary Medicines Authority (APVMA) restricted the use of highly volatile forms of 2,4-D ester. The changes are now seen with the substitution of lower volatile forms of 2,4-D and MCPA. Products with lower 'risk' ester formulations are commonly labelled with LVE (low volatile ester). These formulations of esters have a much lower tendency to volatilise, but caution should remain as they are still prone to droplet drift.

Vapours and minute particles float in the airstream and are poorly collected on catching surfaces. They may be carried for many kilometres in thermal updraughts before being deposited.

Sensitive crops may be up to 10,000 times more sensitive than the crop being sprayed. Even small quantities of drifting herbicide can cause severe damage to highly sensitive plants.

6.8.3 Factors affecting the risk of spray drift

Any herbicide can drift. The drift hazard, or off-target potential, of a herbicide in a particular situation depends on the following factors:

- Volatility of the formulation applied. Volatility refers to the likelihood that the herbicide will evaporate and become a gas. Esters volatilise (evaporate), whereas amines do not.
- Proximity of crops susceptible to the particular herbicide being applied, and their growth stage. For example, cotton is most sensitive to Group I herbicides in the seedling stage.
- Method of application and equipment used. Aerial application releases spray at 3 m above the target and uses relatively low application volumes, while ground-rigs have lower release heights and generally higher application volumes, and a range of nozzle types. Misters produce large numbers of very fine droplets that use wind to carry them to their target.
- Size of the area treated. The greater the area treated the longer it takes to apply the herbicide. If local meteorological conditions change, particularly in the case of 2,4-D ester, then more herbicide is able to volatilise.
- Amount of active ingredient (herbicide) applied. The more herbicide applied per hectare, the greater the amount available to drift or volatilise.
- Efficiency of droplet capture. Bare soil does not have anything to catch drifting droplets, unlike crops, erect pasture species and standing stubbles.
- Weather conditions during and shortly after application. Changing weather conditions can increase the risk of spray drift.

Volatility

Many ester formulations are highly volatile compared with the non-volatile amine, sodium salt and acid formulations. Table 4 is a guide to the more common herbicide active ingredients that are marketed with more than one formulation.

Table 4: *Relative herbicide volatility.*

Form of active	Full name	Product example
NON-VOLATILE		
Amine salts		
MCPA dma	Dimethylamine salt	MCPA 500
2,4-D dma	Dimethylamine salt	2,4-D Amine 500
2,4-D dea	Diethanolamine salt	2,4-D Amine 500 Low Odour®
2,4-D ipa	Isopropylamine salt	Surpass® 300
2,4-D tipa	Triisopropanolamine	Tordon® 75-D
2,4-DB dma	Dimethylamine salt	Buttress®
Dicamba dma	Dimethylamine salt	Banvel® 200
Triclopyr tea	Triethylamine salt	Tordon® Timber Control
Picloram tipa	Triisopropanolamine	Tordon® 75-D
Clopyralid dma	Dimethylamine	Lontrel® Advanced
Clopyralid tipa	Triisopropanolamine	Archer®
Aminopyralid K salt	Potassium salt	Stinger®
Aminopyralid tipa	Triisopropanolamine	Hotshot®
Other salts		
MCPA Na salt	Sodium salt	MCPA 250
MCPA Na/K salt	Sodium & potassium salt	MCPA 250
2,4-DB Na/K salt	Sodium & potassium salt	Buticide®

Form of active	Full name	Product example
Dicamba Na salt	Sodium salt	Cadence®
SOME VOLATILITY		
Ester		
MCPA ehe	Ethylhexyl ester	LVE MCPA
MCPA ioe	Isooctyl ester	LVE MCPA
Triclopyr butoxyl	Butoxyethyl ester	Garlon® 600
Picloram ioe	Isooctyl ester	Access®
2,4-D ehe	Ethylhexyl ester	2,4-D LVE 680
Fluroxypyr M ester	Meptyl ester	Starane® Advanced

Source: Mark Scott, former Agricultural Chemicals Officer, NSW Agriculture

Minimising drift

A significant part of minimising spray drift is the selection of equipment to reduce the number of small droplets produced. However, this in turn may affect coverage of the target, and therefore the possible effectiveness of the pesticide application. This aspect of spraying needs to be carefully considered when planning to spray.

As the number of smaller droplets decreases, so does the coverage of the spray. A good example of this is the use of air-induction nozzles that produce large droplets that splatter. These nozzles produce a droplet pattern and number unsuitable for targets such as seedling grasses that present a small vertical target.

In 2010, APVMA announced new measures to minimise the number of spray drift incidents (Table 5). The changes are restrictions on the droplet-size spectrum an applicator can use, wind speed suitable for spraying and the downwind buffer zone between spraying and a sensitive target. These changes should be evident on current herbicide labels. Hand-held spraying application is exempt from these regulations.

Table 5: *Nozzle selection guide for ground application. Volume median diameter (VMD): 50% of the droplets are less than the stated size and 50% greater. For flat-fan nozzle size, refer to manufacturers' selection charts as droplet size range will vary with recommended pressure; always use the lowest pressure stated to minimise the small droplets. (Adapted from P Hughes, DPI, Queensland)*

Distance downwind to susceptible crop	<1 km	1 to >30 km
Risk	High	Medium
Preferred droplet size (British Crop Protection Council) (to minimise risk)	Coarse to very coarse	Medium to coarse
Volume median diameter (µm)	310	210
Pressure (bars)	2.5	2.5
Flat-fan nozzle size	11,008	11,004
Recommended nozzles (examples only)	*Raindrop:* Whirljet® *Air induction:* Yamaho Turbodrop®, Hardi Injet®, AI Teejet®, Lurmark Drift-beta®	*Drift reduction:* DG TeeJet®, Turbo TeeJet®, Hardi® ISO LD 110, Lurmark® Lo-Drift

Distance downwind to susceptible crop	<1 km	1 to >30 km
CAUTION	Can lead to poor coverage and control of grass weeds. Require higher spray volumes	Suitable for grass control at recommended pressures. Some fine droplets

Source: DPI NSW

Spray release height

- Operate the boom at the minimum practical height. Drift hazard doubles as nozzle height doubles. If possible, angle nozzles forward 30° to allow lower boom height with double overlap. Lower heights, however, can lead to more striping, as the boom sways and dips below the optimum height.
- 110° nozzles produce a higher percentage of fine droplets than 80° nozzles, but they allow a lower boom height while maintaining the required double overlap.
- Operate within the pressure range recommended by the nozzle manufacturer. Production of driftable fine droplets increases as the operating pressure is increased.

Size of area treated

When large areas are treated, greater amounts of active herbicide are applied and the risk of off-target effects increases due to the length of time taken to apply the herbicide. Conditions such as temperature, humidity and wind direction may change during spraying.

Application of volatile formulations to large areas increases the chances of vapour drift damage to susceptible crops and pastures.

Capture surface

Targets vary in their ability to collect or capture spray droplets. Well grown, leafy crops are efficient collectors of droplets. Turbulent airflow normally carries spray droplets down into the crop within a very short distance.

Fallow paddocks or seedling crops have poor catching surfaces. Drift hazard is far greater when applying herbicide in these situations or adjacent to these poor capture surfaces.

The type of catching surface between the sprayed area and susceptible crops should always be considered in conjunction with the characteristics of the target area when assessing drift hazard.

Weather conditions to avoid

Turbulence

- Updrafts during the heat of the day cause rapidly shifting wind directions. Spraying should be avoided during this time of day.

Temperature

- Avoid spraying when temperatures exceed 28°C.

Humidity

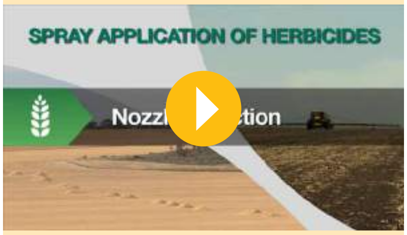
- Avoid spraying under low relative humidity conditions; i.e. when the difference between wet and dry bulbs exceeds 10°C.
- High humidity extends droplet life and can greatly increase the drift hazard under inversion conditions. This results from the increased life of droplets smaller than 100 microns.

Wind

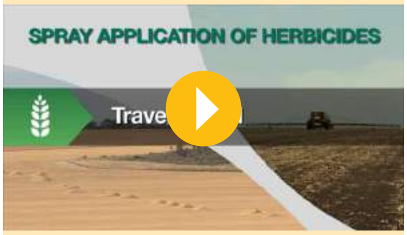
- Avoid spraying under still conditions.

VIDEOS

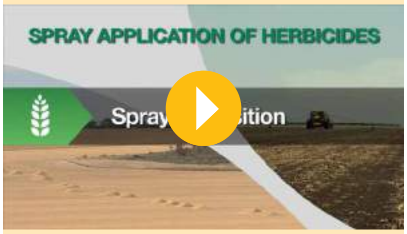
WATCH: Nozzle Selection



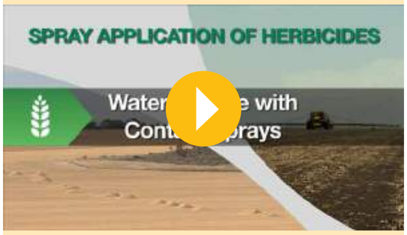
WATCH: Travel Speed



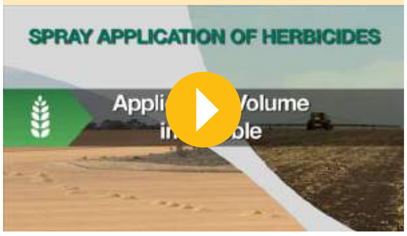
WATCH: Spray deposition



WATCH: Water volume with contact sprays



WATCH: Application volume in stubble



- Ideal safe wind speed is 3–10 km/h, a light breeze (when leaves and twigs are in constant motion).
- A moderate breeze of 11–14 km/h is suitable for spraying if using low-drift nozzles or higher volume application, say 80–120 L/ha. (Small branches move, dust is raised and loose paper is moving.)

VIDEOS

WATCH: Advances in weed management—Webinar 2—Spray application in summer fallows

Inversions

The most hazardous condition for herbicide spray drift is an atmospheric inversion, especially when combined with high humidity. An inversion exists when temperature increases with altitude instead of decreasing. An inversion is like a cold blanket of air above the ground, usually less than 50 m thick. Air will not rise above this blanket, and smoke or fine spray droplets and particles of spray deposited within an inversion will float until the inversion breaks down.

Do not spray under inversion conditions.

Inversions usually occur on clear, calm mornings and nights. Windy or turbulent conditions prevent inversion formation. Blankets of fog, dust or smoke and the tendency for sounds and smells to carry long distances indicate inversion conditions.

Smoke generators or smoky fires can be used to detect inversion conditions. Smoke will not continue to rise but will drift along at a constant height under the inversion 'blanket'. [46]

6.9 Herbicide tolerance ratings, NVT

Within many broadacre crop species, cultivars have been found to vary in sensitivity to commonly used herbicides and tank mixes, thereby resulting in potential grain yield loss and reduced farm profit. With funding from GRDC and state government agencies across Australia, cultivar × herbicide-tolerance trials are conducted annually.

The trials aim to provide grain growers and advisers with information on cultivar sensitivity to commonly used in-crop herbicides and tank mixes for a range of crop species including wheat, barley, triticale, oats, lupin, field peas, lentils, chickpeas and faba beans. The intention is to provide data from at least two years of testing at the time of wide-scale commercial propagation of a new cultivar. [47]

In greenhouse trials in the US, cereal rye showed tolerance similar to oats for a range of residual herbicides (based on injury rating). Cereal rye had a higher potential for injury from the Group K herbicide S-metolachlor. [48]

The good news is that >70% of all crop varieties are tolerant to most herbicides. The remaining varieties can experience yield losses of 10–30%, and in some cases, 50% yield loss has been recorded. This occurs with the use of registered herbicides applied at label rates under good spraying conditions at the appropriate crop growth stage.

To provide growers with clear information about the herbicide interactions of a variety for their region, four regionally based, herbicide tolerance screening projects have been established. The four projects have now been combined under a national program. [49]

46 A Storrie (2015) Reducing herbicide spray drift. NSW Department of Primary Industries, http://www.dpi.nsw.gov.au/content/agriculture/pests-weeds/weeds/images/wid-documents/herbicides/spray-drift

47 NVT. Herbicide tolerance. GRDC, http://www.nvtonline.com.au/herbicide-tolerance/

48 B Hartzler, M Anderson. (2015). Effect of residual herbicides on cover crop establishment. IOWA State University. http://www.weeds.iastate.edu/mgmt/2015/CCherbicides.pdf

49 E Leonard (2012) weed kill without crop damage. GRDC Ground Cover Supplements, November 2012, https://grdc.com.au/Media-Centre/Ground-Cover-Supplements/GCS101/Weed-kill-without-crop-damage

6.10 Potential herbicide damage effect

6.10.1 Avoiding crop damage from residual herbicides

The herbicide label is the primary source of information on residual activity and cropping restrictions following herbicide application and it should be read thoroughly. The following provides an explanation of how herbicides break down and extra notes on some specific herbicides used in broadacre cropping.

What are the issues?

Some herbicides can remain active in the soil for weeks, months or years. This can be an advantage, as it ensures good long-term weed control. However, if the herbicide stays in the soil longer than intended it may damage sensitive crop or pasture species sown in subsequent years.

For example, chlorsulfuron (Glean®) is used in wheat and barley, but it can remain active in the soil for several years and can damage legumes and oilseeds. A problem for growers lies in identifying herbicide residues before they cause a problem.

Growers rely on information provided on the labels about soil type and climate. Herbicide residues are often too small to be detected by chemical analysis, and if testing is possible, it is too expensive to be part of routine farming practice. Once the crop has emerged, diagnosis is difficult because the symptoms of residual herbicide damage can often be confused with, and/or make the crop vulnerable to, other stresses, such as nutrient deficiency or disease. [50]

An option for assessing the potential risk of herbicide residues is to conduct a bioassay involving hand-planting of small test areas of crop into the field in question.

Which herbicides are residual?

The herbicides listed in Table 6 all have some residual activity or planting restrictions.

Table 6: *Active constituent (and example proprietary product) by herbicide group (may not include all current herbicides).*

Herbicide group	Active constituent
Group B: sulfonylureas	Chlorsulfuron (Glean®), iodosulfuron (Hussar®), mesosulfuron (Atlantis®), metsulfuron (Ally®), triasulfuron (Logran®)
Group B: imidazolinones	Imazamox (Raptor®), imazapic (Flame®), imazapyr (Arsenal®)
Group B: triazolopyrimidines (sulfonamides)	Florasulam (Conclude®)
Group C: triazines	Atrazine, simazine
Group C: triazinones	Metribuzin (Sencor®)
Group C: ureas	Diuron
Group D: dinitroanilines	Pendimethalin (Stomp®), trifluralin
Group H: pyrazoles	Pyrasulfotole (Precept®)
Group H: isoxazoles	Isoxaflutole (Balance®)
Group I: phenoxy carboxylic acids	2,4-Ds
Group I: benzoic acids	Dicamba
Group I: pyridine carboxylic acids	Clopyralid (Lontrel®)
Group K: chloroacetamides	Metolachlor
Group K: isoxazolines	Pyroxasulfone (Sakura®)

Source: AgVic.

50 Agriculture Victoria (2013) Avoiding crop damage from residual herbicides. Government of Victoria EDJTR,, http://agriculture.vic.gov.au/agriculture/farm-management/chemical-use/agricultural-chemical-use/chemical-residues/managing-chemical-residues-in-crops-and-produce/avoiding-crop-damage-from-residual-herbicides

How to avoid damage from residual herbicides

Select a herbicide appropriate for the weed population. Consider what the re-cropping limitations may do to future rotation options.

Users of chemicals are required by law to keep good records, including weather conditions, but particularly spray dates, rates, batch numbers, rainfall, soil type and pH (including different soil types in the paddock) (Photo 13). In the case of unexpected damage, good records can be invaluable.

If residues could be present, choose the least susceptible crops (refer to product labels). Optimise growing conditions to reduce the risk of compounding the problem with other stresses such as herbicide spray damage, disease and nutrient deficiency. These stresses make a crop more susceptible to herbicide residues. [51]

Photo 13: *Trial plot showing crop damage with pre-emergent herbicides due to poor separation of herbicide and crop seed.*

Photo: Dr Christopher Preston, Source: GRDC

MORE INFORMATION

NSW DPI: Herbicide residues in soil and water.

6.10.2 Plant-back intervals

Plant-back periods are the obligatory times between the herbicide spraying date and safe planting date of a subsequent crop.

Some herbicides have a long residual. The residual is not the same as the half-life. Although the amount of chemical in the soil may break down rapidly to half the original amount, what remains can persist for long periods (e.g. sulfonylureas (chlorsulfuron). This is shown in Table 7 and 8 where known. Herbicides with long residuals can affect subsequent crops, especially if they are effective at low levels of active ingredient, such as the sulfonylureas. On labels, this will be shown by plant-back periods, which are usually listed under a separate plant-back heading or under the 'Protection of crops etc.' heading in the 'General Instructions' section of the label.

Part of the management of herbicide resistance includes rotation of herbicide groups. Paddock history should be considered. Herbicide residues (e.g. sulfonylurea, triazines, etc.) may be an issue in some paddocks. Remember that plant-back periods begin after rainfall occurs. [52]

51 Agriculture Victoria (2013) Avoiding crop damage from residual herbicides. Government of Victoria EDJTR, http://agriculture.vic.gov.au/agriculture/farm-management/chemical-use/agricultural-chemical-use/chemical-residues/managing-chemical-residues-in-crops-and-produce/avoiding-crop-damage-from-residual-herbicides

52 B Haskins (2012) Using pre-emergent herbicides in conservation farming systems. NSW Department of Primary Industries, http://www.dpi.nsw.gov.au/__data/assets/pdf_file/0003/431247/Using-pre-emergent-herbicides-in-conservation-farming-systems.pdf

Table 7: *Residual persistence of common pre-emergent herbicides, noting residual persistence in broadacre trials and paddock situations.* [53]

Herbicide	Half-life (days)	Residual persistence and prolonged weed control
Logran® (triasulfuron)	19	High. Persists longer in high pH soils. Weed control commonly drops off within 6 weeks
Glean® (chlorsulfuron)	28–42	High. Persists longer in high pH soils. Weed control longer than Logran®
Diuron	90 (range 1 month–1 year, depending on rate)	High. Weed control will drop off within 6 weeks, depending on rate. Has had observed, long-lasting activity on grass weeds such as black/stink grass (*Eragrostis* spp.) and to a lesser extent broadleaf weeds such as fleabane
Atrazine	60–100, up to 1 year if dry	High. Has had observed long-lasting (>3 months) activity on broadleaf weeds such as fleabane
Simazine	60 (range 28–149)	Med./high. 1 year residual in high pH soils. Has had observed, long-lasting (>3 months) activity on broadleaf weeds such as fleabane
Terbyne® (terbulthylazine)	6.5–139	High. Has had observed, long-lasting (>6 months) activity on broadleaf weeds such as fleabane and sowthistle
Triflur® X (trifluralin)	57–126	High. 6–8 months residual. Higher rates longer. Has had observed, long-lasting activity on grass weeds such as black/stink grass
Stomp® (pendimethalin)	40	Medium. 3–4 months residual
Avadex® Xtra (triallate)	56–77	Medium. 3–4 months residual
Balance® (isoxaflutole)	1.3 (metabolite 11.5)	High. Reactivates after each rainfall event. Has had observed, long-lasting (>6 months) activity on broadleaf weeds such as fleabane and sowthistle
Boxer Gold® (prosulfocarb)	12–49	Medium. Typically quicker to break down than trifluralin, but tends to reactivate after each rainfall event.
Sakura® (pyroxasulfone)	10–35	High. Typically quicker breakdown than trifluralin and Boxer Gold®; however, weed control persists longer than Boxer Gold®

53 B Haskins (2012) Using pre-emergent herbicides in conservation farming systems. NSW Department of Primary Industries, http://www.dpi.nsw.gov.au/__data/assets/pdf_file/0003/431247/Using-pre-emergent-herbicides-in-conservation-farming-systems.pdf

Table 8: *Minimum re-cropping intervals and guidelines. NOTE: always read labels to confirm.*

Group and type	Product	pH(H2O) or product rate (mL/ha) as applicable	Minimum re-cropping interval (months after application), and conditions
B, sulfonylurea	Chlorsulfurons, e.g. Glean®, Siege®, Tackle®	<6.5	3 months
		6.6–7.5	3 months, minimum 700 mm
		7.6–8.5	18 months, minimum 700 mm
B, sulfonylurea	Triasulfuron, e.g. Logran®, Nugrain®	7.6–8.5	12 months, >250 mm grain, 300 mm hay
		>8.6	12 months, >250 mm grain, 300 mm hay
B, sulphonamide	Flumetsulam, e.g. Broadstrike®		0 months
B, sulfonylurea	Metsulfuron, e.g. Ally®, Associate®	5.6–8.5	1.5 months
		>8.5	Tolerance of crops grown through to maturity should be determined (small scale) previous season before sowing larger area
B, sulfonylurea	Metsulfuron + thifensulfuron, e.g. Harmony® M	7.8–8.5 Organic matter >1.7%	3 months
		>8.6 or organic matter <1.7%	Tolerance of crops grown through to maturity should be determined (small scale) previous season before sowing larger area
B, sulfonylurea	Sulfosulfuron, e.g. Monza®	<6.5	0 months
		6.5–8.5	10 months

Source: Pulse Australia

Herbicides with long residuals can affect subsequent crops, especially if they are effective at low levels of active ingredient, such as the sulfonylureas. On labels, this will be shown by plant-back periods, which are usually listed under a separate plant-back heading or under the 'Protection of crops etc.' heading in the 'General Instructions' section of the label. [54]

Conditions required for breakdown

Warm, moist soils are required to break down most herbicides through the processes of microbial activity. To be most active, soil microbes need good moisture and an optimum range of soil temperature of 18–30°C. Extreme temperatures above or below this range can adversely affect soil microbial activity and slow herbicide

54 B Haskins (2012) Using pre-emergent herbicides in conservation farming systems. NSW Department of Primary Industries, http://www.dpi.nsw.gov.au/__data/assets/pdf_file/0003/431247/Using-pre-emergent-herbicides-in-conservation-farming-systems.pdf

MORE INFORMATION

Dow AgroSciences: Rotational crop plant-back intervals for northern Australia

breakdown. Very dry soil also reduces breakdown. In addition, when the soil profile is very dry, it requires a lot of rain to maintain topsoil moisture for the microbes to be active for any length of time.

For up-to-date plant-back periods, see the NSW DPI publication: Weed control in winter crops.

6.11 Herbicide resistance

6.11.1 Herbicide resistance facts

- Resistance is the inherited ability of an individual plant to survive and reproduce following a herbicide application that would kill a wild-type individual of the same species.
- Thirty-six weed species in Australia currently have populations that are resistant to at least one herbicide MoA.
- As at June 2014, Australian weed populations have developed resistance to 13 distinct MoAs (click here for up-to-date statistics).
- Herbicide-resistant individuals are present at very low frequencies in weed populations before the herbicide is first applied.
- The frequency of naturally resistant individuals within a population will vary greatly within and between weed species.
- A weed population is defined as resistant when a herbicide at a label rate that once controlled the population is no longer effective (sometimes an arbitrary figure of 20% survival is used for defining resistance in testing).
- The proportion of herbicide-resistant individuals will rise (due to selection pressure) in situations where the same herbicide MoA is applied repeatedly and the survivors are not subsequently controlled.
- Herbicide resistance in weed populations is permanent as long as seed remains viable in the soil. Only weed density can be reduced, not the ratio of resistant to susceptible individuals. The exception is when the resistance gene(s) carries a fitness penalty so that resistant plants produce less seed than susceptible ones—but this is rare.

Key messages

Resistance characteristics:

- Resistance remains for many years, until all resistant weed seeds are gone from the soil seed bank
- Resistance evolves more rapidly in paddocks with frequent use of the same herbicide group, especially if no other control options are used.

Action points:

- Assess your level of risk with the online glyphosate resistance toolkit.
- Aim for maximum effectiveness in control tactics, because resistance is unlikely to develop in paddocks with low weed numbers.
- Do not rely on the same MoA group.
- Monitor your weed control regularly.
- Stop the seedset of survivors. [55]

Herbicide resistance has become far more widespread, reducing the effectiveness of a wide range of herbicide MoAs (Photo 14). Rapid expansion of herbicide resistance and the lack of new MoAs require that non-herbicide tactics must be a significant component of any farming system and weed management strategy. Inclusion of non-herbicide tactics is critical to prolonging the effective life of remaining herbicides, as well as for new products and MoAs that have not yet been released or indeed

55 QDAF (2015) Stopping herbicide resistance in Queensland. Queensland Department of Agriculture and Fisheries, https://www.daf.qld.gov.au/plants/field-crops-and-pastures/broadacre-field-crops/weed-management-in-field-crops/herbicide-resistance

invented. Effective herbicides are key components of profitable cropping systems. Protecting their efficacy directly contributes to the future sustainability and profitability of cropping systems.

Photo 14: *2,4-D resistant radish, Wongan Hills.*

Photo A Storrie, Source: GRDC

Herbicide resistance is an increasing threat across Australia's Northern grain region for both growers and agronomists. Already 14 weeds have been confirmed as herbicide resistant in various parts of this region, and more have been identified at risk of developing resistance, particularly to glyphosate.

In northern NSW, 14 weeds are confirmed resistant to herbicides of Group A, B, C, I, M or Z (see Table 9). As well, ABYG, liverseed grass, common sowthistle and wild oat are at risk of developing resistance to Group M (glyphosate) herbicides (see Table 10). Glyphosate-resistant annual ryegrass has been identified within ~80 farms in the Liverpool Plains area of northern NSW. [56]

56 A Storrie, T Cook, P Moylan, A Maguire, S Walker, M Widderick. Managing herbicide resistance in northern NSW. NSW Department of Primary Industries, http://www.dpi.nsw.gov.au/__data/assets/pdf_file/0006/155148/herbicide-resistance-brochure.pdf

Table 9: *List of confirmed resistant weeds in northern NSW.* [57]

Weed	Herbicide group and product/ chemical (examples only)	Areas with resistance in NSW	Future risk	Detrimental impact
Wild oats	A. Topik® and Wildcat® B. Atlantis® Z. Mataven®	Spread across the main wheat-growing areas. More common in western cropping areas	Areas growing predominantly winter crops	High
Paradoxa grass	A. Wildcat®	North and west of Moree	Areas growing predominantly winter crops	High
Awnless barnyard grass	C. Triazines M. Glyphosate	Mainly between Goondiwindi and Narrabri	No-till or minimum tilled farms with summer fallows	High Very high
Charlock, black bindweed, common sowthistle, Indian hedge mustard, turnip weed	B. Glean®, Ally®	Spread across the main wheat growing areas	Areas growing predominantly winter crops	Moderate
Annual ryegrass	M. Glyphosate B. Glean® A. Verdict®	Group M widespread in Liverpool Plains. Group A and B resistance in central west NSW	Areas with predominantly summer fallows. Winter cropping areas	High High
Fleabane	M. Glyphosate	Spread uniformly across the region	Cotton crops and no-till or minimum tilled systems	Moderate
Wild radish	I. 2,4-D amine	Central-west NSW	Continuous winter cereal cropping	High
Windmill grass	M. Glyphosate	Central-west NSW	Continuous winter cropping and summer fallows	High
Liverseed grass	M. Glyphosate	A few isolated cases	No-till or minimum tilled systems	Moderate
SowthistleA	M. Glyphosate	Liverpool Plains	Winter cereal dominated areas with minimum tillage	High

57 A Storrie, T Cook, P Moylan, A Maguire, S Walker, M Widderick. Managing herbicide resistance in northern NSW. NSW Department of Primary Industries, http://www.dpi.nsw.gov.au/__data/assets/pdf_file/0006/155148/herbicide-resistance-brochure.pdf

Table 10: *List of potential new resistant weeds in northern NSW.* [58]

Weed	Herbicide group and product/ chemical (examples only)	Future risk	Detrimental impact
Barnyard, liverseed and windmill grasses	A. Verdict® L. Paraquat	No-till and minimum tilled systems	Very high Very high
Common sowthistle	I. 2,4-D amine	Winter cereals	High
Paradoxa grass	B. Glean®, Atlantis®	Western wheat growing areas	High
Other brassica weeds including wild radish	B. Glean®, Ally®	Areas growing predominantly winter crops	Moderate
Annual ryegrass	L. Paraquat	Areas with predominantly summer fallows	Very high
Wireweed, black bindweed, melons and cape weed	I. 2,4-D amine, Lontrel®, Starane®	Areas growing predominantly winter crops	High
Fleabane	I. 2,4-D amine L. Paraquat	Cotton crops and no-till or minimum tilled systems	Very high Very high
Other fallow grass weeds	M. Glyphosate	No-till or minimum tilled systems	High

In southern Queensland, seven weeds are confirmed resistant to Group A, B or C herbicides (Table 11). A further four weeds are confirmed resistant to glyphosate (e.g. Roundup®).

Table 11: *List of confirmed resistant weeds in southern Queensland.*

Weed	Herbicide group	Extent of resistance	Future risk	Detrimental impact
Wild oats	A (e.g. Topik® & Wildcat®)	Spread across the main wheat growing areas	Areas growing predominantly winter crops	High
• African turnip weed • Black bindweed • Common sowthistle • Indian hedge mustard • Turnip weed	B (e.g. Glean® & Ally®)	Spread across the main wheat growing area	Areas growing predominantly winter crops	Moderate
Liverseed grass	C (e.g. atrazine)	A few paddocks in eastern Darling Downs	Areas growing predominantly sorghum	High

58 A Storrie T Cook, P Moylan, A Maguire, S Walker, M Widderick. Managing herbicide resistance in northern NSW, NSW Department of Primary Industries, http://www.dpi.nsw.gov.au/__data/assets/pdf_file/0006/155148/herbicide-resistance-brochure.pdf

Weed	Herbicide group	Extent of resistance	Future risk	Detrimental impact
Barnyard grass	M (e.g. glyphosate)	Western Downs	Summer fallows	Very High
• Flaxleaf fleabane • Common sowthistle	M (e.g. glyphosate)	Eastern and Western Downs	Fallows	Very High

Source: QDAF

In central Queensland, the first case of herbicide resistance was confirmed in 2014 with a sweet summer grass population found to be resistant to glyphosate.

Liverseed grass and wild oats are also at risk of developing resistance to Group M (glyphosate) herbicides (see Table 12). While no populations of glyphosate-resistant liverseed grass have been identified in Queensland, four paddocks in the Liverpool Plains area of northern NSW have liverseed grass that is resistant to glyphosate treatment.

Table 12: *List of potential new resistant weeds in central and southern Queensland.*

Weed	Herbicide group	Future risk	Detrimental impact
Wild oats	**M** (e.g. glyphosate)	No-till and minimum-till systems (S Qld)	**High**
Barnyard grass	**C** (e.g. atrazine)	Areas growing predominantly sorghum	**High**
Parthenium	**B** (e.g. Ally®)	Areas growing predominantly winter crops	**High**
Other Brassica weeds	**B** (e.g. Glean® & Ally®)	Areas growing predominantly winter crops	**Moderate**

Source: QDAF

Other broadleaf and grass weeds are also at risk of developing resistance, depending on weed numbers and management practices used. Read more about preventing herbicide resistance in specific weeds.

MORE INFORMATION

GRDC IWM Hub—Herbicide resistance.

How does resistance start?

Resistance starts in a paddock in several ways. Some rare mutations can occur naturally in weeds already in the paddock, with the likelihood varying from 1 plant in 10,000 to 1 in a billion plants, depending on the weed and herbicide. A grower may also import weed seed with the herbicide-resistant gene in contaminated feed, seed or machinery.

Resistance may also be introduced by natural seed spread by wind and water or by pollen, which may blow short distances from a contaminated paddock.

6.11.2 General principles to avoid resistance

Herbicides have a limited life before resistance develops, if they are used repeatedly and exclusively as the sole means of weed control, particularly in zero and minimum tilled systems. Resistance can develop within four–eight years for Group A and B herbicides and after 15 years for Group L and M herbicides (see Table 13 and Figure 3). This can be avoided by:

- keeping weed numbers low
- changing herbicide groups
- using tillage
- rotating crops and agronomic practices.

We have gained further insight into the impact and efficacy of integrated weed management strategy components through a computer-simulated model.

Table 13: *Rules-of-thumb for the number of years of herbicide application before resistance evolves for each Mode of Action group.*

Herbicide group	Years to resistance
A	6–8
B	4–6
C	10–15
D	10–15
L	15+
M	15+

Source: Chris Preston, University of Adelaide, QDAF

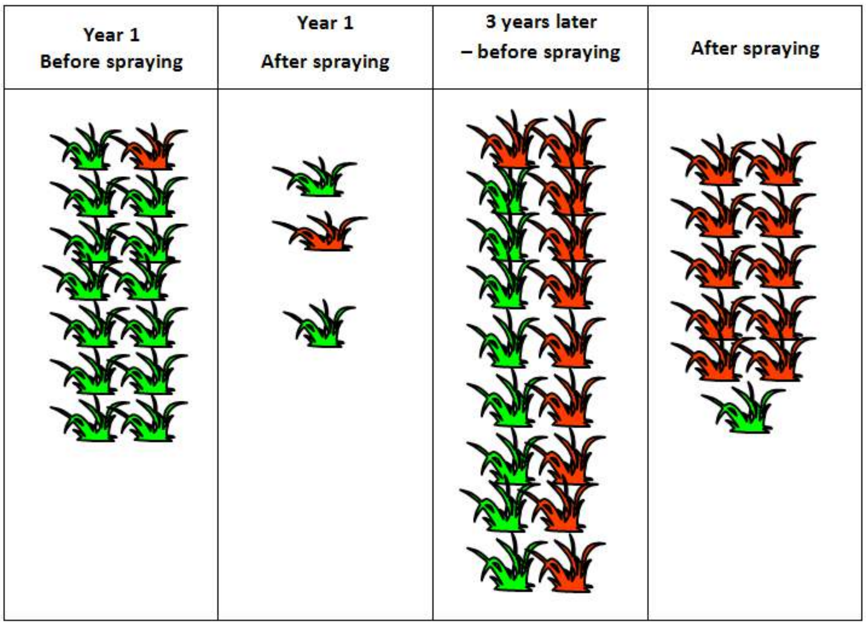


Figure 3: *How a weed population becomes resistant to herbicides.*

Source: GRDC

Strategies to prevent or minimise the risk of resistance developing are based on IWM principles as outlined below:

- Ensure survivors do not set seed and replenish the soil seedbank.
- Keep accurate paddock records of herbicide application and levels of control. Monitor weeds closely for low levels of resistance, especially in paddocks with a history of repeated use of the same herbicide group.
- Rotate between the different herbicide groups, and/or tank mix with an effective herbicide from another MoA group. It is important to use effective 'stand-alone' rates for both herbicides in the mix.
- Aim for maximum effectiveness to keep weed numbers low. The primary aim of weed control is to minimise their impact on productivity, and resistance is much less likely to develop in paddocks with fewer weeds than in heavily infested paddocks.
- Use a wide range of cultural weed-control tools in your weed management plan. Sowing different crops and cultivars provides opportunities to use different weed management options on key weeds. Tillage is useful when it targets a major weed flush and minimises soil inversion, as buried weed seed generally persists

longer than on the soil surface. Competitive crops will reduce seed production on weed survivors.

- Avoid introduction or spread of weeds by contaminated seed, grain, hay or machinery. Also, manage weeds in surrounding non-crop areas to minimise risk of seed and pollen moving into adjacent paddocks.

Specific guidelines for reducing the risk of glyphosate resistance are outlined in Table 14. Aim to include as many as possible of the risk-decreasing factors in your crop and weed management plans.

Table 14: *Balancing the risk for weeds developing glyphosate resistance, devised by the national Glyphosate Sustainability Working Group with minor modifications for the Queensland cropping region.*

Risk increasing	Risk decreasing
Continuous reliance on glyphosate pre-seeding	Double-knock technique
Lack of tillage	Strategic use of alternative knockdown groups
Lack of effective in-crop weed control	Full-disturbance cultivation at sowing
Inter-row glyphosate use (unregistered)	Effective in-crop weed control
Frequent glyphosate-based chemical fallow	Use alternative herbicide groups or tillage for inter-row and fallow weed control
High weed numbers	Non-herbicide practices for weed seed kill
Pre-harvest desiccation with glyphosate	Farm hygiene to prevent resistance movement

Source: QDAF

Glyphosate-resistant weeds in Australia

Glyphosate resistance was first documented for annual ryegrass in 1996 in Victoria. Since then, glyphosate resistance has been confirmed in 11 other weed species. Resistance is known in eight grass species and four broadleaf species. There are four winter-growing weed species and eight summer-growing weed species. The latter have been selected mainly in chemical fallows and on roadsides (Figure 18).

Figure 4: *Winter fallow in northern NSW showing an early glyphosate-resistant sowthistle (Sonchus spp.) infestation.*

Photo: A Storrie, Source: GSWG

MORE INFORMATION

[Australian glyphosate resistance register](http://www.glyphosateresistance.org.au/).

PDF: Strategic risk management FactSheet

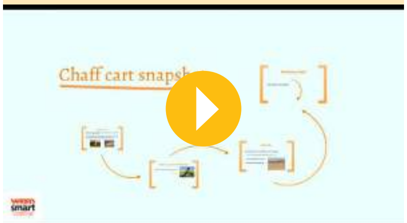
PDF: Farm business management FactSheet

Website: RIM model

VIDEOS

WATCH: Act now: Plan your weed management program

WATCH: Chaff carts 101



WATCH: Capture weed seeds at harvest: Harrington seed destructor

All of the glyphosate-resistant weed populations have occurred in situations where there has been intensive use of glyphosate, often >15 years, few or no other effective herbicides used and few other weed-control practices used. This suggests the following are the main risk factors for the evolution of glyphosate resistance:

- intensive use of glyphosate—every year or multiple times a year for 15 years or more
- heavy reliance on glyphosate for weed control
- no other weed controls targeted to stop seedset.

Farming practices in chemical fallows in the Northern cropping region are heavily dependent on glyphosate for weed control. Therefore, it is highly likely that unconfirmed populations of glyphosate-resistant summer and winter weeds are present in this system.

Farming practices under the vines in vineyards across Australia are heavily dependent on glyphosate for weed control. Therefore, it is highly likely that unconfirmed populations of glyphosate-resistant annual ryegrass are present in this system.

These unconfirmed glyphosate-resistant populations are not recorded on the register of glyphosate-resistant populations in Australia. [59]

The online glyphosate resistance toolkit enables growers and advisers to assess their level of risk for developing glyphosate-resistant weeds on their farm.

6.11.3 10-point plan to weed out herbicide resistance

1. Act now to stop weed seedset

Creating a plan of action is an important first step of IWM. A little bit of planning goes a long way!

- Destroy or capture weed seeds.
- Understand the biology of the weeds present.
- Remember that every successful WeedSmart practice can reduce the weed seedbank over time.
- Be strategic and committed—herbicide resistance management is not a one-year decision.
- Research and plan your WeedSmart strategy.
- You may have to sacrifice yield in the short term to manage resistance—be proactive.

A couple of areas to consider include:

- understanding the biology of your weeds
- being consistent—every successful WeedSmart practice can reduce the weed seed bank over time
- being strategic and committed—herbicide resistance management is not a one-year decision
- being proactive—you may have to sacrifice yield in the short term to manage resistance.

2. Capture weed seeds at harvest

Destroying or capturing weed seeds at harvest is the number one strategy for combating herbicide resistance and driving down the weed seed bank.

- Tow a chaff cart behind the header.
- Check out the new Harrington Seed Destructor (HSD) (Photo 15).
- Create and burn narrow windrows.
- Produce hay where suitable.
- Funnel seed onto tramlines in controlled traffic farming (CTF) systems.

59 C Preston (2016) The Australian Glyphosate Sustainability Working Group. http://www.glyphosateresistance.org.au/

VIDEOS

WATCH: Strategic narrow windrow burning

WATCH: The art of narrow windrow burning

WATCH: Chaff funneling onto tramlines

WATCH: Capture weed seeds at harvest: Bale Direct System

- Use a green or brown manure crop to achieve 100% weed control and build soil N levels.

Controlling weed seeds at harvest is emerging as the key to managing the increasing levels of herbicide resistance, which are putting Australia's no-till farming system at risk.

Photo 15: *Harrington weed seed destructor at work in the paddock.*

Source: GRDC

For information on harvest weed seed control and its application for the Northern grains region, see Section 12: Harvest.

3. Rotate crops and herbicide MoAs

Crop rotation is great for farming systems! Make sure weed management is part of the decision when planning crop rotation.

Crop rotation offers many opportunities to use different weed-control tactics, both herbicide and non-herbicide, against different weeds at different times.

Rotating crops also gives us a range of intervention opportunities. For example, we can crop-top lupins/pulses, swath canola, and delay sowing some crops (e.g. field peas).

Rotations that include both broadleaf crops, like pulses and oilseeds, and cereals allow the use of a wider range of tactics and chemistry.

Growers also have the option of rotating to non-crop (e.g. pastures and fallows).

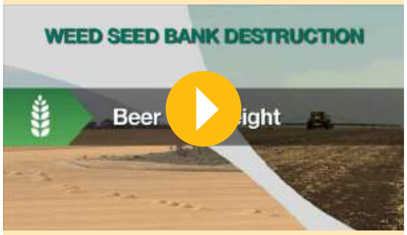
Northern growers can rotate between summer and winter crops to change the weed spectrum.

Within the rotation it is also important to not repeatedly use herbicides from the same MoA group. Some crops have less registered herbicide options than others so this needs to be considered too, along with the opportunities to use other tactics in place of one or more herbicide applications, such as harvest weed-seed control.

Repeated use of herbicides with the same MoA is the single greatest risk factor for herbicide resistance evolution.

VIDEOS

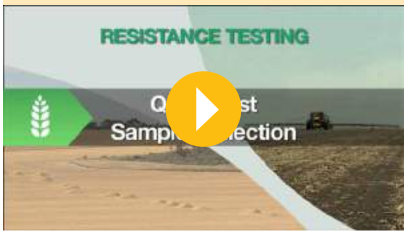
WATCH: IWM: Weed seed vdestruction—Beer can height



WATCH: Crop rotation with Colin McAlpine

WATCH: Test for resistance to establish a clear picture of paddock-by-paddock farm status

WATCH: IWM: Resistance Testing—'Quick-Test' sample collection



4. Test for resistance to establish a clear picture of paddock-by-paddock farm status

- Sample weed seeds prior to harvest for resistance testing to determine effective herbicide options.
- Use the 'Quick-Test' option to test emerged ryegrass plants after sowing to determine effective herbicide options before applying in-crop selective herbicides.
- Collaborate with researchers by collecting weeds for surveys during the double-knock program.
- Visit WeedSmart for more information on herbicide-resistance survey results.

It is clearly too late to prevent resistance evolution for many of our common herbicides. However, a resistance test when something new is observed on-farm can be very useful in developing a plan to contain the problem, and in developing new strategies to prevent this resistance evolving further.

Perhaps the best use for herbicide resistance tests is in a game-changing situation such as the discovery of a rare resistance gene (e.g. glyphosate resistance) or determining whether a patch of surviving weeds is any worse than the grower had observed before. This bad patch of weeds gives insight into the future resistance profile of the farm if it is not contained and resistance testing in these situations can be very useful in building preventative strategies.

5. Never cut the rate

Australian Herbicide Resistance Initiative (AHRI) researcher Dr Roberto Busi found that ryegrass receiving below-rate Sakura® evolved resistance not only to Sakura® but to Boxer Gold® and Avadex® too.

Imagine developing these multiple-resistant, monster weeds just because you cut the rate!

- Use best management practice in spray application.
- Consider selective weed sprayers such as Weedseeker® or Weedit.

6. Do not automatically reach for glyphosate

Glyphosate has long been regarded as the world's most important herbicide, so it is natural to reach for it at the first sign of weeds. But what if it didn't work anymore?

Resistance to this herbicide is shooting through the roof in some areas and this could be the first year we see it fail for growers all across Australia. Why? Too much reliance on one herbicide group gives the weeds opportunity to evolve resistance.

To preserve glyphosate as the wonder weed-killer we know and love we need to break the habit and stop automatically reaching for glyphosate. Introduce paraquat products when dealing with smaller weeds and for a long-term solution, farm with a very low seed bank.

- Use a diversified approach to weed management.
- Consider post-emergent herbicides where suitable.
- Consider strategic tillage.

7. Carefully manage spray events

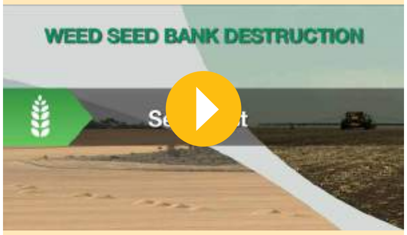
It is important to set up your spray gear to maximise the amount of herbicide applied directly to the target. This makes the spray application more cost-effective by killing the maximum number of weeds possible and protecting other crops and pastures from potential damage and/or contamination.

Spray technology has improved enormously in the last ten years making it far easier for growers to get herbicides where they need to be. Also, many herbicide labels specify the droplet spectrum to be used when applying the herbicide (so take the time to read the label beforehand).

As a rule, medium to coarse droplet size combined with higher application volumes provides better coverage of the target. Using a pre-orifice nozzle slows droplet speed so they are less prone to bouncing off the target.

VIDEOS

WATCH: IWM: Seed test—What's involved



WATCH: Don't cut the rate

WATCH: Don't automatically reach for glyphosate

WATCH: Manage spray drift

WATCH: Plant clean seed into clean paddocks with clean borders

Using oil-based adjuvants with air-induction nozzles can reduce herbicide deposition by reducing the amount of air in the droplets. These droplets then fail to shatter when they hit the target, which increases droplet bounce.

- Stop resistant weeds from returning to the farming system.
- Focus on management of survivors in fallows (Northern grains region).
- Where herbicide failures occur, do not let the weeds seed. Consider cutting for hay or silage, fallowing or brown manuring the paddock.
- Patch-spray areas of resistant weeds only if appropriate.

8. Plant clean seed into clean paddocks with clean borders

Keep it clean! With herbicide resistance on the rise, planting clean seed into clean paddocks with clean borders has become a top priority.

Controlling weeds is easiest before the crop is planted, so be sure to plant weed-free crop seed to prevent the introduction of new weeds and the spread of resistant ones.

Introducing systems that increase farm hygiene will also prevent new weed species and resistant weeds. These systems could include crop rotations, reducing weed burdens in paddocks or a harvest weed-seed control such as the HSD or windrow burning.

Lastly, roadsides and fence lines are often a source of weed infestations. Weeds here set enormous amounts of seed because they have little competition, so it is important to control these initial populations by keeping clean borders.

- It is easier to control weeds before the crop is planted.
- Plant weed-free crop seed to prevent the introduction of new weeds and the spread of resistant weeds.
- A recent AHRI survey showed that 73% of grower-saved crop seed was contaminated with weed seed.
- The density, diversity and fecundity of weeds are generally greatest along paddock borders and areas such as roadsides, channel banks and fence lines.

9. Use the double-knock technique

What is better than an attack on weeds? A second one. Come at them with a different strategy and any survivors left over do not stand a chance. That is the beauty of the double-knock.

To use the double-knock technique, combine two weed-control tactics with different MoAs on a single flush of weeds. These two knocks happen in sequential strategies; the second application designed to control any survivors from the first.

One such strategy is the glyphosate–paraquat double-knock. These two herbicides use different MoAs to eliminate weeds and so make an effective team when paired up. When using this combination ensure the paraquat rate is high.

The best time to initiate a glyphosate/paraquat knock is after rainfall. New weeds will quickly begin to germinate and they should be tackled at this small stage.

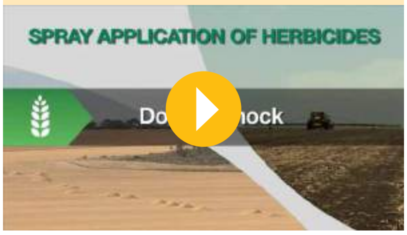
VIDEOS

WATCH: Best results with double-knock tactic

WATCH: Double-knock application—a grower's experience

WATCH: IWM: Double-knock applications—Extent of herbicide resistance in the North

WATCH: Spray application of herbicides—Double-knock



10. Employ crop competitiveness to combat weeds

Help your crops win the war against weeds by increasing their competitiveness against them.

- Consider narrow row spacing and increased seeding rates.
- Consider twin-row seeding points.
- Consider east–west crop orientation.
- Use barley and varieties that tiller well.
- Use high-density pastures as a rotation option.
- Consider brown manure crops.
- Rethink bare fallows.

If you think you have resistant weeds

When resistance is first suspected, we recommend that growers contact their local agronomist.

The following steps are then recommended:

1. Consider the possibility of other common causes of herbicide failure by asking:
2. Was the herbicide applied in conditions and at a rate that should kill the target weed?
3. Did the suspect plants miss herbicide contact or emerge after the herbicide application?
4. Does the pattern of surviving plants suggest a spray miss or other application problem?
5. Has the same herbicide or herbicides with the same MoA been used in the same field or in the general area for several years?
6. Has the uncontrolled species been successfully controlled in the past by the herbicide in question or by the current treatment?
7. Has a decline in the control been noticed in recent years?
8. Is the level of weed control generally good on the other susceptible species?

If resistance is still suspected:

1. Contact the crop and food science researchers at QDAF via the Customer Service Centre for advice on sampling suspect plants for testing of resistance status.
2. Ensure that all suspect plants do not set any seed.
3. If resistance is confirmed, develop a management plan for future years to reduce the impact of resistance and likelihood of further spread. [60]

60 QLD DAF (2015) Stopping herbicide resistance in Queensland. https://www.daf.qld.gov.au/plants/field-crops-and-pastures/broadacre-field-crops/weed-management-in-field-crops/herbicide-resistance

VIDEOS

WATCH: Learn to think outside the drum

WATCH: Crop competition—Increasing wheat seeding rate

WATCH: Crop competition—Row spacing

WATCH: Over the Fence North: Strategic approach to resistant weeds

Testing services

For testing of suspected resistant samples, contact:

- Charles Sturt University Herbicide Resistance Testing
  School of Agricultural and Wine Sciences Charles Sturt University
  Locked Bag 588
  Wagga Wagga, NSW 2678
  02 6933 4001
  http://www.csu.edu.au/research/grahamcentre
  CSU plant testing application form
- Plant Science Consulting P/L
  22 Linley Avenue, Prospect
  SA 5082, Australia
  info@plantscienceconsulting.com.au
  Phone: 0400 66 44 60

6.12 Monitoring weeds

Monitoring of weed populations before and after any spraying is an important part of management:

- Keep accurate records.
- Monitor weed populations and record results of herbicide used.
- If herbicide resistance is suspected, prevent weed seedset.
- If a herbicide does not work, find out why.
- Check that weed survival is not due to spraying error.
- Conduct your own paddock tests to confirm herbicide failure and determine which herbicides remain effective.
- Obtain a herbicide resistance test on seed from suspected plants, testing for resistance to other herbicide (MoA) groups.
- Do not introduce or spread resistant weeds in contaminated grain or hay.

Regular monitoring is required to assess the effectiveness of weed management and the expected situation following weed removal or suppression. Without monitoring, we cannot assess the effectiveness of a management program or determine how it might be modified for improved results. Effective weed management begins with monitoring weeds to assess current or potential threats to crop production, and to determine best methods and timing for control measures.

Regular monitoring and recording details of each paddock allows the grower to:

- spot critical stages of crop and weed development for timely cultivation or other intervention;
- identify the weed flora (species composition), which helps to determine best short- and long-term management strategies; and
- detect new invasive or aggressive weed species while the infestation is still localised and able to be eradicated.

Watch for critical aspects of the weed-crop interaction, such as:

- weed seed germination and seedling emergence
- weed growth sufficient to affect crops if left unchecked
- weed density, height, and cover relative to crop height, cover, and stage of growth
- weed impacts on crops, including harbouring pests, pathogens, or beneficial organisms; or modifying microclimate, air circulation, or soil conditions; as well as direct competition for light, nutrients, and moisture
- flowering, seedset, or vegetative reproduction in weeds
- efficacy of cultivations and other weed management practices.

MORE INFORMATION

Visit CropLife Australia for herbicide resistance management strategies

Australian Glyphosate Sustainability Working Group

Australian Herbicide Resistance Initiative

WEEDpak

Managing herbicide resistance in northern NSW

Information gathered through regular and timely field monitoring helps growers to select the best tools and timing for weed-control tactics. Missing vital cues in weed and crop development can lead to costly efforts to rescue a crop, efforts that may not be fully effective. Good paddock scouting can help the grower to obtain the most effective weed control for the least fuel use, labour cost, chemical application, crop damage and soil disturbance.

6.12.1 Tips for monitoring

To scout weeds, walk slowly through the paddock, examining any vegetation that was not planted. In larger paddocks, walk back and forth in a zigzag pattern to view all parts of the paddock, noting areas of particularly high or low weed infestation. Identify weeds with the help of a good weed guide or identification key for your region, and note the weed species that are most prominent or abundant. Observe how each major weed is distributed through the paddock. Are the weeds randomly scattered, clumped or concentrated in one part of the paddock?

Keep records in a field notebook. Prepare a page for each paddock or crop sown, and take simple notes of weed observations each time the paddock is monitored. Over time, your notes become a timeline of changes in the weed flora over the seasons and in response to crop rotations, cover crops, cultivations and other weed-control practices. Many growers already maintain separate records for each paddock; weed observations (species, numbers, distribution, size) can be included with these.

Insect control

Key messages:

- Cereal rye can attract armyworms. [1]
- An abundance of top growth (when rye is used for cover cropping) that is poorly incorporated may cause poor seed-to-soil contact in the subsequent crop and may attract armyworms or cutworms. [2]
- Cereal rye can attract significant numbers of beneficial insects such as lady beetles. [3]
- Insects are not usually a major problem in winter cereals but sometimes they build up to an extent that control may be warranted.
- Integrated pest management (IPM) strategies encompass chemical, cultural and biological control mechanisms to help improve pest control and limit damage to the environment.
- For current chemical control options refer to the Pest Genie or Australian Pesticides and Veterinary Medical Authority (APVMA).

7.1 Integrated pest management

Pest insects can have adverse and damaging impacts on agricultural production and market access, the natural environment, and our lifestyle. Pest insects may cause problems by damaging crops (Tables 1, 2 and 3) and food production, parasitising livestock, or being a nuisance and health hazard to humans. IPM Guidelines provide an extensive collection of tools and strategies to manage pests in grain cropping systems.

1 WS Curran, DD Lingenfelter, L Garling, P Wagoner (2006) Cover crops for conservation tillage systems. The Pennsylvania State University, http://extension.psu.edu/plants/crops/soil-management/conservation-tillage/cover-crops-for-conservation-tillage-systems

2 Manure $ense (2009) Cereal rye: manure and livestock's new best friend. Michigan State University February 2009

3 A Clark (ed.) 2007 Managing cover crops profitably. 3rd ed. SARE Outreach Handbook Series Book 9. National Agricultural Laboratory, http://www.sare.org/publications/covercrops.htm

Table 1: *Winter cereal pests affecting Northern Region crops.*

	Pre-season	Establishment	Winter	Spring
Aphids	Remove green bridge (weed and volunteer hosts)	High risk: • wet summer/autumn • history of virus If high risk, consider seed dressings. Targeted early control along crop edges or infested patches may delay build-up in the crop.	High risk: Warm conditions favour aphids. Monitor and record aphids and beneficials. Review to determine if populations increase/decrease or are stable. Rainfall >20 mm will reduce aphid populations. Consider delaying insecticide application if rain is forecast. If spray required, use a selective insecticide.	A warm, dry spring encourages population growth. No yield loss will occur if infestations occur later than milky grain. Monitor/record aphids and beneficials. Use suggested thresholds. If spray required, use a selective insecticide. Use of broad spectrum pesticides will kill beneficial insects and increase likelihood of aphid population resurgence.
Common Armyworm	• Control host weeds (especially ryegrass) • Ensure correct ID (armyworm vs *Helicoverpa*.)	Use traps to indicate moth activity (lures of 10% port, 15% raw sugar and 75% water)	High risk: good local rain following a dry period encourages egg laying. Monitoring: • Use traps to monitor for moth activity. • Monitor for larvae at dusk with a sweep net. • Ground search for larvae and droppings. • Look for scalloped leaf margins. Control larvae when small.	Increase monitoring as crop starts to dry down. Small larvae take 8–10 days to reach size capable of head lopping. Determine if crop will be susceptible (dry, except for green nodes) when larvae reach damaging size. Control late in the day when larvae are actively feeding. Use of SPs to control armyworm early can increase likelihood of *Helicoverpa* survival and damage by killing beneficials that would control them.
Helicoverpa armigera	If large numbers of *Helicoverpa* present in previous crop, pupae busting may reduce pest incidence.		• Monitor for larvae with sweep net (can be done when checking for armyworm), or with a beat sheet. • Control small larvae (<7 mm) with NPV	Monitor for larvae using a sweep net or beat sheet. • Large larvae are most damaging to developing grain. (Small larvae (<7 mm) can be controlled with NPV). • Be aware that *H. armigera* have resistance to SPs in all regions.

Source: IPM Guidelines

Table 2: *Insect pest risk for winter cereals in the Northern Region.*

High risk	Moderate risk	Low risk
Soil insects, slugs and snails		
• Some crop rotations increase the likelihood of soil insects: » cereal sown into a long-term pasture phase » high stubble loads » above average rainfall over summer-autumn. • History of soil insects, slugs and snails • Summer volunteers and brassica weeds will increase slug and snail numbers • Cold, wet establishment conditions expose crops to slugs and snails	• Information on pest numbers prior to sowing from soil sampling, trapping and/ or baiting will inform management. • Implementation of integrated slug management strategy (burning stubble, cultivation, baiting) where history of slugs. • Increased sowing rate to compensate for seedling loss caused by establishment pests.	Slugs and snails are rare on sandy soils.
Earth mites		
• Cereals adjacent to long-term pastures may get mite movement into crop edges. • Dry or cool, wet conditions that slow crop growth increase crop susceptibility to damage. • History of high mite pressure.	Leaf curl mite populations (they transmit wheat streak mosaic virus) can be increased by grazing and mild wet summers.	Seed dressings provide some protection, except under extreme pest pressure.
Aphids		
Higher risk of BYDV disease transmission by aphids in higher rainfall areas where grass weeds are present prior to sowing. Wet summer and autumn promotes survival of aphids on weed and volunteer hosts.	Wet autumn and spring promotes the growth of weed hosts (aphids move into crops as weed hosts dry off). • Planting into standing stubble can deter aphids landing. • Use of seed dressings can reduce levels of virus transmission and delay aphid colonisation. • Use of SPs and OPs to control establishment pests can kill beneficial insects and increase the likelihood of aphid survival.	Low rainfall areas have a lower risk of BYDV infection. High beneficial activity (not effective for management of virus transmission).

High risk	Moderate risk	Low risk
Armyworm		
Large larvae present when the crop is at late ripening stage.	High beneficial insect activity (particularly parasitoids). Rapid crop dry down.	No armyworm present at vegetative and grain filling stages.

Source: IPM Guidelines

Table 3: *Impact of insect according to crop stage. * Snails are also a grain contaminant at harvest*

Pest	Crop stage			
	Emergence	Vegetative	Flowering	Grainfill
Wireworms	Damaging	Present		
Cutworm	Damaging			
Black headed cockchafer	Damaging	Present		
Earth mites	Damaging	Present		
Slugs, snails*	Damaging			
Brown wheat mite		Damaging		
Aphids	Present	Damaging	Present	Present
Armyworm		Present	Present	Damaging
Helicoverpa armigera				Damaging

Present — Present in crop but generally not damaging

Damaging — Crop susceptible to damage and loss

Source: IPM Guidelines

Integrated pest management is an approach that uses a combination of biological, cultural and chemical control methods to reduce insect pest populations. A key aim of IPM is to reduce reliance on insecticides as the sole and primary means of pest control. IPM can improve growers' profitability while reducing environmental damage and limiting the risk of on-farm pesticide exposure.

7.1.1 Key IPM strategies for winter cereals:

- Where the risk of establishment pest incidence is low (e.g. earth mites) regular monitoring can be substituted for the prophylactic use of seed dressings.
- Where establishment pests and aphid infestations are clearly a result of invasion from weed hosts around the field edges or neighbouring pasture—a border spray of the affected crop may be sufficient to control the infestation.

Insecticide choices:

- Redlegged earth mite (RLEM), blue oat mite (BOM) and other mite species can occur in mixed populations. Determine species composition before making decisions as they have different susceptibilities to chemicals.
- Establishment pests have differing susceptibilities to insecticides (SPs, OPs in particular). Be aware that the use of some pesticides may select for pests that are more tolerant.

Insecticide resistance:

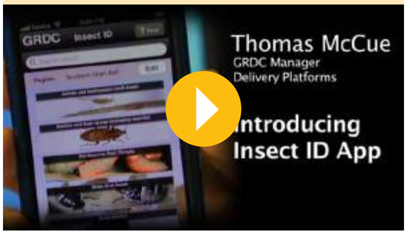
- RLEM has been found to have high levels of resistance to synthetic pyrethroids such as bifenthrin and alpha-cypermethrin.

VIDEOS

WATCH: GCTV2: Integrated pest management

WATCH: Over the Fence North: Vigilance needed for changing insect patterns.

WATCH: GCTV11: GRDC's Insect ID App



MORE INFORMATION

IPM Guidelines for grains

Emerging insect threats in northern grain crops.

IPM Guidelines website.

- *Helicoverpa armigera* has historically had high resistance to pyrethroids and the inclusion of nucleopolyhedrovirus (NPV) is effective where mixed populations of armyworm and *Helicoverpa* occur in maturing winter cereals. [4]

7.1.2 Emerging insect threats in Northern Region crops

Key points:

- Monitor crops frequently so as not to be caught out by new or existing pests.
- Look for and report any unusual pests/damage symptoms—photographs are good.
- Just because a pest is present in large numbers in one year does not mean it will necessarily be so next year—it may be the turn of another spasmodic pest; e.g. soybean moth, to make its presence felt.
- However, be aware of cultural practices that favour pests and rotate cops each year to minimise the build-up of pests and plant diseases.
- Agronomists and growers should monitor their crops and report the first signs of any suspicious activity. [5]

For pest identification see the A-Z pest list or consult the GRDC Insect ID: The Ute Guide.

The Insect ID: The Ute Guide is a comprehensive reference guide for insect pests commonly affecting broadacre crops and growers across Australia, and includes the beneficial insects that may help to control them. Photos have been provided for multiple life cycle stages, and each insect is described in detail, with information on the crops they attack, how they can be monitored and other pests that they may be confused with. Use of this app should result in better management of pests, increased farm profitability and improved chemical usage. [6]

App features:

- Region selection
- Predictive search by common and scientific names
- Compare photos of insects side by side with insects in the app
- Identify beneficial predators and parasites of insect pests
- Opt to download content updates in-app to ensure you are aware of the latest pests affecting crops for each region
- Ensure awareness of international bio-security pests

Insect ID, The Ute Guide is available on Android and iPhone.

4 IPM Guidelines (2016) Winter cereals. GRDC and QDAF, http://ipmguidelinesforgrains.com.au/crops/winter-cereals/

5 H Brier, M Miles (2015) Emerging insect threats in northern grain crops. GRDC Update Paper, 31 July 2015, https://grdc.com.au/Research-and-Development/GRDC-Update-Papers/2015/07/Emerging-insect-threats-in-northern-grain-crops

6 GRDC, https://grdc.com.au/Resources/Apps

7.1.3 Insect sampling methods

Monitoring for insects is an essential part of successful IPMs. Correct identification of immature and adult stages of both pests and beneficials, and accurate assessment of their presence in the field at various crop stages will ensure appropriate and timely management decisions. Good monitoring procedure involves not just a knowledge of and the ability to identify the insects present, but also good sampling and recording techniques and a healthy dose of common sense.

Factors that contribute to quality monitoring:

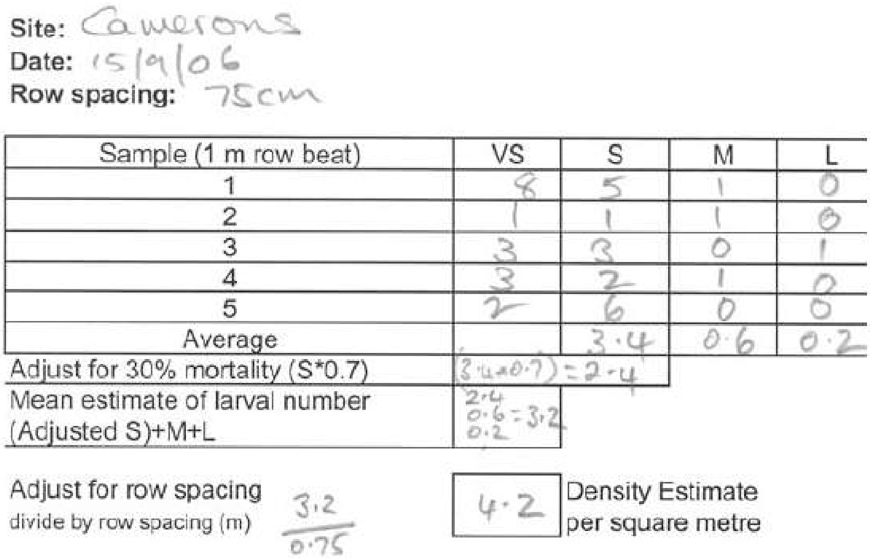
- Knowledge of likely pests/beneficials and their life cycles is essential when planning your monitoring program. As well as visual identification, you need to know where on the plant to look and what is the best time of day to get a representative sample.
- Monitoring frequency and pest focus should be directed at crop stages likely to incur economic damage. Critical stages may include seedling emergence and flowering/grain formation.
- Sampling technique is important to ensure a representative portion of the crop has been monitored since pest activity is often patchy. Having defined sampling parameters (e.g. number of samples per paddock and number of leaves per sample) helps sampling consistency. Actual sampling technique including sample size and number, will depend on crop type, age and paddock size, and is often a compromise between the ideal number and location of samples and what is practical regarding time constraints and distance covered.
- Balancing random sampling with areas of obvious damage is a matter of common sense. Random sampling aims to give a good overall picture of what is happening in the field, but any obvious hotspots should also be investigated. The relative proportion of hotspots in a field must be kept in perspective with less heavily infested areas.

Keeping good records

Accurately recording the results of sampling is critical for good decision making and being able to review the success of control measures (Figure 1). Monitoring record sheets should show the following:

- numbers and types of insects found (including details of adults and immature stages)
- size of insects—this is particularly important for larvae
- date and time
- crop stage and any other relevant information (e.g. row spacings, weather conditions, and general crop observations).

Consider putting the data collected into a visual form that enables you to see trends in pest numbers and plant condition over time. Being able to see whether an insect population is increasing, static or decreasing can be useful in deciding whether an insecticide treatment may be required, and if a treatment has been effective. If you have trouble identifying damage or insects present, keep samples or take photographs for later reference.


Site: Camerons
Date: 15/9/06
Row spacing: 75cm

Sample (1 m row beat)	VS	S	M	L
1	8	5	1	0
2	1	1	1	0
3	3	3	0	1
4	3	2	1	0
5	2	6	0	0
Average		3.4	0.6	0.2
Adjust for 30% mortality (S*0.7)	(3.4*0.7) = 2.4			
Mean estimate of larval number (Adjusted S)+M+L	2.4 0.6 0.2 = 3.2			

Adjust for row spacing
divide by row spacing (m) $\frac{3.2}{0.75}$

4.2 Density Estimate per square metre

Figure 1: *An example of a field check sheet for crops, showing adjustments for field mortality and row spacings.*

Source: QDAF

Records of spray operations should include:

- date and time of day
- conditions (wind speed, wind direction, temperature, presence of dew and humidity)
- product(s) used (including any additives)
- amount of product(s) and volume applied per hectare
- method of application including nozzle types and spray pressure
- any other relevant details.

Sampling methods

Beat sheet

A beat sheet is the main tool used to sample row crops for pests and beneficial insects (Photo 1). Beat sheets are particularly effective for sampling caterpillars, bugs, aphids and mites. A standard beat sheet is made from yellow or white tarpaulin material with heavy dowel on each end. Beat sheets are generally between 1.3–1.5 m wide by 1.5–-2.0 m deep (the larger dimensions are preferred for taller crops). The extra width on each side catches insects thrown out sideways when sampling and the sheet´s depth allows it to be draped over the adjacent plant row. This prevents insects being flung through or escaping through this row.

How to use the beat sheet:

- Place the beat sheet with one edge at the base of plants in the row to be sampled.
- Drape the other end of the beat sheet over the adjacent row. This may be difficult in crops with wide row spacing (one metre or more) and in this case spread the sheet across the inter-row space and up against the base of the next row.
- Using a one-metre stick, shake the plants in the sample row vigorously in the direction of the beat sheet 5–10 times. This will dislodge the insects from the sample row onto the beat sheet.
- Reducing the number of beat sheet shakes per site greatly reduces sampling precision. The use of smaller beat sheets, such as small fertiliser bags, reduces sampling efficiency by as much as 50%.

- Use the datasheets to record type, number and size of insects found on the beat sheet.
- One beat does not equal one sample. The standard sample unit is five non-consecutive one-metre long lengths of row, taken within a 20 m radius; i.e. 5 beats = 1 sample unit. This should be repeated at six locations in the field (i.e. 30 beats per field).
- The more samples that are taken, the more accurate is the assessment of pest activity, particularly for pests that are patchily distributed such as pod-sucking bug nymphs.

When to use the beat sheet:

- Crops should be checked weekly during the vegetative stage and twice weekly from the start of budding onwards.
- Caterpillar pests are not mobile within the canopy, and checking at any time of the day should report similar numbers.
- Pod-sucking bugs, particularly green vegetable bugs, often bask on the top of the canopy during the early morning and are more easily seen at this time.
- Some pod-sucking bugs, such as brown bean bugs, are more flighty in the middle of the day and therefore more difficult to detect when beat sheet sampling. Other insects (e.g. mirid adults) are flighty no matter what time of day they are sampled so it is important to count them first.
- In very windy weather, bean bugs, mirids and other small insects are likely to be blown off the beat sheet.
- Using the beat sheet to determine insect numbers is difficult when the field and plants are wet.

While the recommended method for sampling most insects is the beat sheet, visual checking in buds and terminal structures may also be needed to supplement beat sheet counts of larvae and other more minor pests. Visual sampling will also assist in finding eggs of pests and beneficial insects.

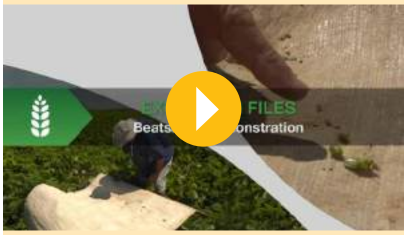
Most thresholds are expressed as pests per square metre (pests/m^2). Hence, insect counts in crops with row spacing less than one metre must be converted to pests/m^2. To do this, divide the 'average insect count per row metre' across all sites by the row spacing in metres. For example, in a crop with 0.75 m (75 cm) row spacing, divide the average pest counts by 0.75.

Other sampling methods:

- Visual checking is not recommended as the sole form of insect checking; however it has an important support role. Leaflets or flowers should be separated when looking for eggs or small larvae, and leaves checked for the presence of aphids and silverleaf whitefly. If required, dig below the soil surface to assess soil insect activity. Visual checking of plants in a crop is also important for estimating how the crop is going in terms of average growth stage, pod retention and other agronomic factors.
- Sweep net sampling is less efficient than beat sheet sampling and can underestimate the abundance of pest insects present in the crop. Sweep netting can be used for flighty insects and is the easiest method for sampling mirids in broadacre crops or crops with narrow row spacing (Photo 1). It is also useful if the field is wet. Sweep netting works best for smaller pests found in the tops of smaller crops (e.g. mirids in mungbeans), is less efficient against larger pests such as pod-sucking bugs, and it is not practical in tall crops with a dense canopy such as coastal or irrigated soybeans. At least 20 sweeps must be taken along a single 20 m row.
- Suction sampling is a quick and relatively easy way to sample for mirids. Its main drawbacks are unacceptably low sampling efficiency, a propensity to suck up flowers and bees, noisy operation, and high purchase cost of the suction machine.

VIDEOS

WATCH: GCTV16: Extension files—IPM beat sheet demo



WATCH: How to use a sweep net to sample for insect pests

MORE INFORMATION

IPM guidelines for monitoring tools and techniques.

- Monitoring with traps (pheromone, volatile, and light traps) can provide general evidence on pest activity and the timing of peak egg lay events for some species. However, it is no substitute for in-field monitoring of actual pest and beneficial numbers. [7]

Photo 1: *Sweep netting for insects (left) and use of a beat sheet (right).*

Source: DAFWA and The Beatsheet

7.2 Russian wheat aphid

Russian wheat aphid (RWA) (*Diuraphis noxia*), a major pest of wheat and barley, poses a major threat to the Australian grains industry. The global distribution of RWA continues to expand, aided by the ease of international travel.

Russian wheat aphid has been confirmed to be present in NSW following detections in South Australia in May and Victoria in June 2016. Grain growers and consultants across NSW are urged to monitor cereal paddocks for signs of RWA, and report suspect aphids or symptoms to NSW DPI.

If not controlled RWA can cause up to 80 and 100% yield loss in wheat and barley respectively. RWA is also a minor pest of oats, rye, sorghum and triticale and a vector of barley yellow dwarf virus (BYDV), brome mosaic virus (BMV) and barley stripe mosaic virus. The RWA's host range also includes several non-crop grass species that occur in Australia.

Russian wheat aphid is adapted to semi-arid dryland climates where annual rainfall is usually less than 600 mm and therefore it is well suited to survive in Australian grain-growing regions. [8]

Secondary hosts are plants that support adults and final instars only. These hosts allow the aphid to survive but not to reproduce. Secondary hosts include rye, oat, and triticale.

Russian wheat aphid can spread by wind, movement of machinery and vehicles and on people's clothing. [9]

It appears that RWA is most often being found in early-sown crops or those sown into paddocks containing volunteer cereals. Early observations also suggest that it is most prevalent in stressed areas within the crop. Overseas data also indicate that RWA is susceptible to heavy winter rainfall so the combination of cold and wet weather may limit its build up over winter. Grass weeds and pasture hosts include barley grass, brome grass, fescue, ryegrass, wild oats, phalaris and couch grass. [10]

7 QDAF (2012) Insect monitoring techniques for field crops. https://www.daf.qld.gov.au/plants/field-crops-and-pastures/broadacre-field-crops/integrated-pest-management/help-pages/insect-monitoring

8 A Nicholas (2016) Exotic pest alert: Identification of Russian Wheat Aphid and associated crop damage. http://cwfs.org.au/wp-content/uploads/2016/06/Exotic-Pest-Alert-Russian-Wheat-Aphid-Identification-and-Associated-Damage.pdf

9 DPI NSW (2016) Russian wheat aphid. http://www.dpi.nsw.gov.au/content/biosecurity/plant/russian-wheat-aphid

10 M Pardy (2016). Riverine Plains Grower Bulletin Issue 2, July 2016

7.2.1 Identification

Russian wheat aphid is a small, (~2 mm) slender-bodied aphid that varies in colour from pale yellowish-green to grey-green and is usually covered in a waxy fine white powder coating (Photo 2). Winged RWAs have dark patches on the thorax and a slightly darker green abdomen than non-winged specimens.

The cornicles (tube-like structures at the rear of the abdomen) are very short, rounded, and although present can be very difficult to see and often appear to be absent.

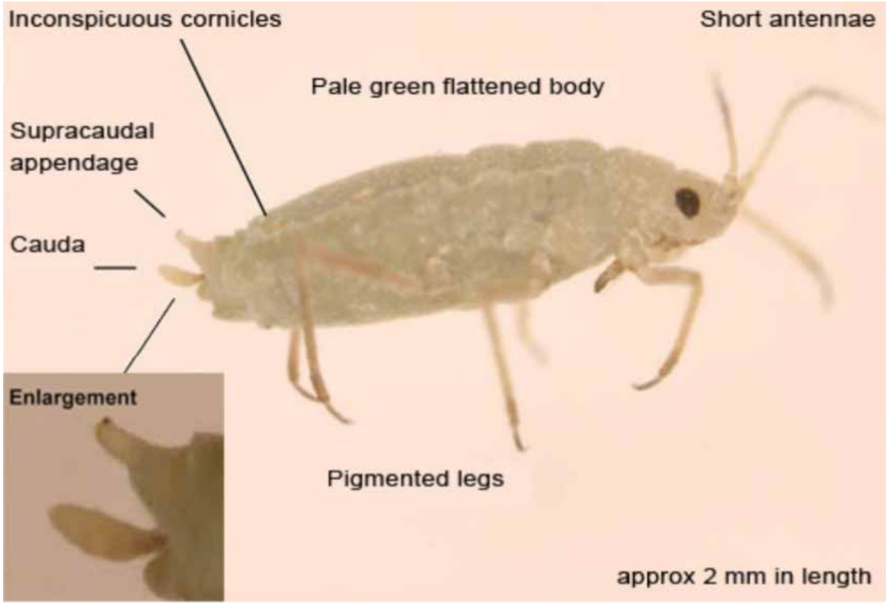


Photo 2: *Key identifying characteristics of RWA.*

Source: DPI NSW

The RWA's most distinguishing feature and what sets it apart from all other cereal aphids is an appendage above the cauda (tail), a supracauda, giving the aphid the appearance of having two tails.

The RWA's supracauda is large and conspicuous on the non-winged forms but shorter and knob-like on winged specimens (Photo 3). With care the supracauda can be seen with a hand lens. [11]

11 A Nicholas (2016) Exotic pest alert: Identification of Russian Wheat Aphid and associated crop damage. http://cwfs.org.au/wp-content/uploads/2016/06/Exotic-Pest-Alert-Russian-Wheat-Aphid-Identification-and-Associated-Damage.pdf

Photo 3: *Colony of RWAs (Diuraphis noxia) in a wheat leaf.*

Photo: Frank Peairs, Source: PIRSA

What to look for

Detection of RWA is most likely to occur with the observation of symptomatic plants. Scout for symptomatic tillers in host crops and inspect for aphids (Photo 4). RWA is very small (less than 2 mm) and a 10× magnification hand lens can be used to examine them.

Photo 4: *Feeding of RWA colonies causes striped discolouration of leaves.*

Source: DPI NSW

Russian wheat aphid may be present in mixed populations. If aphids which are commonly found in cereals are observed it should not be assumed these are the only ones present.

Symptoms associated with the presence of RWA include:

- stunted growth (Photo 5)
- leaves with white, yellowish and red streaks (Photo 6)
- leaf rolling along margins
- awns trapped by rolled flag leaves
- heads with a bleached appearance. [12]

Photo 5: *Stunted growth and leaf discolouration caused by RWA.*

Source: DPI NSW

Leaves infested with RWA develop continuous white, yellowish and red (sometimes described as purplish) streaks along the length of leaf (Photo 6). The occurrence and intensity of colouration varies, with the coloured streaks on young, lightly infested plants often restricted to the leaf edge. This can be difficult to detect and a hand lens is required.

12 DPI NSW (2016) Russian wheat aphid. http://www.dpi.nsw.gov.au/content/biosecurity/plant/russian-wheat-aphid

Figure 2: *Discolouration of wheat leaves caused by RWA.*

Source: DPI NSW

7.2.2 Varietal resistance or tolerance

Russian wheat aphid tends to prefer barley > durum wheat > bread wheat > triticale > cereal rye > oats.

7.2.3 Damage caused by pest

Russian wheat aphid is a major field pest of wheat and barley in many grain producing countries. Yield losses of up to 80% in wheat and 100% in barley have been reported overseas.

Russian wheat aphid injects toxins into the plant during feeding which stunts plant growth. Heavy infestations may kill plants. Toxins injected by the aphid during feeding destroy chlorophyll and prevent carbohydrate formation, with heavy infestations killing the plant. Initially RWA feeding causes a small light brown blotch that can be confused with damage by other insects and more problematically with symptoms caused by disease. [13]

Russian wheat aphid will infest the plant at any growth stage, preferring to feed within the new leaves while they are rolled up; i.e. before the leaf opens. This feeding can prevent the leaf from opening and gives the young plant an onion-leaf like appearance.

Feeding on open leaves causes the leaf to roll inwards around the aphid providing a suitable and protected microclimate. Infested flag leaves that remain unrolled trap the awns which prevents the wheat head from fully emerging and reduces grainfill (Photo 6).

According to SARDI cereal pathologist Dr Hugh Wallwork, RWA does not seem to be a good transmitter of viruses.

13 DPI NSW (2016) Russian wheat aphid. http://www.dpi.nsw.gov.au/content/biosecurity/plant/russian-wheat-aphid

Photo 6: *Wheat awns trapped by flag leaf damaged by RWA feeding*

Photo: Food and Agriculture Organisation, Source: DPI NSW

7.2.4 Thresholds for control

Economic thresholds for control still need to be determined for Australian conditions. However, as with most pests and diseases, spraying should be considered only where aphid levels are high enough to cause economic damage.

Current international advice suggests an economic threshold of 20% of plants infested up to the start of tillering and 10% of plants infested thereafter.

The lower thresholds post-tillering reflects the need to protect the major yield contributing leaves. [14]

7.2.5 Management of insect pest

Monitoring

An aphid sample may be required for accurate identification:

- Leave aphids on host leaves where possible to reduce damage to aphids during transportation.
- Sample suspect plants, ensuring they are infested with aphids. Remove roots and soil.
- Samples should be placed in sealed container, vial or plastic ziplock bag with triple packaging (e.g. vial with two layers of plastic ziplock bags).

14 M Pardy (2016). Riverine Plains Grower Bulletin Issue 2, July 2016

VIDEOS

WATCH: Integrated Pest Management to combat the RWA

MORE INFORMATION

RWA surveillance reporting sheet

Exotic pest alert: Identification of RWA and associated damage

PIRSA RWA—Paddock decontamination protocol

RWA Distribution Map

- All samples should be accompanied by an RWA diagnosis request form.
- Samples should be sent by express post.

Hygiene

It is important to put hygiene practices into place to reduce the risk of transporting pests and diseases on clothing, footwear, vehicles and machinery when moving between paddocks and farms.

If symptoms of suspected RWA are observed it is important to change clothing (including hats) and clean footwear and vehicles before entering another paddock or farm. People entering crops should consider wearing disposable coveralls and changing these between farms. Used coveralls should be bagged and securely disposed of. Clothing worn in a suspected infested crop should be bagged, sealed and washed before being worn again.

Chemical control

It is most important to control RWA from the start of stem elongation through flag leaf development and ear emergence.

If chemical control is required, APVMA has issued an emergency permit [#82792] for the control of RWA. The specific use of these chemicals, however, depends on the state in which the crop is grown, so growers will need to contact their local authorities for further information.

Chemical control should consider economic thresholds, insecticide resistance in other crop pests, natural pest enemies and beneficial insects as part of IPM. [15]

See the GRDC website for the latest nationally developed RWA management guidelines.

- Gloves are up in sustained FITE against RWA

7.3 *Helicoverpa* spp.

The name *Helicoverpa* refers to two species of moth, the larvae of which attack field crops in the Northern grains region of Australia. These two species are *Helicoverpa punctigera* and *H. armigera*. Together, they are the most economically damaging insect pests of field crops in Queensland and northern NSW, and are major pests of irrigated crops in southern NSW.

Helicoverpa armigera is generally regarded as the more serious pest because of its greater capacity to develop resistance to insecticides, its broader host range, and the fact that it persists in cropping areas from year to year, whereas *H. punctigera* numbers fluctuate from year to year based on conditions in its inland breeding areas.

Helicoverpa armigera attacks all crops but is less common in wheat and barley. In contrast, *H. punctigera* only attacks broadleaf crops and is not found on grass or cereal crops such as wheat, barley, sorghum or maize. As it is not unusual to find both *Helicoverpa* and armyworm in cereal crops, correct identification of the species present is important.

Lifecycles of *Helicoverpa* spp. takes 4–6 weeks from egg to adult in summer and 8-12 weeks in spring or autumn. The lifecycle stages are egg, larvae, pupa and adult (moth) (Figure 3).

15 DPI NSW (2016) Russian wheat aphid. http://www.dpi.nsw.gov.au/content/biosecurity/plant/russian-wheat-aphid

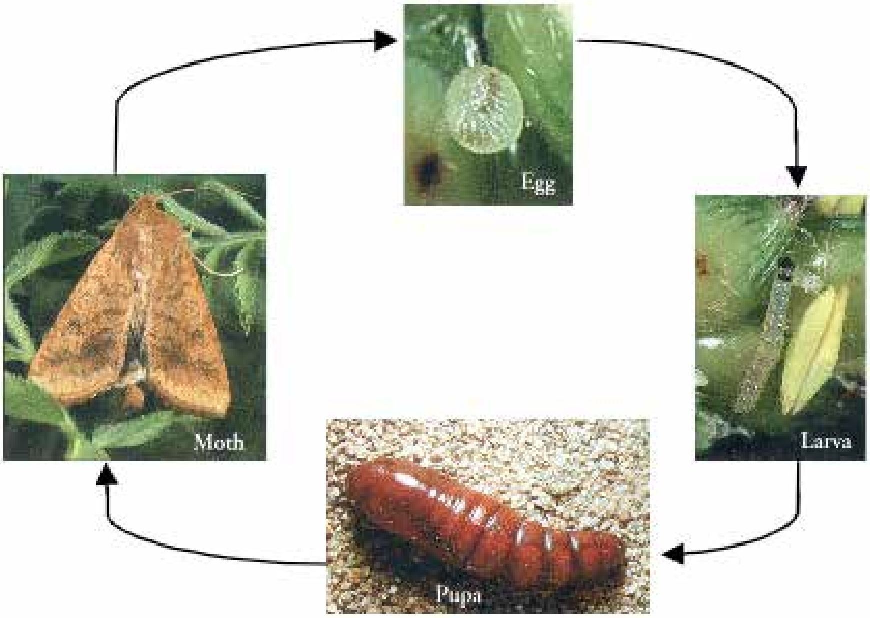


Figure 3: *Lifecycle of Helicoverpa.*

Source: Pulse Australia

Eggs are 0.5 mm in diameter and change from white to brown to a black head stage before hatching. Newly hatched larvae are light in colour with tiny dark spots and dark heads. As larvae develop they become darker and the darker spots become more obvious. Both species look the same at the egg and small larvae stages (Photo 7).

Photo 7: *Left to right: fresh white, brown ring and black larval head in nearly hatching eggs.*

Source: CropIT

Medium larvae develop lines and bands running the length of the body and are variable in colour (Figure 11). *H. armigera* have a saddle of darker pigment on the fourth segment and at the back of the head and dark-coloured legs. *H. punctigera* have no saddle and light-coloured legs.

Large larvae of *H. armigera* have white hairs around the head; *H. punctigera* have black hairs around the head.

Photo 8: *H. armigera larvae showing white hairs on head.*

Source: Cabi

Pupae are found in soil underneath the crop. Healthy pupae wriggle violently when touched. *H. armigera* pupal tail spines are more widely spaced than those of *H. punctigera*.

Moths are a dull light brown with dark markings and are 35 mm long. *H. armigera* has a small light or pale patch in the dark section of the hindwing (Photo 9) while the dark section is uniform in *H. punctigera*. Forewings are brown in the female and cream in the male.

Photo 9: *Adult moth of H. armigera.*

Source: Cabi

7.3.1 Varietal resistance or tolerance

Virtually all *Helicoverpa* present are *H. armigera*, which has developed resistance to many of the older insecticide groups. [16]

16 QDAF (2012) Insect pest management in winter cereals. https://www.daf.qld.gov.au/plants/field-crops-and-pastures/broadacre-field-crops/integrated-pest-management/ipm-information-by-crop/insect-pest-management-in-winter-cereals

7.3.2 Damage caused by *Helicoverpa*

Helicoverpa do not cause the typical head-cutting damage of armyworms. Larvae tend to graze on the exposed tips of a large number of developing grains, rather than totally consuming a low number of whole grains, thus increasing the potential losses. Most (80–90%) of the feeding and crop damage is done by larger larva (the final two instars). [17]

7.3.3 Thresholds for control

While there are no thresholds developed for *Helicoverpa* in winter cereals, using a consumption rate determined for *Helicoverpa* feeding in sorghum (2.4 g/larva), one larvae per m^2 can cause 24 kg grain loss/ha (Table 4).

Table 4: *The value of yield loss incurred by a range of larval densities, using the estimated consumption of 2.4 g/larvae and a range of grain values for wheat. Note that larval damage is irrespective of the crops' yield potential (i.e. each larva will eat its fill whether it is a 1 t/ha crop or a 3 t/ha crop).*

Cereal price ($/t)	Value of crop loss ($/ha)			
	4 larvae/m^2	6 larvae/m^2	8 larvae/m^2	10 larvae/m^2
150	14.4	21.6	28.8	36
200	19.2	28.8	38.4	48
250	24.0	36.0	48.0	60
300	28.8	43.2	57.6	72
350	33.6	50.4	67.2	84
400	38.4	57.6	76.8	96
450	43.2	64.8	86.4	108

Source: QDAF

Based on the preceding information, a crop worth $250/tonne will incur a loss of $6/ha from each *Helicoverpa* larvae. If chemical intervention costs $30/ha (chemical + application costs) the economic threshold or break-even point is 5 larvae/m^2. These parameters can be varied to suit individual costs, and can incorporate a working benefit:cost ratio. A common benefit:cost ratio of 1.5 means that the projected economic benefit of the spray will be 1.5 times the cost of that spray. Spraying at the break-even point (benefit:cost ratio of 1) is not recommended. [18]

7.3.4 Management of *Helicoverpa*

The best approach to managing *Helicoverpa* is to use a combination of both chemical and non-chemical tools. By considering the ecology of *H. armigera* and *H. punctigera*, several key principles emerge that will assist in the successful and sustainable management of these pests.

Chemical control

Presently there are few control options other than the use of chemical insecticides (or biopesticides), for above threshold populations of larvae in a crop. Spraying should be carried out promptly once the threshold has been exceeded. Controlling *Helicoverpa* effectively with insecticides depends on knowing which species are present in the crop.

Helicoverpa punctigera is easily killed by all registered products, including products to which *H. armigera* is resistant (e.g. synthetic pyrethroids). Because *H. punctigera* moths migrate annually into eastern Australian cropping regions, they lose any

17 QDAF (2012) Insect pest management in winter cereals. https://www.daf.qld.gov.au/plants/field-crops-and-pastures/broadacre-field-crops/integrated-pest-management/ipm-information-by-crop/insect-pest-management-in-winter-cereals

18 QDAF (2012) Insect pest management in winter cereals. https://www.daf.qld.gov.au/plants/field-crops-and-pastures/broadacre-field-crops/integrated-pest-management/ipm-information-by-crop/insect-pest-management-in-winter-cereals

resistance they might develop as a result of exposure to insecticides in crops. In contrast, *H. armigera* populations tend to remain local so their resistance to insecticides is maintained in the population from season to season. [19]

Helicoverpa armigera has historically had high resistance to pyrethroids and control of medium-large larvae using pyrethroids is not recommended.

Where winter cereals have previously been treated with broad-spectrum insecticides to control aphids, fewer natural enemies may be present and survival of caterpillar pests could be greater than in an untreated field. [20]

Attract and kill technology

Attract and kill products consist of a liquid insect lure based on floral volatiles that is mixed with an insecticide. This lure plus insecticide mixture is then able to be easily applied to large crop areas.

When the adult (and preferably female) moths are attracted to the treated rows, they feed on the product and the added insecticide, causing their death before all eggs are laid.

Because the aim is to concentrate the feeding moths in the treated rows, a key advantage of the attract and kill approach is that not every row of crop needs to be treated (perhaps under 2% of the total crop area).

By reducing the pest moth population, the number of eggs laid into a crop can be significantly reduced. This reduction in egg lay can:

- delay the need for foliar insecticides
- reduce the subsequent pest pressure.

Because the insecticide applied using attract and kill is only confined to a small percentage of the crop area, another key advantage is that most natural enemies will be unaffected. Research to date suggests that these products generally only attract the target pest plus a range of other minor or non-pest moth species. [21]

For current chemical control options see Pest Genie or APVMA.

Spray smart

Timing and coverage are both critical to achieving good control of *Helicoverpa* larvae, whether using a chemical insecticide or a biopesticide (like (nucleopolyhedrovirus (NPV) or Bt).

A poor level of control from inappropriate timing risks crop loss and the costs of re-treating the field. Poor timing also increases the likelihood of insecticide resistance by exposing larvae to sub-lethal doses of insecticide. Regular crop scouting enables assessment of both the number of *Helicoverpa* larvae in the crop and the age structure of the population.

- Ensure crops are being checked when they are susceptible to Helicoverpa damage as early detection is critical to ensure effective timing of sprays. Larvae that are feeding or moving in the open are more easily contacted by spray droplets. Target larvae before they move into protected feeding locations (e.g. flowers, cobs, pods or bolls).
- Ensure larvae are at an appropriate size to control effectively with the intended product.
  Very small (1–3 mm) to small (4–7 mm) larvae are the most susceptible stages and require a lower dose to kill. Larvae grow rapidly—if a spray application is delayed more than two days, the crop should be rechecked and reassessed.

19 QDAF (2012) Key management principles of *Helicoverpa*. https://www.daf.qld.gov.au/plants/field-crops-and-pastures/broadacre-field-crops/integrated-pest-management/a-z-insect-pest-list/helicoverpa/helicoverpa-biology-and-ecology/key-management-principles

20 QDAF (2012) Insect pest management in winter cereals. https://www.daf.qld.gov.au/plants/field-crops-and-pastures/broadacre-field-crops/integrated-pest-management/ipm-information-by-crop/insect-pest-management-in-winter-cereals

21 QDAF (2011) Attract and kill technology for *Helicoverpa* management. https://www.daf.qld.gov.au/plants/field-crops-and-pastures/broadacre-field-crops/integrated-pest-management/a-z-insect-pest-list/helicoverpa/attract-and-kill

- Assess if the larvae are doing economic damage (i.e. only spray if the value of the crop saved is more than the cost of spraying). Vegetative feeding generally does not equate to significant yield loss.

Good coverage is increasingly important with the introduction of ingestion-active products because the larvae must actually feed on plant material covered with an adequate dose of the insecticide or biopesticide.

Attract and kill products such as Magnet® consist of a liquid moth lure based on floral volatiles mixed with an insecticide. Only a relatively small area needs to be treated (less than 2% of the total crop), minimising impact on natural enemies. Reducing the pest moth population decreases the number of eggs laid into a crop, which can lower subsequent pest pressure and delay the need for foliar insecticides.

Note that due to the resistance that *Helicoverpa* has developed to major chemical groups, registered chemicals will not necessarily give adequate control in every situation. Local knowledge of which chemicals are working in a particular area should be sought from consultants and agronomists in your area to ensure you are not spraying unnecessarily or promoting the further development of resistance through your choice of insecticide.

Control without insecticides

While insecticides are an important tool for controlling and managing *Helicoverpa*, other management tools are also available.

- Be smart with your beneficials. Be aware of the presence of beneficial insects and pathogens in the crop, and factor their likely impact into any management decisions.
- Pupae busting remains an important, non-chemical tool to reduce both the size of overwintering *H. armigera* populations and the carryover of insecticide-resistant individuals from season to season. Cultivating to a depth of 10 cm before the end of August will kill a large proportion of overwintering pupae. Check fields that had larvae present after mid-March to assess pupal numbers.
- Weed management in and around crops can prevent the build-up of *Helicoverpa* and other insect pests.
- Spring trap crops have been successfully used as an area-wide management tool for reducing the size of the overall *Helicoverpa* population as it emerges from diapause in spring.

Natural enemies

A variety of predatory and parasitic insects, spiders, birds, bats, rodents and diseases attack *Helicoverpa* at different stages of its life cycle.

Predators

Some predators are relatively permanent residents in fields (e.g. ants), while others migrate from nearby fields or other vegetation. Many predators are opportunity feeders that also feed on prey other than *Helicoverpa*. Some predators found commonly in crops will not feed on *Helicoverpa* at all and some may only feed on certain stages (for example, larvae of a particular size, or only eggs). Knowing what predators eat is important when making management decisions.

Predators of *Helicoverpa* eggs and larvae include spined predatory shield bug, glossy shield bug, damsel bug and bigeyed bug.

The most common predators of *Helicoverpa* in field crops are:

- predatory bugs (e.g. spined predatory shield bug, assassin bug, and damsel bug)
- predatory beetles (e.g. ladybirds, red and blue beetle, carab beetle, and soldier beetle)
- spiders
- lacewings (green and brown)
- ants.

MORE INFORMATION

Important natural enemies of *Helicoverpa*: microplitis and ascovirus.

Parasitoids

Some wasps and flies attack *Helicoverpa* eggs, larvae and pupae. Parasitoids kill their host to complete their development. The parasitoids most active in field crops include:

- smaller wasp species such as Microplitis, Trichogramma and Telenomus
- relatively large parasitoid wasps (Netelia, Heteropelma, Ichneumon)
- flies (Carcelia and Chaetophthalmus)

Parasitoids that attack *Helicoverpa* larvae do not kill their hosts immediately (Figure 13). However, they do stop or slow down caterpillar feeding, which reduces the impact of the pest on the crop. When parasitoids attack late instar larvae or pupae, they stop moths developing and going on to produce further eggs and larvae.

Photo 10: *Normal Helicoverpa egg (left) and a black parasitised egg (right).*

Source: QDAF

Pathogens

Pathogens are viruses, fungi or bacteria that infect insects. Many naturally occurring diseases infect and kill *Helicoverpa* larvae, including NPV and fungal pathogens (Metarhizium, Nomuraea and Beauveria). Another disease—ascovirus— stunts larval development, and is spread by wasp parasitoids.

Two pathogens that affect *Helicoverpa* are available commercially as biopesticides:

- Helicoverpa NPV is a highly selective product that infects only *Helicoverpa* larvae and is harmless to humans, wildlife and beneficial insects.
- Bt is a bacterial toxin from Bacillus thuringiensis available as a selective spray that only kills moth larvae. Genes from the Bt organism have also been used to genetically modify cotton plants so that the toxin is expressed in the plant's tissues. When young *Helicoverpa* larvae feed on a Bt cotton plant, the toxin kills susceptible individuals.

Small larvae (less than 7 mm) can be controlled with biopesticides (e.g. NPV). Biopesticides are not effective on larger larvae. Larger larvae are more difficult to control than are small larvae, and NPV (*Helicoverpa* nucleopolyhedrovirus) is most effective when larvae less than 13 mm in length are targeted.

Conserving natural enemies

Natural enemies will rarely eradicate all eggs or larvae, but may reduce infestations to below economic threshold if predators and parasitoids are not disrupted by broad-spectrum insecticides. The amount of disruption that insecticides cause to natural enemy activity varies depending on which chemicals are used and which natural enemies are active.

Take a whole-farm or regional approach

There is no simple solution to *Helicoverpa* control in a farming system that provides a wide range of food sources throughout the year. The continuous availability of hosts potentially allows successive generations to build up in a cropping region throughout the year. A whole-farm approach to *Helicoverpa* involves managing the local population by:

- having a good knowledge of pest and life cycle
- checking crops regularly
- being familiar with the economic thresholds for different crops
- basing chemical choices on the latest Insecticide Resistance Management Strategy (IRMS)
- achieving appropriate timing and coverage of sprays
- conserving populations of predatory and parasitic insects
- using trap cropping if appropriate
- cultivating to destroy overwintering pupae
- destroying weed hosts within the crop and surrounding areas.

Area-wide management strategies are designed to manage *Helicoverpa* at a regional level rather than each farmer making *Helicoverpa* control actions in isolation. It requires a high level of communication and cooperation between farmers, consultants, and research/extension personnel. [22]

7.3.5 *Helicoverpa* and insecticide resistance

Insecticide Resistance Management Strategy (IRMS)

This strategy is developed each year in order to contain the increase in resistance of *H. armigera* to insecticides including pyrethroids, carbamates, organophosphates and endosulfan. In its present form it mainly applies to summer crops, especially cotton, but as more insecticides are registered in grain crops the IRMS is being expanded to a Farming Systems IRMS (FS-IRMS) that considers insecticide use in all broadacre crops throughout the year.

The FS-IRMS aims to ensure that there is a sufficient break, of at least one *Helicoverpa* generation, in the use of each insecticide group, across all crops.

Major FS-IRMS guidelines:

1. Currently there are no restrictions on the number of pyrethroid sprays that can be applied to non-cotton crops, but there are a number of considerations that apply to the use of pyrethroids in the farming systems.
2. It is strongly recommended that pyrethroids not be used on *Helicoverpa armigera*, as they are unreliable.
3. Pyrethroids should be targeted only on small larvae (i.e. less than 7 mm long) as application on larger resistant larvae will be ineffective and will increase levels of pyrethroid resistance. (Note: even for insecticide groups for which resistance is not established, small larvae are still more susceptible than larger larvae).
4. If you are intending to spray a population of *Helicoverpa*, consider where the moths that laid the eggs may have originated. If they are likely to be survivors from a crop that was previously sprayed (e.g. with a pyrethroid), spraying again with the same insecticide will exacerbate resistance.
5. Avoid using broad-spectrum sprays such as organophosphates or pyrethroids early in the season. They reduce the numbers of beneficial insects and increase the chances of aphid, mite and further *Helicoverpa* outbreaks.
6. Be aware that in 2005 there were major changes to the registration for endosulfan. Endosulfan has been withdrawn from use in grain crops, with a few

22 QDAF (2012) Key management principles of *Helicoverpa*. https://www.daf.qld.gov.au/plants/field-crops-and-pastures/broadacre-field-crops/integrated-pest-management/a-z-insect-pest-list/helicoverpa/helicoverpa-biology-and-ecology/key-management-principles

exceptions for control of pests in seedling crops. Endosulfan can no longer be used in soybean, sunflower, mungbean or other summer grain crops.

7. The use of ovicides may be warranted in the event of high egg pressure—use methomyl before the black head egg stage.
8. Use recommended larval thresholds to minimise pesticide use and reduce resistance selection. Sprays should only be applied if the larvae are doing economic damage (i.e. the value of the crop saved should exceed the cost of spraying).
9. Cultivate host-crop residues as soon as possible after harvest to destroy pupae. Cultivation must be completed no later than one month after large larvae were observed in the field, otherwise the moths will emerge and move elsewhere.
10. Do not respray an apparent failure with a product of the same chemistry.

Helicoverpa control on an area-wide basis

Farmers are faced with increasing problems of controlling resistant *Helicoverpa*. In response to this a *Helicoverpa* Regional Management Strategy (HRMS), or area-wide management (AWM) strategy, was formulated by producers, consultants, researchers and extension personnel and was implemented in two pilot study areas on the Darling Downs in 1998–2001.

The HRMS was designed to manage *Helicoverpa* at a regional level rather than each farmer making *Helicoverpa* control actions in isolation. The HRMS pilot trial resulted in a high level of communication and cooperation between farmers and consultants in an effort to better manage *Helicoverpa*.

The basic principles of the strategy involve a yearly cycle of management practices, which includes tactics that aim to reduce:

- the population of overwintering *Helicoverpa* pupae (March–June)
- the early season build-up of *Helicoverpa* on a regional/district scale (July–November)
- the mid-season population pressure on *Helicoverpa*-sensitive crops (December–March).

Key components of AWM include:

- crop checking
- pupae busting
- improved management for commercial crops
- trap crops
- using information from pheromone traps
- monitoring the contribution of beneficial insects
- insecticide management

Many areas outside the original pilot study areas are now implementing similar strategies. In the pilot study areas, many of the original HRMS/AWM groups continue to meet and discuss pest management issues. Contact your local extension officer, consultant or Department of Employment, Economic Development and Innovation IPM Development Extension Officer for information on existing groups in your region, or how to form a new group.

Control considerations

Presently there are few control options other than the use of chemical insecticides, or virus, for *Helicoverpa* larvae once in a crop. Spraying should be carried out promptly once the threshold for each insect has been reached.

Spray small or spray fail

Helicoverpa grow rapidly and a few days' delay in spraying can result in major crop damage and increased difficulty in control. If a spray application is delayed for more than 2 days, for any reason, the crop should be rechecked and reassessed.

Make sure that crops are being checked when they are susceptible to *Helicoverpa* damage. Early detection of infestation is critical to ensure the most effective timing of sprays.

Ensure *Helicoverpa* larvae in the crop are at an appropriate size to control effectively with the product you are intending to use. Spray only if the larvae are doing economic damage (i.e. the value of the crop saved should exceed the cost of spraying).

Seek professional advice to ensure you are NOT:

- spraying unnecessarily (i.e. below threshold)
- planning to use an insecticide to which the pest is likely to be resistant
- promoting the further development of resistance through your choice of insecticide.

Common insecticides and registered application rates can be found by individual crop. These are not complete lists of all products registered in winter crops and it is recommended that you check Infopest before applying a chemical. As always, read the label.

Due to the resistance that *Helicoverpa* has developed to major chemical groups, it is important to remember that registered chemicals will not necessarily give adequate control in each situation. Local knowledge of which chemicals are working in a particular area should be sought from consultants and agronomists in your area. [23]

MORE INFORMATION

Insect sampling methods

7.3.6 Monitoring

Check for larvae on the plant throughout the growing season (monitoring can be done in conjunction with sampling for armyworm). Using a sweep net, check a number of sites throughout the paddock.

7.4 Aphids

Aphids are usually regarded as a minor pest of winter cereals, but in some seasons they can build up to very high densities. Aphids are most prevalent on cereals in late winter and early spring. High numbers often occur in years when there is an early break in the season and mild weather in autumn and early winter provides favourable conditions for colonisation and multiplication.

Four different species of aphid can infest winter cereals:

1. Oat or wheat aphid
2. Corn aphid
3. Rose-grain aphid
4. Rice root aphid

7.4.1 Oat or wheat aphid

Oat or wheat aphid (*Rhopalosiphum padi*) is one of the most common aphid infesting winter cereals (Photo 11). Typically this species colonises the base and lower portions of the plant including the basal leaves, stems and back of ears of cereal plants (Table 5). [24] Oat aphids predominantly attack oats, wheat and barley but can occur on corn and all cereals and grasses. [25]

23 QDAF (2011) *Helicoverpa* and insecticide resistance. https://www.daf.qld.gov.au/plants/field-crops-and-pastures/broadacre-field-crops/integrated-pest-management/a-z-insect-pest-list/helicoverpa/insecticide-resistance

24 IPM Guidelines. (2016). Aphids in winter cereals. http://ipmguidelinesforgrains.com.au/pests/aphids/aphids-in-winter-cereals/

25 GRDC (2016). Crop Aphids, Back pocket guide. https://grdc.com.au/resources-and-publications/all-publications/publications/2016/11/crop-aphids-back-pocket-guide

Photo 11: *Apterous viviparous female and nymphs of oat or wheat aphid on grass leaf.*

Source: PBase

Table 5: *Oat or wheat aphid description and management information.*

Scientific name	*Rhopalosiphum padi*
Description	Adults are 2 mm long, olive-green to black with a red rust patch at the rear end and may have wings. Antennae extend to half the body length. Nymphs are similar but smaller. Wheat and oat aphids are very similar to corn aphids.
Distribution	An introduced species found in all states of Australia.
Crops attacked	Barley, wheat and oats.
Life cycle	A species that produces many generations through the growing season. Winged and non-winged forms occur.
Damage	Aphids feed directly on stems, leaves and heads, and in high densities cause yield losses and plants may appear generally unthrifty. This type of damage is rare throughout the grainbelt. Aphids can spread BYDV in wheat and barley.
Monitoring and action level	Aphids can affect any crop stage but are unlikely to cause economic damage to cereal crops expected to yield less than 3 t/ha. Consider treatment if there are 10–20+ aphids on 50% of the tillers.
Control	Chemical control: Apply a foliar insecticide in late winter or spring to avoid direct damage to tillers and heads. To prevent losses from BYDV in virus-prone areas, control aphids early in the cropping year. For current chemical control options see Pest Genie or APVMA. Cultural control: There are no known effective cultural control methods.
Host-plant resistance	In virus-prone areas, use resistant plant varieties to minimise losses due to BYDV.
Natural enemies	Predation by hoverflies, lacewings and ladybeetles and parasitism by wasps can reduce aphid populations, but this does not happen in every season. Heavy rain may reduce aphid populations significantly.

Source: QDAF

MORE INFORMATION

PestNotes: Oat aphid.

7.4.2 Corn aphid

Corn aphid (*Rhopalosiphum maidis*) is also a common species found in winter cereals (Photo 12). It generally colonises the upper parts of the plant, particularly the rolled up terminal leaf. It can be found inside the leaf whorl of the plant, with cast skins indicating their presence (Table 6). They rarely infest wheat or oats. [26] While corn aphids are most likely found in barley crops, they also occur in wheat, sorghum, maize and many grasses. [27]

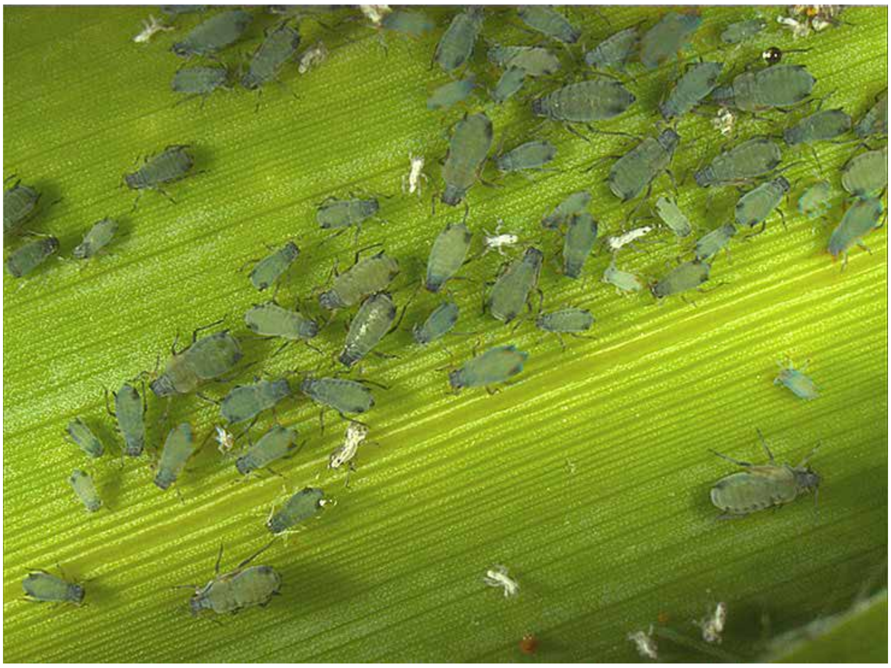


Photo 12: *Corn aphid: note dark legs and cornicles, relatively short antennae.*

Source: KSU

Table 6: *Corn aphid description and management.*

Scientific name	*Rhopalosiphum maidis*
Description	Up to 2 mm long, light to dark olive-green with a purple area at the base of small tube-like projections at the rear of the body. Adults are generally wingless. Antennae extend to about a third of body length. Nymphs are similar, but smaller in size.
Similar species	Other species of aphids.
Distribution	An introduced species, probably Asiatic in origin, found in all states of Australia.
Crops attacked	Sorghum, maize, winter cereals and many grasses.
	Life cycle on sorghum: Corn aphids breed throughout the summer on sorghum with a life cycle of about a week. There can be up to 13 generations on a sorghum crop and 30 generations a year.
	Life cycle on cereals: A parthenogenetic species that undergoes many generations through the growing season. Both winged and non-winged forms occur.

26 IPM Guidelines (2016) Aphids in winter cereals. http://ipmguidelinesforgrains.com.au/pests/aphids/aphids-in-winter-cereals/

27 GRDC (2016). Crop Aphids, Back pocket guide. https://grdc.com.au/resources-and-publications/all-publications/publications/2016/11/crop-aphids-back-pocket-guide

Damage	In sorghum: Adults and nymphs suck sap and produce honeydew. Very high numbers may turn plants yellow. High populations on heads produce sticky grain and clog harvesters. Rain will readily remove honeydew. Water-stressed dryland crops lose yield. In cereal: Aphids feed on stems, leaves and heads, and in high densities cause yield losses. However, this type of damage is uncommon throughout the cereal belt. Risk period In sorghum: All stages of the crop are attacked, but the most serious damage occurs when high populations infest heads. In cereals: Most prevalent on cereals in late winter and early spring. High numbers often occur in years when an early break in the season and mild weather in autumn and early winter provide favourable conditions for colonisation and multiplication.
Monitoring	Estimate percentage of plants infested and percentage of leaf area covered by aphids.
Action level	The action level in the vegetative stage of sorghum is 100% of plants with 80% of the leaf area covered by aphids. On the heads it is 75% of heads with 50% of the head covered by aphids. Aphids are unlikely to cause economic damage to cereal crops expected to yield less than 3 t/ha. To avoid direct-feeding damage, consider treatment if there are 10–20 or more aphids on 50% of the tillers.
Chemical control	Chemical control is cost-effective. See Pest Genie or APVMA for current control options. Conservation of natural enemies: A range of parasitoids and predators will help reduce aphid populations. Predators of aphids include: ladybird larvae, damsel bugs, bigeyed bugs and the larvae of green lacewings and hoverflies. Wasp parasitoids mummify and kill aphids
Host-plant resistance	In sorghum, hybrids with open heads are less infested than tight-headed hybrids

Source: QDAF

MORE INFORMATION

PestNotes: Corn aphid.

7.4.3 Rose-grain aphid

Rose-grain aphid (*Metopolophium dirhodum*) (Photo 13) generally colonises the undersides of the leaves, and moves upwards as these leaves die, high in the canopy (Table 7). [28] These aphids attack cereals and grasses including barley, oats, wheat and triticale. [29]

28 IPM Guidelines (2016) Aphids in winter cereals. http://ipmguidelinesforgrains.com.au/pests/aphids/aphids-in-winter-cereals/

29 GRDC (2016). Crop Aphids, Back pocket guide. https://grdc.com.au/resources-and-publications/all-publications/publications/2016/11/crop-aphids-back-pocket-guide

Photo 13: *Rose-grain aphid with nymphs.*

Source: BugGuide

Table 7: *Description and management of rose-grain aphids.*

Scientific name	Metopolophium dirhodum
Description	Adults are 3 mm long, green to yellow-green with long and pale siphunculi (tube-like projections on either side at the rear of the body) and may have wings. There is a dark green stripe down the middle of the back. Antennae reach beyond the base of the siphunculi. Nymphs are similar but smaller in size.
Similar species	Because of its distinctive colour, it is unlikely to be confused with other aphids.
Distribution	An introduced species that has been recorded from NSW, Queensland, South Australia, Tasmania and Victoria.
Crops attacked	Wheat, barley, triticale, oats.
Life cycle	Undergoes many generations during the growing season; winged and non-winged forms occur.
Damage	Adults and nymphs are sap-suckers. Under heavy infestations, plant may turn yellow and appear unthrifty. Can spread BYDV in wheat and barley.
Monitoring and action level	Can affect any crop stage; assess the potential for direct-feeding damage in late winter. Estimate the number of aphids per tiller. Aphids are unlikely to cause economic damage to cereal crops expected to yield less than 3 t/ha.
Control	Chemical control: Apply a foliar insecticide in late winter or spring to avoid damage to tillers. To prevent losses from BYDV in virus-prone areas, control aphids early in the cropping year. For current chemical control options see Pest Genie or APVMA. Cultural control: There are no known effective cultural control methods for this aphid.
Natural enemies	Predation by hoverflies, lacewings and ladybird beetles, parasitism by wasps and heavy rainfall can reduce aphid populations.

Source: QDAF

7.4.4 Rice root aphid

Rice root aphid (QLD) (*Rhopalosiphum rufiabdominalis*) (Photo 14) colonises the roots of the plants under the soil surface, and colonies may extend up from the roots to the base of the plant. Noticeable when the bases of plants are exposed—often during periods of moisture stress (Table 8). [30]

Photo 14: *Adult rice root aphid.*

Source: UCANR

Table 8: *Description and management of rice root aphids.*

Scientific name	*Rhopalosiphum rufiabdominalis*
Description	Fully grown aphids are 1.2–2.2 mm long and dark green to grey-brown in colour. Nymphs are lighter in colour with a reddish area at the tip of the abdomen.
Damage	Rice root aphids suck fluids from the plant roots, but only do so when the bases of plants are exposed.
Control	Rice root aphids cannot be controlled using contact insecticides because of their below-ground location on plants. Seed dressings may be effective.

Source: QDAF

Damage caused by aphids

Aphids can impair growth in the early stages of crop and prolonged infestations can reduce tillering and result in earlier leaf senescence. Infestations during booting to milky dough stage, particularly where aphids are colonising the flag leaf, stem and ear, result in yield loss development, and aphid infestations during the grainfill period may result in low protein grain (Photo 15).

30 IPM Guidelines (2016) Aphids in winter cereals. http://ipmguidelinesforgrains.com.au/pests/aphids/aphids-in-winter-cereals/

Photo 15: *Corn aphids are found in furled leaves and tillers any time from seedling to head emergence.*

Source: cesar

As aphids may compete for nitrogen (N) with the crop, crops grown with marginal levels of N can be more susceptible to the impact of an aphid infestation. In barley, aphids can spread BYDV. While this can have a large effect on barley yield in some areas, it is not considered a major problem in Queensland in most seasons. In virus-prone areas, use resistant plant varieties to minimise losses due to BYDV.

Inspect for aphids throughout the growing season by monitoring leaves, stems and heads as well as exposed roots. Choose six widely spaced positions in the crop and at each position examine five consecutive plants in a row. Research is currently underway into damage thresholds and control options for cereal aphids. Some research indicates that aphid infestations can reduce yield by around 10% on average.

Adults and nymphs suck sap and produce honeydew. Very high numbers may cause stress in the plants (yellowing or wilting in extreme infestations). These symptoms are more common in moisture-stressed crops.

Direct-feeding damage may occur when colonies develop on stems, heads, leaves. Aphids can affect root development, the number of tillers, seed set and grain size.

Aphids can transmit BYDV. Significant yield losses occur when aphids transmit virus in the first 8–10 weeks after emergence.

Aphid infestations may initially be detected on crop edges. Winged aphids will disperse throughout the field and colonise, creating hotspots across the field. As populations grow, infestations will become more uniform across the field. [31]

7.4.5 Thresholds for control

Current notional thresholds suggest control is warranted when there are 10–20 or more aphids on 50% of the tillers. The decision to control aphids on winter cereals depends on both the size of the aphid population and the duration and timing of the infestation.

- Early infestations (emergence to booting): When 20% of tillers have 10 or more aphids
- Later infestations (flag–soft dough): When 50% of tillers have 15 or more aphids

Aphid populations can decline rapidly, which may make control unnecessary. In many years aphid populations will not reach threshold levels. [32]

31 IPM Guidelines (2016) Aphids in winter cereals. http://ipmguidelinesforgrains.com.au/pests/aphids/aphids-in-winter-cereals/

32 IPM Guidelines (2016) Aphids in winter cereals. http://ipmguidelinesforgrains.com.au/pests/aphids/aphids-in-winter-cereals/

There are no specific control thresholds for infestations in cereal rye crops.

7.4.6 Management of aphids

Controlling aphids during early crop development generally results in a recovery of the rate of root and shoot development, but there can be a delay. Aphids are more readily controlled in seedling and pre-tillering crops which are less bulky than post-tillering crops. Corn aphids in the terminal leaf tend to disappear as crops come into head, and other species generally also decline in abundance about this time as natural enemy populations build up. Note that the rice root aphid feeds below ground and cannot be effectively controlled by non-systemic foliar treatments.

Prophylactic seed dressings may be effective in delaying the build-up of aphid populations in a crop, but because aphids are sporadic (not occurring every season), it can be difficult to decide if a seed dressing is warranted. A locally wet summer and autumn is generally a precursor to an aphid outbreak, as there are abundant alternative hosts to breed up on.

Delay any planned chemical control if rain is forecast and check again after rain as intense rainfalls can reduce aphid infestations by dislodging aphids from the plants. Delay chemical control if heavy rain is forecast. Heavy rain can reduce aphid populations.

Early control of infestations around the edge of the crop (using a border spray) may delay or prevent more widespread infestation of the crop.

Use aphid-selective products (e.g. pirimicarb) to preserve beneficial insects and potentially reduce the need for follow-up applications.

Seed treatments may be effective in minimising the spread of BYDV and delay the build-up of aphids in the crop. Be mindful of the relevant withholding periods when applying seed treatments close to harvest.

The prophylactic use of synthetic pyrethroids is not recommended as it encourages build-up of resistance in aphids and other non-target insects.

Foliar insecticides registered for aphid control are generally broad spectrum, meaning they kill natural enemies (beneficial insects such as ladybird beetles and larvae, hover fly larvae, lacewing larvae or parasitic wasps) as well as aphids. Preserving natural enemies is important in managing aphid populations long term. Natural enemies can exert effective control on small to moderate aphid infestations. Large aphid populations can also be controlled, but often not until the crop is maturing, which may be too late to prevent impact on yield. Broad-spectrum insecticides kill natural enemies and increase likelihood of subsequent aphid infestations later in the season. Refer to the beneficial impact table to identify products least likely to impact on non-target beneficials. Natural enemies can also be effective in suppressing aphid numbers that may survive post-treatment, preventing the need for subsequent treatments. [33]

Natural enemies

Beneficials include parasitic wasps, lacewings, hoverflies, ladybird beetles. They can exert effective control of small to moderate populations of aphids, however they may not arrive early enough to prevent the build-up of aphids to above threshold. They are useful in controlling individuals and small colonies that may survive an insecticide application. For this reason, the use of soft options (e.g. pirimicarb) for aphid control should be considered, particularly if the aphid infestation is being treated in the early stages of crop development (prior to grainfill) when there is the potential for aphid infestations to resurge.

The presence of bloated aphids with pale gold/bronze sheen (mummies) indicates parasitoid activity in the crop.

33 QDAF (2012) Insect pest management in winter cereals. https://www.daf.qld.gov.au/plants/field-crops-and-pastures/broadacre-field-crops/integrated-pest-management/ipm-information-by-crop/insect-pest-management-in-winter-cereals

Aphid fungal diseases can cause a rapid reduction in aphid population in wetter seasons. Fungal infection is detected by the presence of white, fluffy growth on aphids, particularly on lower leaves and stems.

Cultural control

Control weeds and volunteers to minimise early infestation of crops. Aphids, and BYDV, survive over summer on self-sown cereal and perennial grasses.

In some seasons, aphid movement may occur over large distances and local weed management will have little impact.

Encourage beneficial populations through the preservation of native vegetation which provides a refuge for beneficials. [34]

7.4.7 Monitoring

Monitor all crop stages from seedling stage onwards. Look on leaf sheaths, stems, within whorls and heads, and record the number of large and small aphids (adults and juveniles), beneficials (including parasitised mummies), and the impact of the infestation on the crop.

Stem elongation to late flowering is the most vulnerable stage. Frequent monitoring is required to detect rapid increases of aphid populations.

Check regularly—at least five points in the field and sample 20 plants at each point. Populations may be patchy—densities at crop edges may not be representative of the whole field.

Average number of aphids per stem/tiller samples gives a useful measurement of their density. Repeated sampling will provide information on whether the population is increasing (lots of juveniles relative to adults), stable, or declining (lots of adults and winged adults). [35]

7.5 Cutworm (*Agrotis* spp.)

Several species of cutworms (*Agrotis* spp.) attack establishing cereal crops in Queensland and NSW. As their name suggests, cutworm larvae sever the stems of young seedlings at or near ground level, causing the collapse of the plant.

An abundance of top growth that is poorly incorporated may cause poor seed-to-soil contact in the subsequent crop and may attract armyworms or cutworms. [36]

Larvae are up to 50 mm long, hairless with dark heads and usually darkish coloured bodies, often with longitudinal lines and/or dark spots (Photo 16). Larvae curl up and remain still if picked up. Moths are dull brown-black colour. [37]

34 IPM Guidelines (2016) Aphids in winter cereals. http://ipmguidelinesforgrains.com.au/pests/aphids/aphids-in-winter-cereals/

35 IPM Guidelines (2016) Aphids in winter cereals. http://ipmguidelinesforgrains.com.au/pests/aphids/aphids-in-winter-cereals/

36 Manure $ense (2009) Cereal rye: manure and livestock's new best friend. Michigan State University February 2009

37 QDAF (2010) Cutworm. https://www.daf.qld.gov.au/plants/field-crops-and-pastures/broadacre-field-crops/integrated-pest-management/a-z-insect-pest-list/soil-insects/cutworm

Photo 16: *Common cutworm larva in typical curled position*

Source: cesar

7.5.1 Varietal resistance or tolerance

All field crops can be attacked. Crops are at most risk during seedling and early vegetative stages. [38]

7.5.2 Damage caused by pest

Damage usually shows up as general patchiness or as distinct bare areas in a very short time (Photo 17). Young caterpillars climb plants and skeletonise the leaves or eat small holes. The older larvae may also climb to browse or cut off leaves, but commonly cut through stems at ground level and feed on the top growth of felled plants. Caterpillars that are almost fully grown often remain underground and chew into plants at or below ground level. They usually feed in the late afternoon or at night. By day they hide under debris or in the soil. [39]

38 QDAF (2010) Cutworm. https://www.daf.qld.gov.au/plants/field-crops-and-pastures/broadacre-field-crops/integrated-pest-management/a-z-insect-pest-list/soil-insects/cutworm

39 QDAF (2010) Cutworm. https://www.daf.qld.gov.au/plants/field-crops-and-pastures/broadacre-field-crops/integrated-pest-management/a-z-insect-pest-list/soil-insects/cutworm

Photo 17: *Pink cutworm damage.*

Source: cesar

7.5.3 Conditions favouring development

Usually a single generation during early vegetative stages. Moths prefer to lay their eggs in soil in lightly vegetated (e.g. a weedy fallow) or bare areas. Early autumn egg-laying results in most damage to young cereals. Larvae hatch and feed on host plants right through to maturity. Mature larvae pupate in the soil. Under favourable conditions, the duration from egg lay to adult emergence is 8–11 weeks, depending on the species. [40]

7.5.4 Thresholds for control

Inspect crop twice weekly in seedling and early vegetative stage. Larvae feed late afternoons and evenings.

Chemical control is warranted when there is a rapidly increasing area or proportion of crop damage.

Chemical control may be warranted if larval numbers exceed 1 larva/ m^2 in emerging crops. [41]

7.5.5 Management of insect pest

Controlling weeds in the fallow prior to planting will assist in reducing cutworm population and reduce crop damage - at least 3–4 weeks prior to sowing.

The best time to monitor is late afternoons and evenings when larvae feed. During the day, scratch away soil around damaged plants to find larvae sheltering in the soil. For more information read how to recognise and monitor for soil insects. [42]

Chemical control: Insecticide application is cost-effective. The whole crop may not need to be sprayed if distribution is patchy; spot spraying may suffice. See Pest Genie or APVMA for current control options.

Cultural control: Control weeds 3–4 weeks prior to sowing.

Natural enemies: Cutworms are attacked by a number of predators, parasites and diseases.

MORE INFORMATION

PestNotes: Cutworm.

40 QDAF (2010) Cutworm. https://www.daf.qld.gov.au/plants/field-crops-and-pastures/broadacre-field-crops/integrated-pest-management/a-z-insect-pest-list/soil-insects/cutworm

41 QDAF (2010) Cutworm. https://www.daf.qld.gov.au/plants/field-crops-and-pastures/broadacre-field-crops/integrated-pest-management/a-z-insect-pest-list/soil-insects/cutworm

42 QDAF (2012) Insect pest management in winter cereals. https://www.daf.qld.gov.au/plants/field-crops-and-pastures/broadacre-field-crops/integrated-pest-management/ipm-information-by-crop/insect-pest-management-in-winter-cereals

7.6 Armyworm

Armyworm is the caterpillar stage of certain moths and can occur in large numbers especially after good rain follows a dry period. During the day armyworms shelter in the throats of plants or in the soil and emerge after sunset to feed on the leaves of all winter cereals, particularly barley and oats, generally during September and October. They like to feed on young leaf tissue, giving the leaf margins a tattered appearance. Heavy feeding leaves only the midrib of the leaf. Control is rarely warranted except where large numbers attack small plants. [43]

Cereal rye can attract armyworms. [44] An abundance of top growth that is poorly incorporated may cause poor seed-to-soil contact in the subsequent crop and may attract armyworms or cutworms. [45]

Leafy cereal plants can tolerate considerable feeding and control in the vegetative stage is seldom warranted unless large numbers of armyworms are distributed throughout the crop or are moving in a 'front', destroying young seedlings or completely stripping older plants of leaf. The most serious damage occurs when larvae feed on the upper flag leaf and stem node as the crop matures, or in barley when the older larvae start feeding on the green stem just below the head as the crop matures.

The most common species are common and northern armyworm (*Leucania convecta* and *L. separata*) (Photo 18), and lawn armyworm (*Spodoptera mauritia*). Infestations are evident by the scalloping on margins of leaves caused by feeding of the older larvae.

Photo 18: *Common armyworm (Leucania convecta).*

Source: The Beatsheet

Check for larvae on the plant and in the soil litter under the plant. The best time to check is late in the day when armyworms are most active. Alternatively, check around the base of damaged plants where the larvae may be sheltering in the soil during the day. Using a sweep net (or swing a bucket), check a number of sites throughout the paddock. Sweep sampling is particularly useful early in an infestation when larvae

43 QDAF (2010) Armyworms in field crops. https://www.daf.qld.gov.au/plants/field-crops-and-pastures/broadacre-field-crops/integrated-pest-management/a-z-insect-pest-list/armyworm-overview

44 WS Curran, DD Lingenfelter, L Garling, P Wagoner (2006) Cover crops for conservation tillage systems. The Pennsylvania State University, http://extension.psu.edu/plants/crops/soil-management/conservation-tillage/cover-crops-for-conservation-tillage-systems

45 Manure $ense (2009) Cereal rye: manure and livestock's new best friend. Michigan State University February 2009

are small and actively feeding in the canopy. One full sweep with a net samples the equivalent to a square metre of crop.

Early recognition of the problem is vital as cereal crops can be almost destroyed by armyworm in just a few days. While large larvae do the head lopping, controlling smaller larvae that are still leaf feeding may be more achievable. Prior to chemical intervention consider how quickly the larvae will reach damaging size and the development stage of the crops. Small larvae take 8–10 days to reach a size capable of head lopping, so if small larvae are found in crops nearing full maturity/harvest no spray may be needed, whereas small larvae in late crops which are still green and at early seed fill may reach a damaging size in time to significantly reduce crop yield.

7.6.1 Damage caused by armyworm

Larvae target the stem node as the leaves become dry and unpalatable, and the stem is often the last part of the plant to dry.

A larva takes around 8–10 days to develop through the final, most damaging instars with crops susceptible to maximum damage for this period. One larva/m^2 can cause a loss of 70 kg/ha grain per day (Photo 19). The most serious damage results from the habit of the older larvae of feeding on the green stem just below the head of maturing cereal. The severed heads fall to the ground and cannot be harvested.

Photo 19: *Ragged flag and other leaves on a maturing cereal crop.*

Source: The Beatsheet

7.6.2 Thresholds for control

Table 9 shows the value of yield loss incurred by 1 and 2 larva/m^2 per day, based on approximate values for wheat and an estimated loss of 70 kg/ha per larva. Based on these figures, and the relatively low cost of controlling armyworm, populations in ripening crops in excess of 1 large larva/m^2 will warrant spraying.

Table 9: *Value of yield loss based on approximate values for wheat.*

Value of grain ($/t)	Value of yield loss ($) per day	
	1 larva/m^2	2 larva/m^2
$140	$9.80	$19.60
$160	$11.20	$22.40
$180	$12.60	$25.20
$200	$14.00	$28.00
$220	$15.40	$30.80
$250	$17.50	$35.00
$300	$21.00	$42.00
$350	$24.50	$49.00
$400	$28.00	$56.00

Source: QDAF

Control is warranted if the armyworm population distributed throughout the crop is likely to cause the loss of 7–15 heads per square metre (Photo 20).

Photo 20: *Armyworms feeding on grain heads.*

Source: World of Wheat

MORE INFORMATION

PestNotes: Armyworm.

Armyworms in field crops

7.6.3 Management of armyworms

Many chemicals will control armyworms. However, their effectiveness is often dependent on good penetration into the crop to get contact with the caterpillars. Control may be more difficult in high-yielding thick canopy crops, particularly when larvae are resting under soil at the base of plants. As larvae are most active at night, spraying in the afternoon or evening may produce the best results. If applying sprays close to harvest, be aware of relevant withholding periods.

Biological control agents may be important in some years. These include parasitic flies and wasps, predatory beetles and diseases. *Helicoverpa* NPV is not effective against armyworm. [46]

46 QDAF (2012) Insect pest management in winter cereals. https://www.daf.qld.gov.au/plants/field-crops-and-pastures/broadacre-field-crops/integrated-pest-management/ipm-information-by-crop/insect-pest-management-in-winter-cereals

7.7 Mites

7.7.1 Brown wheat mite

Brown wheat mite (Petrobia latens) damage is only severe in dry seasons. The mature wheat mite is about the size of a pinhead, globe-shaped and brown (Photo 24). It has been a sporadic pest of winter cereals. Populations reach troublesome levels only under very dry conditions (Table 10). [47]

Photo 21: *Brown wheat mite on cereal leaf*

Photo: P Sloderbeck, Source: IPM Images

Table 10: *Description and management of brown wheat mite.*

Scientific name	*Petrobia latens*
Description	Adults are oval, up to 0.6 mm long and have 8 legs. The front legs are significantly longer than the others. The mite is brown and appears dark greenish-brown to black when on a green leaf. It is significantly smaller than, and has finer legs than, the BOM. Immature mites are smaller and orange-red.
Similar species	A very small mite that is unlikely to be confused with the blue oat mite or redlegged earth mite.
Crops attacked	Cereal rye, wheat, barley, triticale, oats, cotton and grasses. Crops are at risk during warm, dry periods.
Damage	Adults and nymphs pierce and suck on leaves, resulting in a mottled and 'drought-like' appearance. Crops with heavy infestations appear bronzed or yellowish and seedlings can die.
Monitor	Check from planting to early vegetative stage, particularly in dry seasons.
Action level	Spray if mottled patches appear throughout the crop and if conditions are dry.
Chemical control	Foliar treatments may sometimes be cost-effective. For current chemical control options see Pest Genie or APVMA.
Natural enemies	No natural enemies recorded.

Source: QDAF

47 QDAF (2010) Brown wheat mite. https://www.daf.qld.gov.au/plants/field-crops-and-pastures/broadacre-field-crops/integrated-pest-management/a-z-insect-pest-list/mites-overview/brown-wheat-mite

7.7.2 Blue oat mite

Blue oat mite (BOM) (*Penthaleus species*) are important pests of seedling winter cereals, but are generally restricted to cooler grain-growing regions (southern Queensland through eastern NSW, Victoria, South Australia and southern Western Australia) (Figure 4). The BOM is an important pest of seedling winter cereals. When infestations are severe, the leaf tips wither and eventually the seedlings die. Eggs laid in the soil hibernate over winter, allowing populations to build up over a number of years. This can cause severe damage if crop rotation is not practised (Table 11). Check from planting to early vegetative stage, particularly in dry seasons, monitoring a number of sites throughout the field. BOM are most easily seen in the cooler part of the day, or when it is cloudy. They shelter on the soil surface when conditions are warm and sunny. If pale-green or greyish irregular patches appear in the crop, check for the presence of BOM at the leaf base. [48]

Figure 4: *Distinguishing characteristics and description of the BOM.*

Source: cesar

48 QDAF (2012) Insect pest management in winter cereals. https://www.daf.qld.gov.au/plants/field-crops-and-pastures/broadacre-field-crops/integrated-pest-management/ipm-information-by-crop/insect-pest-management-in-winter-cereals

Table 11: *Description and management of the BOM.*

Scientific name	*Penthaleus major*
Description	Adults are 1 mm long and have 8 legs. Adults and nymphs have a purplish-blue, rounded body with red legs. They move quickly when disturbed. The presence of a small red area on the back distinguishes it from the RLEM.
Similar species	Brown wheat mite Redlegged earth mite
Crops attacked	Mainly a pest of cereals and grass pastures, but will feed on pasture legumes and many weeds.
Damage	Adults and nymphs pierce and suck on leaves resulting in silvering of the leaf tips in cereals. When heavy infestations occur, the leaf tip withers and the seedling can die. In canola, leaves are mottled or whitened in appearance.
Monitor	Check from planting to early vegetative stage, particularly in dry seasons. Most easily seen in the late afternoon when they begin feeding on the leaves.
Control	Foliar applications of insecticides may be cost-effective if applied within 2–3 weeks of emergence in autumn. The use of control tactics solely in spring will not prevent the carryover of eggs into the following autumn. For current chemical control options see Pest Genie or APVMA.
Natural enemies	Thrips and ladybirds.

Source: QDAF

MORE INFORMATION

PestNotes: Blue oat mite.

7.7.3 Damage caused by pest

Adults and nymph mites pierce and suck leaves resulting in silvering of the leaf tips. Feeding causes a fine mottling of the leaves, similar to the effects of drought. Heavily infested crops may have a bronzed appearance and severe infestations cause leaf tips to wither and can lead to seedling death. Damage is most likely during dry seasons when mites in large numbers make moisture stress worse and control may be warranted in this situation. [49]

7.7.4 Thresholds for control

There are no economic thresholds established for this pest.

7.7.5 Management of insect pest

Where warranted, foliar application of registered insecticide may be cost-effective. Check with the most recent research to determine the likely susceptibility of BOM to the available registered products. Chemicals are the most common method of control against earth mites. Unfortunately, all currently registered pesticides are only effective against the active stages of mites; they do not kill mite eggs. For low–moderate mite populations, insecticide seed dressings are an effective method. Avoid prophylactic sprays; apply insecticides only if control is warranted and if you are sure of the mite identity. Pesticides used at or after sowing should be applied within three weeks of the first appearance of mites, before adults commence laying eggs.

Cultural control methods can contribute to the reduction in the size of the autumn mite population (e.g. cultivation, burning, controlling weed hosts in fallow, grazing and maintenance of predator populations). Since eggs laid in the soil hibernate throughout the winter, populations of the mite can build up over a number of years

49 QDAF (2012) Insect pest management in winter cereals. https://www.daf.qld.gov.au/plants/field-crops-and-pastures/broadacre-field-crops/integrated-pest-management/ipm-information-by-crop/insect-pest-management-in-winter-cereals

and cause severe damage if crop rotation is not practised. The use of control tactics solely in spring will not prevent the carryover of eggs into the following autumn.

Predators of BOM include spiders, ants, predatory beetles and the predatory anystis mite and snout mite. BOM are also susceptible to infection by a fungal pathogen (*Neozygites acaracida*), particularly in wet seasons. [50]

7.8 Slaters

Slaters (also known as woodlice, sowbugs and pill bugs) are multi-legged, land-living crustaceans found all over Australia. Slaters are not generally regarded as a pest of broad acre agriculture and tend to feed on decaying vegetation and dead animal matter. Overall, they perform an important recycling role in the environment however on rare occasions they can also attack seedlings of broad acre crops. Recently damage from slaters has increased in the Northern region, with a number of reports of infestations in winter cereal crops in northern NSW and southern Qld.

The native slater species doing the damage to cereal crops is *Australiodillo bifrons*. This species has a light brown oval shaped and flattened body with a dark brown stripe in the middle of the back (Photo 22). This native slater is commonly found in low lying swampy regions and tends to be more active after rain periods. [51]

Photo 22: *Common slater (Porcellio scaber).*

Photo: J Douglas, Source: cesar.

Slaters are crustaceans related to the normally aquatic or marine crabs, lobsters and prawns but are adapted to living on land. Slaters are easily recognised by their heavily armoured, flattened bodies. They are oval, dull-grey and segmented, growing from 8-20 mm in length, depending on the species. They have 1 pair of prominent antennae, 1 pair of inconspicuous antennae and 7 pairs of legs (1 pair per segment).

There are three species of slaters found in broadacre situations, although they vary in their distribution. The common slater originally introduced from Europe, *Porcellio scaber*, is the most widespread species in Australia. This species is usually pale grey, although brown, yellow or orange variations are not uncommon, and can reach 20 mm in length. The Pill bug, *Armadillidium vulgare*, is also a European species and occurs commonly across Australia. It is characterised by its ability to roll into a ball when disturbed. It can grow to 18 mm and is dark brown to black in colour. The flood bug, *Australiodillo bifrons*, is a native slater that forms large swarms of tens of thousands of individuals. Flood bugs have recently been recorded attacking cereal crops. Populations of flood bugs have increased in parts of New South Wales

50 QDAF (2012) Insect pest management in winter cereals. https://www.daf.qld.gov.au/plants/field-crops-and-pastures/broadacre-field-crops/integrated-pest-management/ipm-information-by-crop/insect-pest-management-in-winter-cereals

51 The Beatsheet. (2009). Slaters and other winter cereal establishment pests. http://thebeatsheet.com.au/slaters-and-other-winter-cereal-establishment-pests/

MORE INFORMATION

Slaters - cesar.

particularly those areas that are prone to flooding. *A. bifrons* is about 7-8 mm long and 4 mm wide with an oval-shaped and flattened body, light brown colour with darker irregular spots, and has a dark brown stripe down the middle of its back. It is a species adapted to low-land swampy soil or marshy environments. [52]

7.8.1 Damage caused by slaters

Although the reported incidence of slater damage to crops has grown in recent years, feeding damage on emerging crop seedlings is still relatively rare. When it does occur, slater feeding on plants results in an uneven rasping-type damage that can appear similar to slug and snail damage. They can chew the tops of emerging cotyledons or leaves of crop seedlings, leaving only the seedling stumps. Other damage includes ring-barking of stems and young branches. However, the presence of slaters in a paddock, even in high numbers, does not always mean crop damage will occur because the slaters will generally be feeding on decaying organic matter. It is not known what makes slaters suddenly shift from eating organic matter to seedlings. [53]

7.8.2 Thresholds for control

There are no economic thresholds established for slaters.

7.8.3 Managing Slaters

Biological:

There has been no research on natural enemies of slaters, although ground beetles (carabids) and some species of spiders are common predators in the United Kingdom.

Cultural:

Management options are limited after crop emergence so prevention is a key part of control.

Managing stubble is likely to be the most effective strategy to reduce slater numbers. Some growers have had success managing slaters ahead of canola rotations through burning crop residues.

Slater populations can be suppressed by reducing stubble loads, or disturbing stubble in summer, exposing insects to the hot soil.

Chemical:

There are no insecticides registered to control slaters in broadacre situations. Slaters are relatively unaffected by most foliar applications of synthetic pyrethroids and organophosphates to control other crop-establishment pests, even when applied at very high rates. Insecticides are probably ineffective because slaters hide under cover and thus avoid contact with insecticide sprays. There are chemical baits registered for use against slaters in horticulture, and there is evidence to suggest some success with chlorpyrifos baits in Western Australia. [54]

7.9 Soil insects in the Northern region

Key points:

- There are a number of soil insects that can damage establishing crops.
- The germinating grain bait technique is recommended for pest detection.
- Thresholds for control are different for summer and winter crops.
- Different soil insect pests occur under different cultivation systems.

52 Hangartner S, McDonald G. (2015). Slaters. cesar http://www.cesaraustralia.com/sustainable-agriculture/pestnotes/insect/slaters

53 Hangartner S, McDonald G. (2015). Slaters. cesar http://www.cesaraustralia.com/sustainable-agriculture/pestnotes/insect/slaters

54 Hangartner S, McDonald G. (2015). Slaters. cesar http://www.cesaraustralia.com/sustainable-agriculture/pestnotes/insect/slaters

- Weedy fallows and volunteer crops encourage soil insect build-up.
- Zero tillage encourages beneficial predatory insects and earthworms.

Soil-dwelling insect pests can seriously reduce plant establishment and populations, and subsequent yield potential. They are often difficult to detect as they hide under trash or in the soil. Fact sheets on the common soil insects are available:

- wingless cockroaches
- black field crickets
- black field earwigs
- black sunflower scarab beetles
- cutworms
- false wireworm
- true wireworm

Other soil insects are common, but do not damage crops.

- Centipedes are long, many-segmented animals with legs all along the body. They have long feelers and tail appendages and can move very quickly.
- Millipedes have a long, cylindrical, segmented body with an extremely high number of legs. They have short feelers, no tail appendages and move more slowly than centipedes. When disturbed, they coil up into a spiral.
- Isopods (woodlice or slaters) are small grey animals up to 7–10 mm long with long feelers and eight pairs of legs. They are usually found in groups under trash and in cracks in the soil.
- Earthworms are true soil animals, unlike centipedes, millipedes and isopods, which live on or near the soil surface. Earthworms are valuable in improving soil texture.
- Ants live in colonies which are mostly underground. The wingless workers gather food, particularly pasture seeds when available, for the colony.

Different soil insects occur under different cultivation systems and farm management can directly influence the type and number of these pests:

- Weedy fallows and volunteer crops encourage soil insect build-up.
- Insect numbers decline during a clean long fallow due to lack of food.
- Summer cereals followed by volunteer winter crops promote the build-up of earwigs and crickets.
- High stubble levels on the soil surface can promote some soil insects due to a food source but this can also mean that pests continue feeding on the stubble instead of germinating crops.
- Zero tillage encourages beneficial predatory insects and earthworms.
- Incorporating stubble promotes black field earwig populations.
- False wireworms are found under all intensities of cultivation but decline if stubble levels are very low.

Soil insect control measures are normally applied at sowing. Since different insects require different control measures, the species of soil insects must be identified before planting.

Monitoring for soil insects

1. Take a number of spade samples from random locations across the field.
2. Check that all spade samples are deep enough to take in the moist soil layer (this is essential).
3. Hand sort samples to determine type and number of soil insects.

Spade sampling is laborious, time consuming and difficult in heavy clay or wet soils.

Management—germinating seed bait technique

Immediately following planting rain:

1. Soak insecticide-free crop seed in water for at least two hours to initiate germination.
2. Bury a dessertspoon full of the seed under 1 cm of soil at each corner of a 5 m × 5 m square at 5 widely spaced sites per 100 ha.
3. Mark the position of the seed baits as high populations of soil insects can completely destroy the baits.
4. One day after seedling emergence, dig up the plants and count the insects.

Trials have shown that there is no difference in the type of seed used when it comes to attracting soil-dwelling insects. However, using the type of seed to be sown as a crop is likely to indicate the species of pests which could damage that crop.

The major disadvantage of the germinating grain bait method is the delay between the seed placement and assessment. [55]

55 QDAF (2011) How to recognise and monitor insect pests. https://www.daf.qld.gov.au/plants/field-crops-and-pastures/broadacre-field-crops/integrated-pest-management/help-pages/recognising-and-monitoring-soil-insects

Nematode management

Key messages:

- Rye is resistant to cereal cyst nematodes (CCN) and is a poor host to the root-lesion nematode (*Pratylenchus neglectus*) providing an alternative management approach for these diseases. [1]
- Rye can reduce the amount of CCN in a paddock. In one study, the biggest reduction in CCN numbers occurred in cereal rye (cv. South Australia), which reduced populations by 92% in the first year. [2]
- Root-lesion nematodes (RLN) (*Pratylenchus thorne*i and *P. neglectus*) cost Australian growers in excess of $250 million/annum.
- Rye is a poor host to the RLN (*Pratylenchus neglectus*) providing a break crop for this nematode.
- Variety choice is critical in managing nematode populations in the soil.
- Soil testing is the best way to diagnose nematode infestations in paddocks and will subsequently inform management decisions.

Nematodes (or roundworms) are one of the most abundant life-forms on earth. They are adapted to nearly all environments. In cropping situations they can range from being beneficial to detrimental to plant health.

8.1 Root-lesion nematode (RLN)

Key points:

- Root-lesion nematodes (*Pratylenchus* spp.) are microscopic worm-like animals that extract nutrients from plants, causing yield loss.
- In the Northern Grains Region, the RLNs are found in three-quarters of fields tested—*Pratylenchus thornei* predominates but *P. neglectus* is also found.
- Intolerant crops such as wheat and chickpea can lose 20–50% in yield when nematode populations are high.
- Resistance and susceptibility of crops can differ for each RLN species.
- Rye is a poor host to the RLN (*Pratylenchus neglectus*) providing an alternative management approach for this nematode. [3]
- Successful management relies on:
- farm hygiene to keep fields free of RLN
- growing tolerant varieties when RLNs are present, to maximise yields
- rotating with resistant crops to keep RLNs at low levels.
- Test soil to monitor population changes in rotations and to determine RLN species and population density.
- Avoid consecutive susceptible crops in rotations to limit the build-up of RLN populations.
- Choose rotation crops with high resistance ratings, so that fewer nematodes remain in the soil to infect subsequent crops.

Root-lesion nematode are a genus of microscopic plant parasitic nematode that are soil-borne, ~0.5–0.75 mm in length and will feed and reproduce inside roots of susceptible crops or plants. There are two common species of RLN in the Northern Grains Region; *Pratylenchus thornei* (*Pt*) and *Pratylenchus neglectus (Pn)*.

1 L Martin (2015) Growing cereal rye to increase carbon and prevent wind erosion. Liebe Group March 2015, http://www.liebegroup.org.au/wp-content/uploads/2015/03/Case-Study-Jeff-Pearse-March-2015.pdf

2 JM Fisher, TW Hancock (1991) Population dynamics of *Heterodera avenae* Woll. in South Australia. Crop and Pasture Science, 42(1), 53–68.

3 L Martin (2015) Growing cereal rye to increase carbon and prevent wind erosion. Liebe Group March 2015, http://www.liebegroup.org.au/wp-content/uploads/2015/03/Case-Study-Jeff-Pearse-March-2015.pdf

Root-lesion nematode are migratory root endoparasites that are widely distributed in the wheat-growing regions of Australia and can reduce grain yield by up to 50% in many current wheat varieties.

Rye is a poor host to the RLN (*Pratylenchus neglectus*) providing an alternative management approach for this nematode, [4] especially in southern NSW where this nematode commonly occurs.

P. thornei is the most damaging species and occurs commonly in the Northern Grains Region (Photo 1). *P. neglectus* occurs less frequently than *P. thornei* but is still quite common.

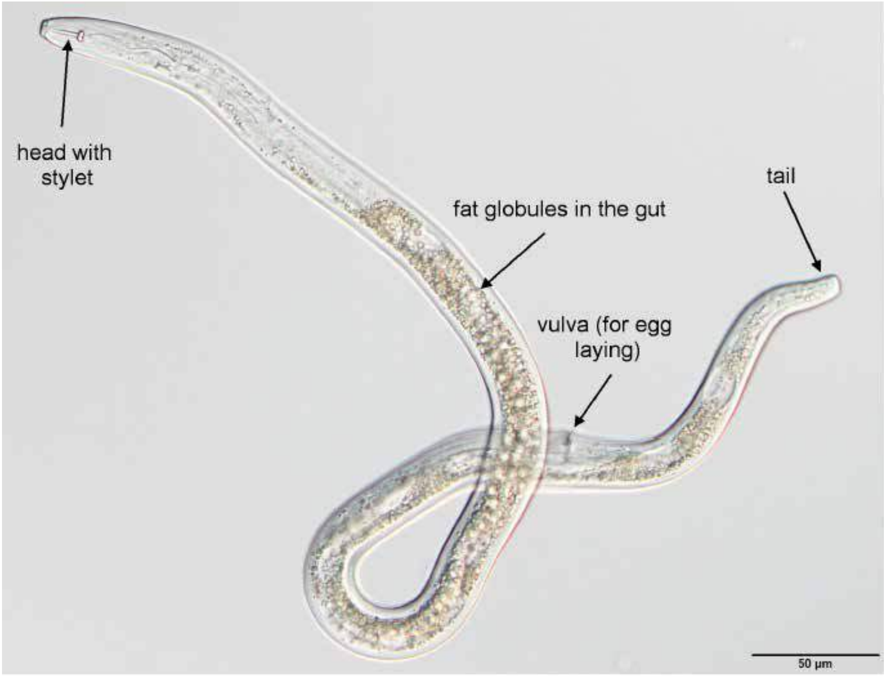


Photo 1: *A Pratylenchus thornei adult female viewed under the microscope. The nematode is approximately 0.65 mm long.*

Source: GRDC

The two species of RLNs occur in the soils of southern Queensland and New South Wales (NSW). In a survey of soil samples from 596 paddocks in this region, 42% had *P. thornei* alone, 27% had both *P. thornei* and *P. neglectus*, 5% had *P. neglectus* alone, while 26% had neither species.

Maps of the distribution of *P. thornei* and *P. neglectus* from samples submitted to PreDicta B™ have been recently generated (Figure 1). Results from autumn 2015 show that *Pratylenchus thornei* is more widely distributed and found in greater, more damaging populations than *P. neglectus* in the Northern Grains Region. In the Northern Region, paddocks with more than 15 *P.* thornei/g soil or 15,000/kg soil by the PreDicta B™ test are considered high risk for crops. However, in the Northern Region, even populations of *P. thornei* classified as medium risk by PreDicta B™, that is 2–15/g soil or 2,000–15,000/kg soil, can cause substantial yield loss of intolerant wheat varieties in warm wet growing seasons conducive to nematode reproduction in the roots. [5]

4 L Martin (2015) Growing cereal rye to increase carbon and prevent wind erosion. Liebe Group March 2015, http://www.liebegroup.org.au/wp-content/uploads/2015/03/Case-Study-Jeff-Pearse-March-2015.pdf

5 K Owen, T Clewett, J Sheedy, J Thompson (2016) Managing grain crops in nematode infested fields to minimise loss and optimise profit. GRDC Update Papers 2 March 2016, https://grdc.com.au/Research-and-Development/GRDC-Update-Papers/2016/03/Managing-grain-crops-in-nematode-infested-fields-to-minimise-loss-and-optimise-profit

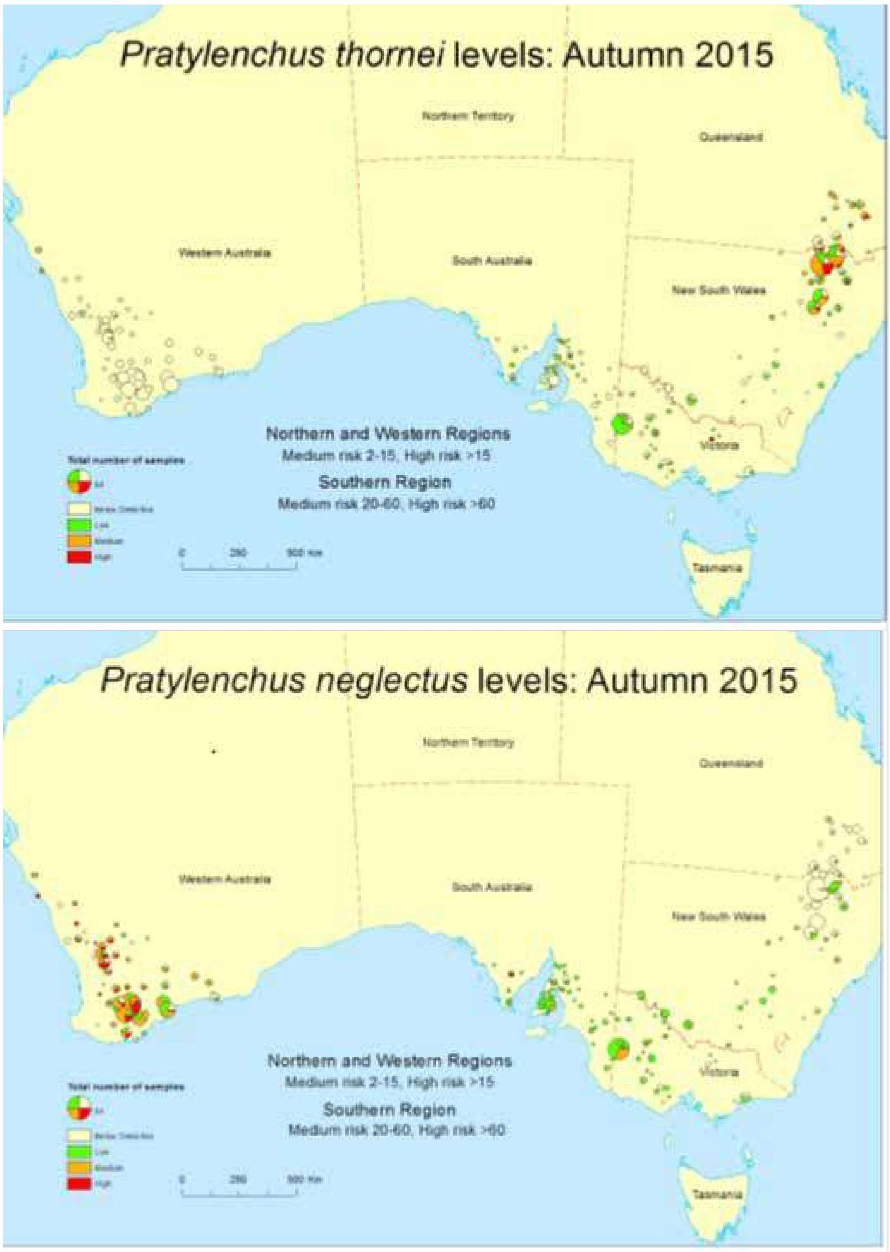


Figure 1: *The distribution and risk of causing yield loss of samples submitted to PreDicta B™, SARDI in autumn 2015 for (top) Pratylenchus thornei and (bottom) P. neglectus.*

Maps are reproduced with permission from SARDI.

Source: GRDC

Other crop species are also hosts of RLNs and care should be taken in sowing susceptible varieties after crops such as black gram and chickpeas in nematode-infested paddocks.

Nematodes penetrate the plant root, digesting the cells' contents and laying eggs within the roots. High populations develop quickly following planting, so that the root systems become inefficient in absorbing water and nutrients. [6]

MORE INFORMATION

Managing grain crops in nematode-infested fields.

VIDEOS

WATCH: GCTV6: Root-lesion nematodes

WATCH: Understanding root-lesion nematodes

6 GRDC (2015) Root-lesion nematodes Northern Region. GRDC Tips and Tactics February 2015, www.grdc.com.au/TT-RootLesionNematodes

Why the focus on Pt?

Pratylenchus neglectus occurs more commonly in southern NSW whereas, *Pratylenchus thornei* (*Pt*) is the most commonly occurring RLN in Queensland and northern NSW.

- *Pt* are widespread in the Northern grains Region. Surveys conducted within NSW and southern Queensland cropping areas consistently show *Pt* presence in ~60–70% of paddocks
- *Pt* are frequently at concerning levels. Found at >2 *Pt*/g soil in ~30–40% of paddocks
- Yield losses in wheat of up to 50% are not uncommon when *Pt*-intolerant wheat varieties are grown in paddocks infested with *Pt*
- Yield losses in chickpeas of up to 20% have also been measured in QDAF trials
- There is no easy solution to RLN infestation. Variety and crop rotation are currently our major management tools [7]

Impact of Pratylenchus thornei, Macalister 2015

Take home messages:

- Multi-crop and variety trials were conducted over strips of 'medium' and 'high' *Pratylenchus thornei* (*Pt*) pressure.
- Site characterised by generally high crop yields (cereals ~4–5.5 t/ha, chickpeas ~3.5–4.0 t/ha) combined with lower levels of *Pt* yield impact.
- Negligible decline in *Pt* population during the 21-month fallow leading up to the winter trials being planted.
- No evidence of yield impact from *Pt* in the brassica, faba bean, chickpea and barley trials.
- Greater yield loss observed in the wheat trials compared to the barley and broadleaf crops at this site.
- Addition of crown rot inoculum together with 'high' *Pt* pressure significantly increased mean yield loss (~30%) over a set of six wheat varieties compared to either the effect from crown rot inoculum alone (~13%) or *Pt* alone (~8%).

This trial was conducted to allow a sound scientific evaluation of the impact of *Pt* on the yield of a broad range of winter crops and varieties and subsequently to measure the crop impact on *Pt* population (i.e. rotational impact and fit). Trial results indicate that there was no significant difference in yield within varieties of canola, faba bean, chickpea and barley between low versus high nematode populations. However, significant yield reductions were recorded for varieties in the early wheat, main wheat and durum National Variety Trials (NVTs). In addition, significant yield losses were also recorded in the CR × RLN interaction trial.

MORE INFORMATION

GRDC Update Paper: Impact from Pratylenchus thornei, Macalister 2015.

8.1.1 Symptoms and detection

Signs of nematode infection in roots include dark lesions or poor root structure. The damaged roots are inefficient at taking-up water and nutrients (particularly nitrogen (N), phosphorus and zinc) causing symptoms of nutrient deficiency and wilting in the plant tops. Intolerant wheat varieties may appear stunted, with lower leaf yellowing and poor tillering (Photo 2).

7 B Burton, R Norton, R Daniel (2015) Root-lesion nematodes: importance, impact and management. GRDC Update Paper 3 August 2015, https://grdc.com.au/Research-and-Development/GRDC-Update-Papers/2015/08/Root-lesion-nematodes-importance-impact-and-management

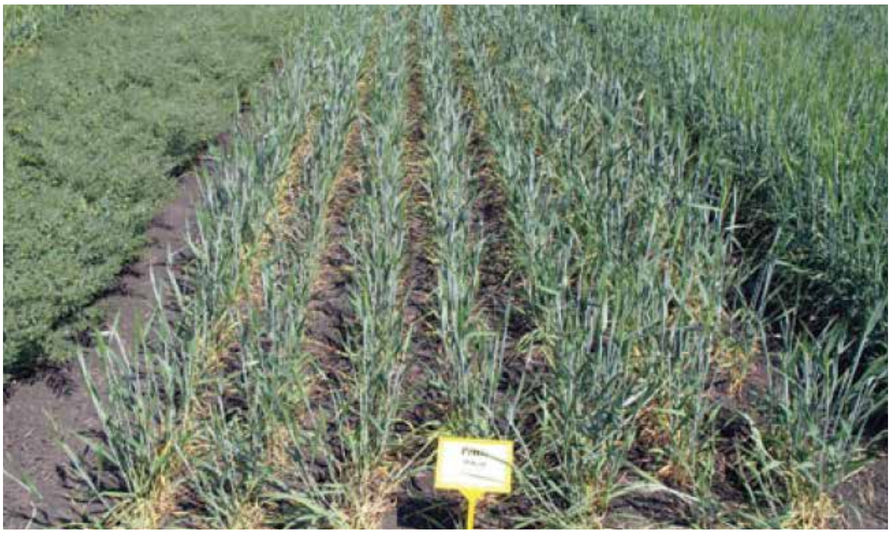


Photo 2: *Symptoms of RLN infection of an intolerant cereal variety include lower leaf yellowing, decreased tillers and wilting. There are no obvious symptoms in the susceptible chickpea and faba bean plots on either side of the wheat.*

Photo: Kirsty Owen, QDAF, Source: Soilquality.org

Crops are patchy, show lower leaf yellowing and appear drought affected and nutrient deficient. As peak nematode numbers often occur at depths in the soil of 30–60 cm, the condition of the plant deteriorates as the roots go deeper. Grain yield can be severely reduced in susceptible varieties.

What to look for

Paddock:

- Crops appear patchy with uneven growth, and may appear nutrient deficient (Photo 3).
- Double sown and more fertile areas are often less affected.

Plant:

- Affected plants stunted and poorly tillered and can wilt despite moist soil.
- Roots can have indistinct brown lesions or, more often, generalised root browning.
- Badly affected roots are thin and poorly branched with fewer and shorter laterals (Photo 4).
- Roots may appear withered with crown roots often less affected than primary roots.
- Roots can assume a 'noodle-like' root thickening appearance. [8]

8 DAFWA (2016) Diagnosing Root-lesion nematodes in cereal. https://www.agric.wa.gov.au/mycrop/diagnosing-root-lesion-nematode-cereals

Photo 3: *Patchiness in crop caused by RLN.*

Photo by V Vanstone, DAFWA, Source: Soilquality.org

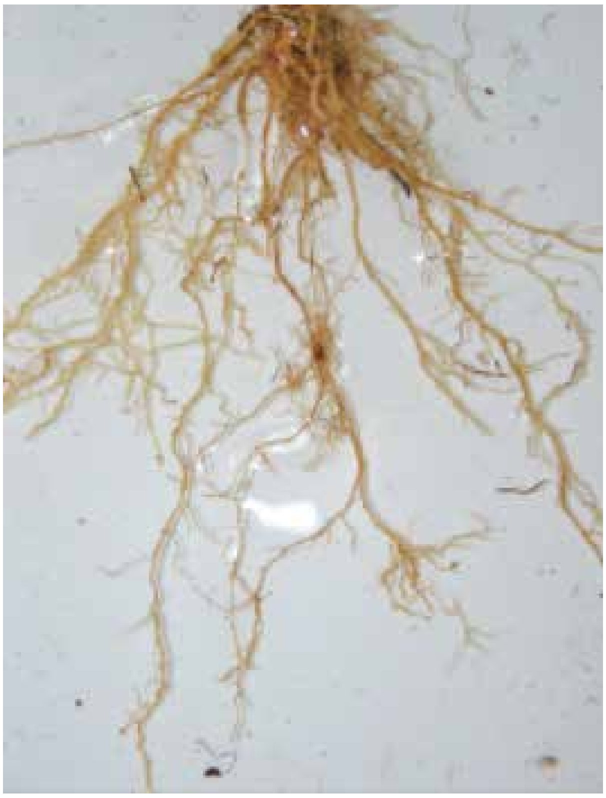


Photo 4: *Cereal roots show general discolouration and reduction in length and number of lateral root branches.*

Photo by V Vanstone, DAFWA, Source: Soilquality.org

VIDEOS

How to diagnose RLN

Soil testing

It is important to know whether nematodes are on your farm and if so, which species are present. This is important because varietal tolerance information for *P. thornei* does not hold true for *P. neglectus*, as they are distinct species.

Proper species identification can help minimise losses that arise from planting intolerant varieties in nematode-infested land.

The Queensland Department of Agriculture and Fisheries (QDAF) Leslie Research Centre can test for and diagnose their presence: Test your farm for nematodes.

Samples for analysis

Since nematodes may not be evenly spread across a paddock, particularly with new infestations, it is important to take samples from several locations within a paddock. For practicality, nine cores bulked in groups of three are recommended.

It is recommended that two layers, 0–15 cm and 15–30 cm, is sampled with either a hand corer or a mattock if no corer is available. Topsoil (0–15 cm) only samples can give inaccurate results and should always be accompanied by a 15–30 cm sample. If deeper samples are already being taken for other analysis (e.g. nitrate), a nematode assessment can be made of the depths 0–30 cm, 30–60 cm and 60–90 cm.

Procedure:

1. Take nine cores across the paddock in two depths, 0–15 cm and 15–30 cm.
2. As you go, bulk the topsoil of the first three cores in one plastic bag labelled A0–15 and in a second bag labelled A15–30, the next three cores as B0–15 and B15–30 and the last three cores as C0–15 and C15–30.
3. Note which parts of the paddock were A, B and C respectively. Break up the soil by hand in a bucket so that all pieces are less than 1 cm in size keeping the six lots separate. About 500 g of soil or more is required in each bag. Seal the bags securely with a twist-tie or string to prevent the soil drying out.
4. Do not expose the bags of soil to heating from sun in the field or in vehicles or from proximity to exhaust pipes etc. Preferably place the soil in a polystyrene box for transport to Leslie Research Centre although a cardboard box or a poly or hessian bag will do if heating is avoided.
5. Fill out the sample submission form with details on the paddock history and forward this with the samples to Leslie Research Centre. Completed forms must be sent with the samples for them to be processed. The centre will then determine which species are present and their population for each of the six soil samples. This will provide a good indication whether RLN are present and likely to pose problems.

Send samples to:

Soil Microbiology Section
Leslie Research Centre
PO Box 2282
Toowoomba Qld 4350
13 Holberton Street
Toowoomba Qld 4350

Phone: 07 4639 8888
Fax: 07 4639 8800

PreDicta B™

Cereal root diseases cost grain growers in excess of $200 million a year in lost production. Much of this can be prevented.

PreDicta B™ (B = broadacre) is a DNA-based soil testing service that identifies which soil-borne pathogens pose a significant risk to broadacre crops prior to seeding (Photo 5).

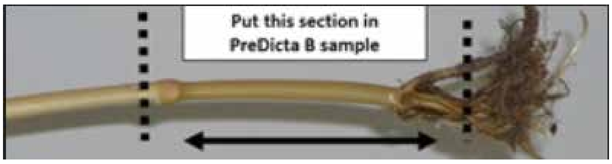


Photo 5: *Add one piece of cereal stubble (if present) to the sample bag at each of the 15 sampling locations – this improves the detection of crown rot. Each piece should be from the base of the plant and include the crown to the first node (discard material from above the first node).*

Source: GRDC

PreDicta B™ includes tests for:

- Take-all (*Gaeumannomyces graminis var tritici (Ggt)* and *G. graminis var avenae (Gga)*)
- Rhizoctonia barepatch (*Rhizoctonia solani AG8*)
- Crown rot (*Fusarium pseudograminearum and F. culmorum*)
- Blackspot of peas (*Mycosphaerella pinodes, Phoma medicaginis var pinodella* and *Phoma koolunga*)

Access PreDicta B™ testing service

Growers can access PreDicta B™ diagnostic testing services through a SARDI accredited agronomist. They will interpret the results and give advice on management options to reduce the risk of yield loss.

SARDI processes PreDicta B™ samples weekly between February to mid-May (prior to crops being sown) every year.

These timeframes help assist growers with their cropping program.

PreDicta B™ is not intended for in-crop diagnosis. See the crop diagnostic webpage for other services. [9]

8.1.2 Varietal resistance or tolerance

Rye is resistant to *P. neglectus* [10] limiting the expansion of this nematode within a paddock. There is limited research on the tolerance of cereal rye to *P. thornei*.

8.1.3 Damage caused by pest

These nematodes can severely affect yields. *P. thornei* is the most common RLN in the Northern grains region and is capable of causing crop damage and yield loss up to 70%, [11] however, cereal rye is unlikely to incur this amount of yield loss.

8.1.4 Conditions favouring development

Nematodes can spread through a district in surface water (e.g. floodwater) and can be moved from one area to another in soil adhering to vehicles and machinery. They have the ability to quickly build up populations in the roots of susceptible crops and remain in the soil during fallow. As a result the yield of following crops can be significantly reduced.

How long does it take to reduce Pt in soils?

Key points:

- *P. thornei* populations greater than 40,000/kg at harvest will require a double break of around 40 months free of a host to reduce the population below the

MORE INFORMATION

GRDC Update Paper: Root-lesion nematodes: importance, impact and management.

VIDEOS

WATCH: Root-lesion nematodes. Resistant cereal varieties have surprising impacts on RLN numbers.

9 PIRSA, SARDI (2016) PreDicta B™. http://pir.sa.gov.au/research/services/molecular_diagnostics/predicta_b

10 A Wherrett, V Vanstone Root lesion nematode. Soilquality Fact Sheet,Soilquality.org.au, http://soilquality.org.au/factsheets/root-lesion-nematode

11 GRDC (2009) Plant parasitic nematodes Factsheet—Northern Region. https://grdc.com.au/resources-and-publications/all-publications/bookshop/2010/10/plant-parasitic-nematodes-fact-sheet-northern-region

accepted threshold of 2,000 *Pt*/kg. *P. thornei* populations greater than 10,000/kg at harvest will requires a single break of around 30 months free of a host to reduce the population below the accepted threshold of 2,000 *Pt*/kg.

- Weeds can be a host so fallows must be weed free and free of volunteers.

Following two consecutive wheat crops using wheat cultivars with different levels of tolerance and resistance, a range of nematode populations were created in the soil. At the harvest of the second wheat crop the nematode population from each plot was recorded and characterised as high, (H >20,000 *Pt*/cm^2/1.2 m profile), medium (M >10,000 *Pt*/cm^2/1.2 m profile), low (L >5,000 *Pt*/cm^2/1.2 m profile) and very low populations (VL <5,000 *Pt*/cm^2/1.2 m profile) calculated as the sum of nematodes across the whole profile. Over the next 30 months soil samples were collected from these plots to monitor the change in nematode population over time. Two 1.8 m soil cores were collected from each plot and divided into eight layers (the top four being of 15 cm and the bottom four of 30 cm). Nematodes were extracted from the soil and manually counted to give a live nematode population estimate for each soil layer. The rotation over the 30 months was long fallow from wheat to sorghum then long fallow from sorghum to wheat. In the fallow commencing in 2011 no sorghum was sown due to drought.

High population of 80 nematodes/cm3 (~80,000 *Pt*/kg) took four years to reduce below the threshold. This would require two non-host crops such as sorghum and fallows to reduce the population. A moderate initial population of 50 nematodes/cm3 took three and a half years (Figure 2), requiring the equivalent of a single non-host summer crop and fallows. A population of 20 nematodes/cm3 took 24 months. The long survival mechanisms of RLN highlight the importance of knowing the size of the population at the end of each season. Once a population increases, non-host, resistant crops or fallows are required to reduce the population below the damage threshold. Planting susceptible or tolerant crops within this time period will increase populations to higher levels that will take longer to reduce, thereby limiting cropping options, and potentially reducing the profitability of the overall farming system. As resistant wheat varieties are released they can be used to provide a winter decline option to increase non-host periods within the rotation. [12]

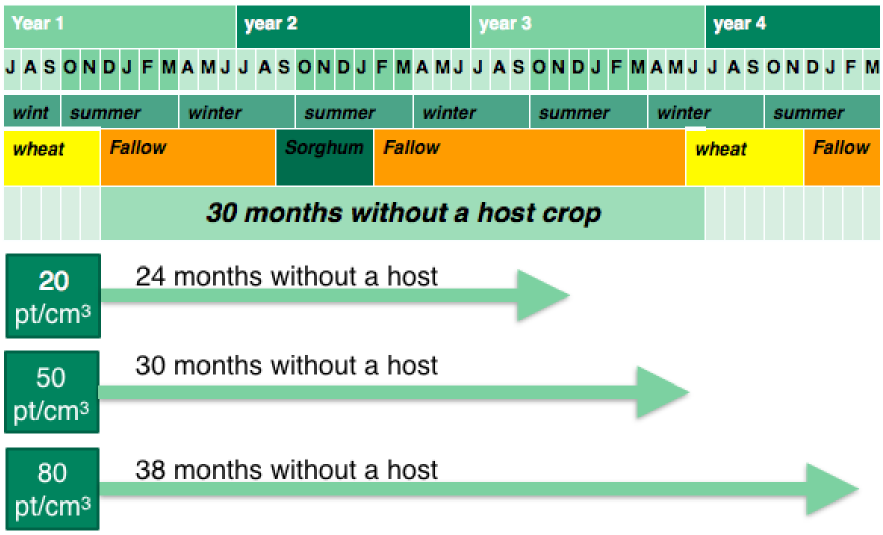


Figure 2: *An example of a non-host fallow showing the time required to reduce different starting populations of RLN.*

Source: GRDC

MORE INFORMATION

How long does it take to reduce Pratylenchus thornei (Root-lesion nematode) population in the soil?

12 J Whish, J Thompson (2016) How long does it take to reduce *Pt* (RLN) population in the soil? GRDC Update Paper 23 February 2016, https://grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2016/02/how-long-does-it-take-to-reduce-pratylenchus-thornei-populations-in-the-soil

8.1.5 Thresholds for control

The damage threshold has been estimated at 2,000 nematodes/kg soil (or 2/g soil). Control is warranted for paddocks with populations over this density threshold. [13]

8.1.6 Management

Key points:

- *Know your enemy*—soil test to determine whether RLN are an issue and which species are present
- Select wheat varieties with *high tolerance ratings to minimise yield losses* in RLN infected paddocks
- To manage RLN populations, it is important to *increase the frequency of RLN resistant crops* in the rotation
- Multiple resistant crops in a rotation will be necessary for long-term management of RLN populations
- There are *consistent varietal differences in Pt resistance* within wheat and chickpea varieties
- Avoid crops or varieties that allow the build-up of large populations of RLN in infected paddocks
- Monitor the impact of your rotation

There are four key strategies in reducing the risk of root-lesion nematodes:

1. Have soil tested for nematodes in a laboratory (Figure 3).
2. Protect paddocks that are free of nematodes by controlling soil and water run-off and cleaning machinery; plant nematode-free paddocks first.
3. Choose tolerant wheat varieties to maximise yields (go to nvtonline.com.au). Tolerant varieties grow and yield well when RLN are present.
4. Rotate with resistant crops to prevent increases in RLNs. When high populations of RLN are detected you may need to grow at least two resistant crops consecutively to decrease populations. In addition, ensure that fertiliser is applied at the recommended rate to ensure that the yield potential of tolerant varieties is achieved.

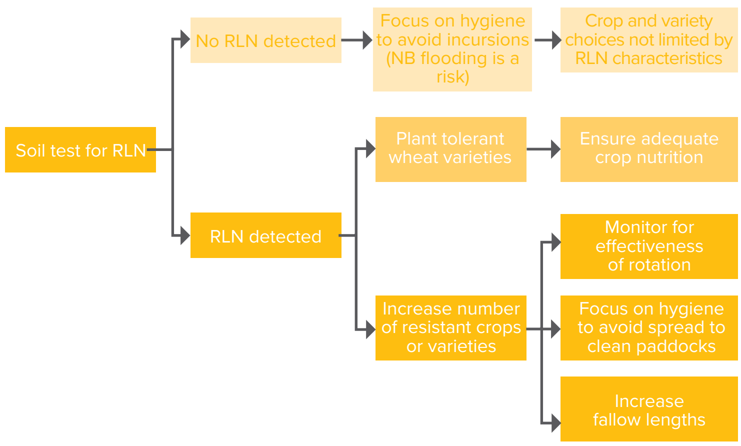


Figure 3: *RLN management flow chart—A simplified chart that highlights the critical first step in the management of RLN is to test your soil and determine whether or not you have an issue to manage. NB where RLN are present, growers should focus on both 1) planting tolerant wheat varieties and 2) increasing the number of resistant crops/varieties in the rotation.*

Source: GRDC

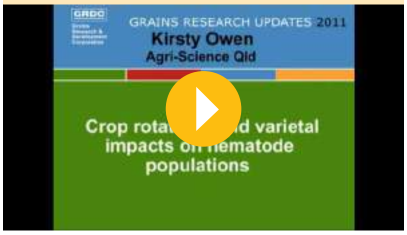
13 GRDC (2015) Root-lesion nematodes Northern Region. GRDC Tips and Tactics February 2015, www.grdc.com.au/TT-RootLesionNematodes

VIDEOS

WATCH: Root-lesion nematodes—What can I do?

WATCH: Crop variety effect on nematodes

WATCH: RLN in Northern Region—crop rotation and varietal impacts on nematode populations



There are four major control strategies against RLN:

1. *Nematicides* (control in a drum): there are no registered nematicides for RLN in broadacre cropping in Australia. Screening of potential candidates continues to be conducted but RLN are a very difficult target with populations frequently deep in the soil profile.
2. *Nutrition*: damage from RLN reduces the ability of cereal roots to access nutrients and soil moisture and can induce nutrient deficiencies. Under-fertilising is likely to exacerbate RLN yield impacts; however over-fertilising is still unlikely to compensate for a poor variety choice.
3. *Variety choice and crop rotation: These are currently our most effective management tools for RLN.* However the focus is on two different characteristics—*Tolerance* (ability of the variety to yield under RLN pressure) and *Resistance* (impact of the variety on the build-up of RLN populations). NB varieties and crops often have varied tolerance and resistance levels to *Pt* and *Pn*.
4. *Fallow*: RLN populations will generally decrease during a 'clean' fallow but the process is slow and expensive in lost 'potential' income. Additionally long fallows may decrease Mycorrhizal (VAM) levels and create more cropping issues than they solve. [14]

Natural enemies

Biological suppression is a potential method of reducing populations of *P. thornei* and *P. neglectus*. Recent research has identified that Northern grain-growing soils are capable of suppressing RLNs, especially in the top layer (0–15 cm) of soil, and this capacity can be enhanced by increasing the biological activity of that soil, mainly through carbon inputs and minimising soil disturbance.

Several key organisms that prey on nematodes have been found in Northern soils, such as *Pasteuria* bacteria that infect and eventually kill *Pratylenchus* spp.

Several species of fungi including some that trap nematodes and predatory nematodes have also been found, all of which have potential to reduce RLN populations.

Research is continuing to develop methods of increasing biological activity to enhance suppressiveness deeper in the profile.

Biological suppression of RLN in northern soils

Key points:

- Biological suppression does occur in most soils tested from the Northern region, showing that populations of *P. thornei* are being reduced by parasites and predators.
- Suppression was found to be greater in the top 10 cm of soil than at deeper layers (e.g. 30–45 cm). Practices such as zero tillage with stubble retention enhanced suppression. Without these practices, it is estimated that RLN multiplication would be significantly greater, especially in top soils, and this would result in much greater losses in the productivity of susceptible crops.
- Several antagonists of *Pratylenchus* were found in Northern grain-growing soils such as nematode trapping fungi, predatory nematodes, parasitic bacteria and root-colonising fungi that enhance the plant's resistance to nematodes. Further research is focussing on these organisms as they are likely to be contributing to the suppressiveness of the soils.

Enhancing the suppressiveness of soil to RLNs is a control option that deserves some consideration. Disease suppression is defined as the ability of a soil to suppress disease incidence or severity even in the presence of the pathogen, host plant and favourable environmental conditions. The vast array of organisms in the soil can

14 B Burton, R Norton, R Daniel (2015) Root-lesion nematode; importance, impact and management. GRDC Update Paper 3 August 2015, https://grdc.com.au/Research-and-Development/GRDC-Update-Papers/2015/08/Root-lesion-nematodes-importance-impact-and-management

provide a degree of biological buffering against pathogens. Disease reduction results from the combined effects of many antagonists acting collectively and mediated through inputs of organic matter (general suppression) and direct antagonism by a limited number of organisms (specific suppression).

A recent GRDC-funded project aimed to better understand the suppressive nature of grain-growing soils and provide growers with methods to enhance suppressiveness of their soils to RLNs.

Over four years, a total of 24 different sites were sampled to test the suppressiveness of the soils. This included several farmer paddocks and three long-term farm management trial sites with several fertiliser or tillage treatments. Also, seven of the sites were comparisons of cropped and pasture or native/scrub remnant soils that were in close proximity, to gain an understanding of the impact cropping may have on suppressiveness to RLNs.

Repeated studies over four years of multiple soils from northern NSW and southern Queensland consistently showed general suppressiveness to RLNs does exist in a variety of soils. In glasshouse tests, it was also found that a 10% addition of suppressive field soil to a sterilised soil (heated at 60˚C for 45 mins) is sufficient to reduce RLN multiplication by 60–90%, showing that the suppressive effect was biological and could be transferred or added to a less suppressive soil.

Implications:

Suppression does occur in most soils tested from the Northern region showing that populations of *P. thornei* are being reduced due to biological activity. Suppression was found to be greater in the top 10 cm of soil than at deeper layers (e.g. 30–45 cm), and practices such as zero tillage with stubble retention enhanced suppression.

Maintenance of a healthy topsoil through diverse organic matter inputs will preserve the suppressive potential of soils against RLN.

Heavy rates of stubble (up to 20 t/ha) increased general suppression of RLN in the short term. This coincided with high levels of microbial activity.

The presence of a crop for longer periods of time and the associated input of root exudates may have provided a better environment for sustained microbial activity and hence suppression of RLN.

Growers using no-till, stubble retention practices and cropping when soil moisture allows are probably doing a great deal toward enhancing the suppressiveness in their top soil. Without these practices, RLN multiplication would be significantly greater, especially in top soils, and therefore lead to much greater losses in productivity of susceptible crops.v

More work is required to confirm the biological control agents found to be present in our grain-growing soils can have a significant impact on RLN populations on a broad-scale. [15]

MORE INFORMATION

Biological suppression of RLN in the Northern Region.

GRDC Tips and tactics: Root-lesion nematodes Northern Region.

Cultural control

Crop rotation with resistant crops such as cereal rye, grain sorghum, millet, sunflower and canary will reduce the numbers of nematodes in the soil to a level where susceptible wheat varieties can be grown, but will not eliminate them completely. [16]

15 N Seymour, G Stirling, J Li (2016) Biological suppression of RLN in northern grain growing soils. GRDC Update Papers 1 March 2016, https://grdc.com.au/Research-and-Development/GRDC-Update-Papers/2016/03/Biological-suppression-of-root-lesion-nematodes-in-northern-grain-growing-soils

16 QDAF (2015) Wheat—diseases, physiological disorders and frost. https://www.daf.qld.gov.au/plants/field-crops-and-pastures/broadacre-field-crops/wheat/diseases

8.2 Cereal cyst nematode (CCN)

Key points:

- Cereal cyst nematode is more of an issue in the Southern and Western growing regions than in the Northern cropping region. It is rarely found north of northern NSW, however can be found in southern NSW.
- Rye is resistant to CCN, providing an alternative management approach for these diseases. [17]
- Rye can reduce the amount of CCN in a paddock. In one study, the biggest reduction in CCN numbers occurred in cereal rye (cv. South Australia), which reduced populations by 92% in the first year. [18]
- Rotations—use break crops to minimise carryover of CCN host species (canola, lupins, chickpeas etc.) as non-host crops are more effective than resistant cereals in reducing levels of CCN.
- Be aware of and try to minimise consecutive cereal hosts during your rotation. CCN levels can become damaging after only one or two seasons of a susceptible crop.
- Grow resistant cereal cultivars to limit levels of CCN in the soil.
- Control volunteer cereal hosts and grass weeds during late summer/early autumn and in break crops.
- Sow early where possible to ensure better root development.
- Maintain optimum soil fertility to 'get-ahead' of CCN infections.

There have been isolated reports of CCN (*Heterodera avenae*) near Tamworth and Dubbo on lighter-textured soils and friable black soils. If growers suspect CCN they should contact a local agronomist. [19]

Cereal cyst nematode is a pest of graminaceous crops worldwide. This nematode is a significant problem across eastern Australia. CCN becomes more problematic in areas where intensive cereal cropping occurs. CCN will only infect, feed and develop on cereals and other grasses (particularly wild oat). Non-cereal crops will not host the nematode, so are useful in rotations to limit damage caused to cereals.

Cereal rye is tolerant and will yield well despite being attacked.

CCN usually occurs early in the season and can occur on heavy or light soils.

IN FOCUS

The effect of plant hosts on populations of CCN (Heterodera a venae) and on the subsequent yield of wheat

Microplots containing soil, naturally infested with CCN were left fallow or sown to one of nine cereal cultivars or grass species for five consecutive years. Wild oat was the most efficient host and, after three plantings, the nematode reached a potential increase ceiling of 42.2 eggs/g soil. Of the cereal cultivars tested, wheat (cv. Olympic) and barley (cv. Prior) were the most efficient hosts and levels of approximately 40 eggs/g were reached after five plantings. Barley grass was less efficient than Wimmera ryegrass which maintained a ceiling population of about 10 eggs/g. Under fallow, populations declined to 0.5 eggs/g after four years. The most inefficient cereal hosts were the oat (cv. Avon) and cereal rye (cv. South Australian). The low populations maintained under continuous cropping with these

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17 L Martin (2015) Growing cereal rye to increase carbon and prevent wind erosion. Liebe Group March 2015, http://www.liebegroup.org.au/wp-content/uploads/2015/03/Case-Study-Jeff-Pearse-March-2015.pdf

18 JM Fisher, TW Hancock (1991) Population dynamics of *Heterodera avenae* Woll. in South Australia. Crop and Pasture Science, 42(1), 53–68

19 GRDC (2009) Plant parasitic nematodes Factsheet—Northern Region. https://grdc.com.au/resources-and-publications/all-publications/bookshop/2010/10/plant-parasitic-nematodes-fact-sheet-northern-region

cereals suggested that a rapid selection of a resistance-breaking biotype is unlikely to result from the continued use of inefficient hosts. Growth and yield of a subsequent wheat crop on all plots reflected the relative levels of nematode populations. At the low levels of infestation, grain yields were more than double those on heavily infested plots. [20]

Cereal cyst nematode juveniles hatch from eggs contained in the cysts remaining from previous seasons in response to lower temperatures and autumn rains. Hatching is delayed by late breaks or dry autumns and this increases the risk of crop damage. Once hatched the young nematodes seek out the roots of host plants. While the male nematodes remain free-living in the soil, the females penetrate roots and begin feeding. Following mating, the females produce eggs within their body. As the season progresses the females remain feeding at the same infection site and begin to swell into the characteristic white spheres. This process takes 6–9 weeks, and the CCN females remain like this until the host plant begins to senesce. The females die and their cuticle hardens and turns brown to form a cyst. Cysts are particularly hardy, and remain in the soil over summer until temperatures fall and the autumn rains begin which stimulates hatching of the next generation. CCNs have only one life cycle/year (Figure 4). However, each cyst contains several hundred eggs, so populations can increase rapidly on susceptible cereals. [21]

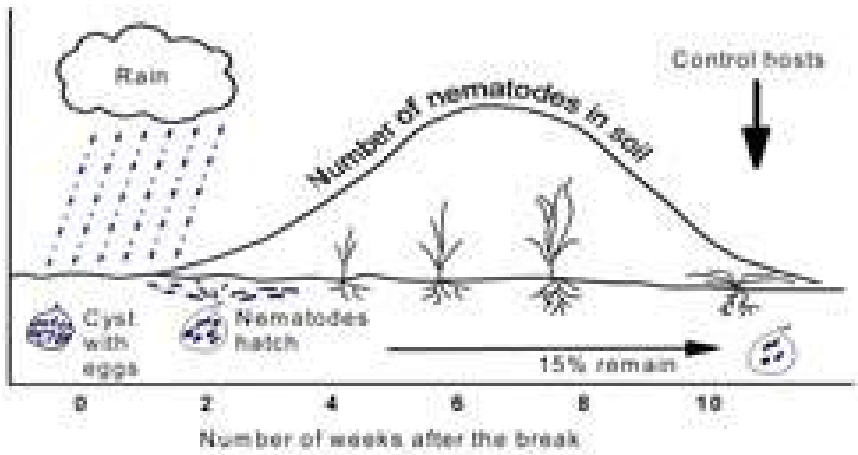


Figure 4: *Life cycle of the CCN.*

Source: AgVic

8.2.1 Symptoms and detection

The symptoms of CCN infection can be readily recognised. Above ground, patches of unthrifty yellowed and stunted plants can be observed (Photo 6). Planting a susceptible crop in successive years will result in these patches becoming larger with time.

Closer examination of the roots will reveal symptoms that are typical of CCN. Below ground, wheat and barley roots will be 'knotted' (Figure 7), and oat roots (Figure 8) appear 'ropey' and swollen. Development of root systems is retarded and shallow. In spring, characteristic 'white cysts' (about the size of a pin head) can be seen with the

20 JW Meagher, RH Brown (1974) Microplot experiments on the effect of plant hosts on populations of the cereal cyst nematode (*Heterodera avenae*) and on the subsequent yield of wheat. Nematologica, 20(3), 337–346

21 A Wherrett, V Vanstone Cereal cyst nematode. Soilquality Fact Sheet,Soilquality.org.au, http://www.soilquality.org.au/factsheets/cereal-cyst-nematode

naked eye if roots are carefully dug and washed free of soil. These are the swollen bodies of the female CCN, each containing several hundred eggs. [22]

Photo 6: *CCN will cause distinct patches of yellowed and stunted plants. Note the likeness of symptoms to poor nutrition or water stress.*

Photo: V Vanstone, DAFWA, Source: Soilquality.org

Photo 7: *CCN produce 'knotting' of cereal roots.*

Photo: V Vanstone, DAFWA, Source: Soilquality.org

22 A Wherrett, V Vanstone Cereal cyst nematode. Soilquality Fact Sheet,Soilquality.org.au, http://www.soilquality.org.au/factsheets/cereal-cyst-nematode

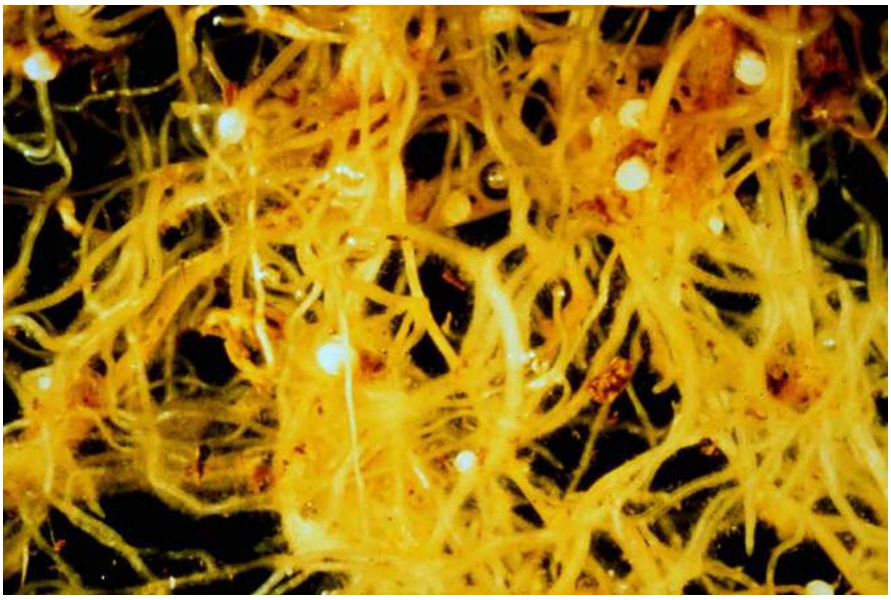


Photo 8: *Cereal roots infected with CCN appear 'ropey' and swollen.*

Source: CropPro

8.2.2 Management

As with other nematodes, there is no effective or economically feasible means of controlling CCN through chemical application. Chemical nematicides are expensive to use, toxic to humans and the success of applications is often highly variable. CCN is best controlled through effective rotation management. Only 70–80 % of eggs hatch each season, regardless of the crop host. As a result, it can take several years for high CCN levels to be reduced by rotation with resistant or non-host crops. The use of a break crop (e.g. canola, lupins, chickpeas) ensures a large proportion of the CCN population is removed. In serious outbreaks of CCN, it may be important to avoid cereals for two years to ensure an adequate reduction in the population. Just two CCN eggs per of gram soil can cause significant economic loss to intolerant cereal crops. Levels of 1–5 eggs per gram of soil can reduce yield of wheat and oat by up to 20% (Figure 13).

Photo 9: *Yield loss in a cereal crop due to CCN.*

Photo: V Vanstone, DAFWA, Source: Soilquality.org

Ryegrass, wild oats and other grass are also good hosts for CCN, although reproduction rates may be lower than on the cropping species. For this reason is important to realise that during a pasture phase in a rotation, the existence of cereal weeds will assist the development of a CCN population. Likewise, if there are grasses present following summer rains or around paddock borders it provides a carryover for the nematode population.

Ensuring optimum soil fertility is maintained helps to minimise the effects of CCN. Allowing the emerging crop access to adequate nutrition allows the root systems to establish and 'get-ahead' of any potential nematode infections. Although this does not decrease the nematode population, losses associated with CCN infections will be minimised.

Finally, in paddocks where there is a known population of cereal cyst nematode and the planting of a cereal cannot be avoided it is important to choose cultivars displaying CCN resistance. [23]

MORE INFORMATION

Cereal cyst nematode - cropPro

Disease breaks for CCN:

- grass free pulse and oilseed crops or legume pasture
- resistant cereals, including cereal rye
- chemical fallow prepared early in the season before nematodes have produced viable eggs. [24]

8.3 Nematodes and crown rot

While all winter cereals host the crown rot fungus, yield loss due to infection varies with cereal type. The approximate order of increasing yield loss is cereal rye, oats, barley, bread wheat, triticale and durum wheat. [25]

Many trials concentrate on crown rot, but in the Northern Region, it is becoming more important to build a picture of the interaction of crown rot with other factors, especially in combination with *Pt* levels. As well as reducing yield, *Pt* reduces grain quality and N-use efficiency, and increases the severity of crown rot infections. [26]

The NGA has been involved in numerous field trials since 2007, in collaboration NSW DPI, evaluating the impact of crown rot on a range of winter-cereal crop types and varieties.

This work has greatly improved the understanding of crown rot impact and variety tolerance, but also indicates that growers may be suffering significant yield losses from another 'disease' that often goes unnoticed.

Although the trials were not designed to focus on nematodes, a convincing trend was apparent after 2008 that indicated *P. thornei* was having a frequent and large impact on wheat variety yield. [27]

Where *Pt* combines with high levels of crown rot (a common scenario), yield losses can be exacerbated if varieties are susceptible to *Pt*. Instead of a 10% yield loss from *Pt* in a susceptible variety it could be 30–50% if crown rot is combined with a *Pt*-intolerant variety (Photo 10).

The research has also shown that not only does *Pt* cause high yield loss in susceptible varieties, but *Pt* numbers can increase much faster than in an area in

23 A Wherrett, V Vanstone Cereal cyst nematode. Soilquality Fact Sheet,Soilquality.org.au, http://www.soilquality.org.au/factsheets/cereal-cyst-nematode

24 CropPro Cereal cyst nematode. Identification and management of field crop diseases in Victoria, Soil-borne diseases of cereals, http://www.croppro.com.au/crop_disease_manual/ch03s03.php

25 GRDC (2016) Crown rot in winter cereals—Southern Region. GRDC Tips and Tactics, February 2016, https://grdc.com.au/Resources/Factsheets/2016/02/Crown-rot-in-winter-cereals

26 T Dixon (2013) Balancing Crown rot and nematodes in wheat. Ground Cover Issue 104, May–June 2013. https://grdc.com.au/Media-Centre/Ground-Cover/Ground-Cover-Issue-104-May-June-2013/Balancing-crown-rot-and-nematodes-in-wheat

27 R Daniel (2013) Managing root-lesion nematodes: how important are crop and variety choice? GRDC Update Paper, 16 July 2013, https://grdc.com.au/Research-and-Development/GRDC-Update-Papers/2013/07/Managing-root-lesion-nematodes-how-important-are-crop-and-variety-choice

which tolerant varieties are growing. These increased *Pt* numbers can lead to even greater damage in future crops. [28]

Photo 10: *Grass plant showing both parasitic nematode damage to roots and crown rot in above ground tissues.*

Source: NCSU

VIDEOS

WATCH: GCTV9: Crown rot and root-lesion nematode

8.3.1 Management

Variety choice is the key management option when it comes to managing *Pt* risk. However, when it comes to crown rot management, although varieties have some impact, rotation and stubble management are by far our most important management tools. RLNs, especially *Pt*, need to be taken far more seriously and better factored into crop rotation considerations as well as variety choice. [29]

Soil testing

Crown Analytical Services has the first Australian commercial test for crown rot based on five years of laboratory research.

The frequency of the disease has increased in recent years due to continuous cropping of wheat. Crown rot causes significant yield losses. Some of the current strategies for management of the disease are to control grass hosts prior to cropping, rotate susceptible cereals with non-host break crops, burn infected stubble and grow tolerant wheat varieties.

Therefore, it is very important for crown rot testing to be carried out on a paddock. It allows for growers and consultants to determine if there is crown rot present in a paddock and if so, how severe it is. An informed decision can then be made regarding crop choice and farming system.

Testing involves carrying out a visual assessment on stubble followed by a precise plating test. This is the only way of accurately testing for the disease. Results are provided to the grower and consultant within approximately four weeks of receiving the sample.

28 B Freebairn (2011) Nematodes and crown rot: a costly union. Ground Cover Issue 91, March–April 2011, https://grdc.com.au/Media-Centre/Ground-Cover/Ground-Cover-Issue-91-March-April-2011/Nematodes-and-crown-rot-a-costly-union

29 B Freebairn (2011) Nematodes and crown rot: a costly union. Ground Cover Issue 91, March–April 2011, https://grdc.com.au/Media-Centre/Ground-Cover/Ground-Cover-Issue-91-March-April-2011/Nematodes-and-crown-rot-a-costly-union

VIDEOS

WATCH: Over the Fence North: Drew Penberthy

Crown Analytical Services provides sample bags and postage paid packs. Go to Protocol to better understand the process, or Contact Crown Analytical services.

Varietal choice

Crop rotation and variety choice are the important factors in protection against both diseases. Choosing a variety solely on crown rot resistance is not critical, especially if appropriate management techniques have been carried out, but choice of variety is crucial when it comes to RLN tolerance.

Further research into varietal tolerance to crown rot and nematodes has revealed that choosing a variety is difficult. Determining the relative tolerance of varieties to crown rot is complex as it can be significantly influenced by background inoculum levels, RLN populations, differential variety tolerance to *Pn* versus *Pt* and varietal interaction with the expression of crown rot. Other soil-borne pathogens such as *Bipolaris sorokiniana*, which causes common root rot, also need to be accounted for in the interaction between crown rot and varieties. Starting soil water, in-crop rainfall, relative biomass production, sowing date and resulting variety phenology in respect to moisture and/or temperature stress during grainfill can all differentially influence the expression of crown rot in different varieties. [30]

The approximate order of increasing yield loss to crown rot is: cereal rye, oats, barley, bread wheat, triticale and durum wheat. [31] There is limited research on the tolerance of cereal rye to *P. thornei*.

30 S Simpfendorfer, M Gardner, G Brooke, L Jenkins (2014) Crown rot and nematodes—are you growing the right variety? GRDC Update Papers 6 March 2014, https://grdc.com.au/Research-and-Development/GRDC-Update-Papers/2014/03/Crown-rot-and-nematodes

31 GRDC. (2016). Tips and Tactics: Crown rot in winter cereals. Southern region. https://grdc.com.au/__data/assets/pdf_file/0029/165917/grdc_tips_and_tactics_crown_rot_southern_web.pdf.pdf

Diseases

Key messages

- Rye has good tolerance to cereal-root diseases.
- The most important disease of rye is ergot (*Claviceps purpurea*). Feeding stock with ergot-infested grain can result in serious stock losses: grain with three ergots per 1,000 kernels can be toxic.
- Stem and leaf rusts are seen on cereal rye in most years, but they are only occasionally a serious problem.
- All commercial cereal rye varieties have resistance to the current pathotypes of stripe rust. However, the outcrossing nature of the species means that under high disease pressure, 15–20% of the crop may show evidence of the disease. Other diseases are usually insignificant. Be wary that varietal resistance can change with the outbreak of new strains.
- Cereal rye has tolerance to take-all, making it a useful break crop following grassy pastures.
- Bevy is a host for the root disease take-all and this should be carefully monitored.

For disease to occur, the pathogen must have virulence to the particular variety, inoculum must be available and easily transported, and there must be favourable conditions for infection and disease development.

General disease-management strategies

- Use resistant or partially resistant varieties.
- Use disease-free seed.
- Use fungicidal seed treatments to kill fungi carried on the seed coat or in the seed.
- Have a planned in-crop fungicide regime.
- Conduct in-crop disease audits to determine the severity of disease. This can be used as a tool to determine what crop is grown in what paddock the following year.
- Conduct in-fallow disease audits to determine the severity of disease, e.g. yellow leaf spot and crown rot. This can also be used as a tool to determine what crop is grown in what paddock the following year.
- Send plant or stubble samples for analysis to determine the pathogen or strain you are dealing with, or the severity of the disease.
- Keep the farm free of weeds, which may carry over some diseases to the next season or crop. This includes cereals over summer that may act as a green bridge.
- Rotate crops.

MORE INFORMATION

GRDC's Cereal root and crown diseases: the back pocket guide.

9.1 Ergot

The most important disease of rye is ergot (*Claviceps purpurea*). Ergot, a purplish-black fungal disease that makes grains unsafe for consumption, is a prevalent problem in cereal rye crops.

Ergot produces black growths called sclerotia (Photo 1), which are visible in the heads of the rye (Photo 2). The fungi infect young, usually unfertilised ovaries, replacing the seeds with the sclerotia, which are dark mycelial masses. Usually, ergot infestations affect the borders of rye fields first, so it is important to take note of the presence of ergot and harvest infested sections of the field separately, especially if you are saving rye seed for next year's crop.

Photo 1: *Ergot bodies (sclerotia) taken from rye grain head.*

Photo: University of Hawaii

Good crop-rotation practices will minimise the chances of damage from disease, but rye crops should always be tested before human consumption. [1]

Ergot occurs throughout the world and affects many grass species, including cultivated cereals. Although it is relatively rare in Australian grains, it is considered to be a constant threat as it contains toxic chemicals (alkaloids) that are very harmful to both animals and humans. For this reason, ergot in grain could prove damaging to our trade. [2]

Ergot produces alkaloids similar to the psychotomimetic drug LSD. [3] Two types of sweet scabious intoxication have been reported: gangrenous ergotism, from consuming a small amount over a long period; and convulsive ergotism. Both affect people and animals.

Grain with three ergots per 1,000 kernels can be toxic. [4]

When using grain with known low levels of ergot from a silo, it is important to continue to monitor the concentration of ergot because it is often in highest concentration in the bottom 10% of silo content. [5]

9.1.1 Varietal resistance

Cereal rye and many grass species (including ryegrass) are particularly susceptible to ergot because they are open-flowered species.

MORE INFORMATION

MR Lee (2009) The history of ergot of rye (Claviceps purpurea) I: From antiquity to 1900. Journal of the Royal College of Physicians Edinburgh. 39, 179–184.

1 UVM Extension Crops and Soils Team (2011) Cereal rye, http://northerngraingrowers.org/wp-content/uploads/RYE.pdf

2 AWB Grower Services. Ergot: wheat quality fact sheet. AWB, https://www.awb.com.au/NR/rdonlyres/BFA96F0A-1967-4B8D-8B6C-631A00F15478/0/ERGOT_factsheet.pdf

3 Ergot of rye. 1: Introduction and history. Faculty of Botany. University of Hawaii, http://www.botany.hawaii.edu/faculty/wong/BOT135/LECT12.HTM

4 HerbiGuide. Rye. HerbiGuide, http://www.herbiguide.com.au/Descriptions/hg_Rye.htm

5 DAFWA (2015) Look out for ergots when selecting stock feed. DAFWA, https://www.agric.wa.gov.au/news/media-releases/look-out-ergots-when-selecting-stock-feed

9.1.2 Damage caused by disease

Ergot bodies contain alkaloid chemicals that can cause lameness, gangrene of the extremities, and nervous convulsions (staggers) that can lead to death in both humans and animals. As these toxins accumulate in the body, symptoms may begin to occur only after long periods of low-level ingestion. Crops affected by ergot generally do not result in significant yield losses, but economic losses can be quite severe when grain tendered by growers is rejected at receival. [6]

Gangrenous ergotism of humans and cattle

In humans and in other animals, gangrenous ergotism results in a blockage of circulation to the extremities, tingling in the fingers, vomiting, diarrhoea, gangrene of the toes and fingers, and ulceration of the mouth. Limbs may fall off. This is a dry form of gangrene.

In cattle, there is lameness, especially in the hindquarters, and gangrene of the feet, ears and tail. Pregnant cows may abort. There is a characteristic band where the gangrenous tissue ends.

Convulsive ergotism

Convulsive ergotism has symptoms similar to those of gangrenous ergotism. The appearance of physical symptoms is followed in humans by painful spasms of the limbs, epilepsy-like convulsions, and delirium. Cattle become excitable and run with a swaying, uncoordinated gait. [7]

9.1.3 Symptoms

Characteristically ergot pieces have a purple–black surface with a white to grey interior (Photo 2). They are usually horn-like in shape, and replace one or more grains in the heads of cereals and grasses. These ergot bodies can be up to four times larger than normal grain.

What to look for in the crop

- Hard dry purple–black fungal bodies (ergots) that replace the grain in the seed head.
- Yellow droplets of sugary slime in infected heads during flowering. [8]

Photo 2: *Ergot bodies in rye grain head.*

Photo: Cary Wolinsky, National Geographic Creative

What to look for in stock

Producers are encouraged to keep an eye on animals that may be eating ergot-infected grain, especially in hot or sunny weather (see Photo 3). Signs of ergot poisoning include animals seeking shade, being reluctant to move, and panting and

6 AWB Grower Services. Ergot: wheat quality fact sheet. AWB, https://www.awb.com.au/NR/rdonlyres/BFA96F0A-1967-4B8D-8B6C-631A00F15478/0/ERGOT_factsheet.pdf

7 HerbiGuide. Rye. HerbiGuide, http://www.herbiguide.com.au/Descriptions/hg_Rye.htm

8 DAFWA (2015) Diagnosing ergot. DAFWA, https://www.agric.wa.gov.au/mycrop/diagnosing-ergot

distress following any exercise. Animals may also drool, have an increased respiratory rate and reduced feed intake. [9]

Photo 3: *Producers need to be aware that even a small amount of ergot in grain can cause serious illness to their stock.*

Photo: Michael Raine

9.1.4 Conditions favouring development

- Ergots survive in the soil for up to one year, and can then produce spores that infect plants during flowering.
- Infection is more likely when there is cool wet weather at flowering.
- It can be spread by rain splash or by insects attracted to the sugary droplets.
- High levels of grass-weed contamination can increase ergot infection in cereals, and ergots produced in grasses can contaminate grain samples.

The development of ergot is favoured by moist soil surfaces during spring and early summer. In addition, wet conditions during the flowering of cereals and grasses increase the period of infection.

The disease cycle of ergot consists of two stages. The cycle begins in spring when the ergot bodies germinate in wet soils after winter, and develop fruiting bodies that contain spores (ascospores). The spores can be spread to neighbouring susceptible plants by wind and rain. To infect plants, the spores must land on the florets; within five days the second stage commences. This is referred to as the 'honeydew' stage. During this stage the infected florets exude a sugary slime that contains spores (conidia). These spores can infect other florets via insect vectors, rain splash and/or wind. This period of infection lasts for as long as the susceptible plants are in flower. The ovary in the floret becomes infected, then enlarges and is replaced by the purple–black ergot body, which can survive in soil for up to one year.

9 DAFWA (2015) Look out for ergots when selecting stock feed. DAFWA, https://www.agric.wa.gov.au/news/media-releases/look-out-ergots-when-selecting-stock-feed

Crops are generally perceived to be at greatest risk when grass-weed populations are high. Infected grasses usually produce slender ergots, and in some cases can be fully responsible for the contamination of grain samples. [10]

Ongoing periods of spring and summer rain can increase the occurrence of ergots in ryegrass; therefore ergots are more likely to develop in crops in years of above-average rain when ryegrass is flowering. Ergots produced in grasses outside the crop can contaminate grain samples. [11]

9.1.5 Managing ergot

- Give contaminated paddocks a one-year break without cereals or grasses.
- Manage grass-weed contamination in crops.
- Use clean seed.

Grain-cleaning equipment can be used to remove most ergot bodies in contaminated grain (Photo 4). However, the grower will need to determine whether this is economically viable.

Photo 4: *Ergot-contaminated seed.*

Photo: DAFWA

Tactics to reduce the risk of ergot infection

Key points:

- Use ergot-free seed if possible.
- Rotate with crops such as flax, canola and legumes, that are resistant to ergot.

10 AWB Grower Services. Ergot: wheat quality fact sheet. AWB, https://www.awb.com.au/NR/rdonlyres/BFA96F0A-1967-4B8D-8B6C-631A00F15478/0/ERGOT_factsheet.pdf

11 DAFWA (2015) Look out for ergots when selecting stock feed. DAFWA, https://www.agric.wa.gov.au/news/media-releases/look-out-ergots-when-selecting-stock-feed

- As the source of ergot infection is often the grass in headlands or ditches, mowing this grass before it flowers or sets seed will greatly reduce or eliminate the chances of ergot infection.
- Ergots germinate at or near the soil surface. To prevent them from germinating, work the field to a depth greater than 5 cm to bury the ergot bodies.
- Plant crop seed at a uniform depth and as shallow as possible for adequate moisture to obtain a uniform early emergence.
- Separate the seed collected from the first few combine rounds to prevent contamination of the entire lot as most of the ergot infested grain will likely be concentrated in this region. [12]

To avoid the development of ergot in subsequent cereal crops, effective farm management practices are required. One option available to growers is the use of crop rotations to stay away from cereals for at least one year to reduce the number of viable ergot pieces in the soil to negligible levels.

Another tactic is to use only clean seed during planting. [13] This is necessary, as there is currently no effective treatment seed dressing against ergot. For growers using conventional tillage, ergot pieces need to be buried to a minimum depth of 4 cm. This prevents the fruiting bodies from reaching the soil surface and releasing spores. As this may have an effect on the usual sowing operations, guidance should be sought.

Finally, to eliminate the development of host reservoirs, growers may be able to mow or spray grass pastures to prevent flowering. [14]

Control of grasses within cereal crops will help prevent cross-infection. This is best achieved by preventing seedset in the previous season, by clear fallowing, hard grazing or hay cutting, together with the use of selective herbicides. [15]

There are no ergot-resistant rye varieties. The only practical control is to sow clean, year-old seed on land that hasn't grown rye for at least a year. Mowing roadside and headland grass before they set seed will reduce or eliminate this major source of ergot re-infestation. [16]

Marketing options

IN FOCUS

Alkaloids in Australian rye ergot sclerotia: implications for food and stockfeed regulations.

Rye ergot (*Claviceps purpurea*) occasionally causes toxicity (chiefly expressed as hyperthermia, in which the body becomes overheated) in Australian livestock, either because they have grazed on infected annual ryegrass (*Lolium rigidum*) and perennial ryegrass (*L. perenne*), or when the ergot sclerotia produced in ryegrasses contaminate grain crops used as stockfood. Researchers wanted to determine whether current regulations on the permissible limits of ergot in food and stockfeed were sufficient, as the limit had been set many years previously on the basis of very limited toxicological data. They took alkaloids from 30 samples of Australian rye ergot sclerotia from ryegrasses and grain screenings, and some samples from contaminated feed, and analysed how potent they were.

12 Alberta Agriculture and Forestry (2016) Fall rye production. Agdex 117/20-1. Alberta Agriculture and Forestry, http://www1.agric.gov.ab.ca/$department/deptdocs.nsf/all/agdex1269/$file/117_20-1.pdf

13 DAFWA (2015) Diagnosing ergot. DAFWA, https://www.agric.wa.gov.au/mycrop/diagnosing-ergot

14 AWB Grower Services. Ergot: wheat quality fact sheet. AWB, https://www.awb.com.au/NR/rdonlyres/BFA96F0A-1967-4B8D-8B6C-631A00F15478/0/ERGOT_factsheet.pdf

15 R Clarke (1999) Ergot of pasture grasses. Note AG0721. Agriculture Victoria, http://agriculture.vic.gov.au/agriculture/pests-diseases-and-weeds/plant-diseases/grains-pulses-and-cereals/ergot-of-pasture-grasses

16 Alberta Agriculture and Forestry (2016) Fall rye production. Agdex 117/20-1. Alberta Agriculture and Forestry, http://www1.agric.gov.ab.ca/$department/deptdocs.nsf/all/agdex1269/$file/117_20-1.pdf

Bulk grain traders limit rye ergot sclerotia by length (laid end to end). The maximum limits set by Grain Trade Australia for 2009–10 for rye ergot sclerotia per half litre of grain were: wheat, 2 cm; barley, 0.5 cm; oats, 2 cm; triticale, nil; rye, nil. As well, rye ergot sclerotia are restricted to 0.02% weight per weight (w/w) in grain under Queensland Stockfood Regulations. The limit of 0.02% (200 mg ergot/kg) is roughly equivalent to 8 cm of rye ergot sclerotia per half litre of grain.

The researchers reviewed cases of livestock poisoning and limited experiments on the effects of ergot poisoning. They concluded that ruminants that are exposed to the sun are more sensitive to the effects of ergot than humans and other monogastric animals are. The material they reviewed showed severe hyperthermia in ruminants fed 1–2 mg ergot alkaloids/kg of feed. This suggested that the total alkaloid content of feed should be restricted to <0.5 mg/kg.

They argued that an extra safety margin was desirable to allow for the irregular distribution of ergot sclerotia in bulk grain, and variations in individual susceptibility to ergot, and recommended a limit of <0.1 mg/kg. This equates to ~0.004% rye ergot sclerotia (40 mg/kg) for sclerotia having an alkaloid content of around 2,500 mg/kg (<2 cm sclerotia per half litre of grain). However, other risk factors include the unknown role of the ergot pigments in exacerbating hyperthermia in sunlight-exposed stock.

All these variables combine to indicate that feed likely to contain any detectable rye ergot should be avoided in ruminant feedlot rations. Poultry and non-lactating mature (finisher) pigs are able to tolerate lightly contaminated grain. [17]

9.2 Take-all

Key points:

- Cereal rye has tolerance to take-all, making is a useful break crop following grassy pastures.
- Monitor rainfall patterns (when and how much), and adjust sowing times where possible.
- Control weeds during late summer and early autumn.
- Use ammonium-based nitrogenous fertilisers to improve crop nutrition and decrease the incidence of take-all.
- In severe take-all outbreaks, consider using grass-free cropping as a management strategy.

Take-all (*Gaeumannomyces graminis*) is a soil-borne disease of cereal crops and is most severe on wheat crops in southern Australia. In New South Wales, the disease is caused by two variations of the *Gaeumannomyces graminis* fungus, *G. graminis* var. *tritici (Ggt)* and *G. graminis* var. *avenae (Gga),* and is most severe in the high-rainfall areas of the agricultural region (i.e. southern cropping regions and areas closer to the coast). Control of take-all is predominantly cultural, and relies on practices which minimise carry-over of the disease from one cereal crop to the next. [18]

PODCAST

GRDC (2016) Crown rot and take-all warning. MP3 (audio) GRDC Radio (Northern Update).

17 BJ Blaney, JB Molloy and IJ Brock (2009) Alkaloids in Australian rye ergot (Claviceps purpurea) sclerotia: implications for food and stockfeed regulations. Animal Production Science, 49 (11), 975–982, http://www.publish.csiro.au/an/AN09030

18 A Wherrett and B MacLeod (2016) Take-all disease: New South Wales. Fact sheet. Soilquality, http://www.soilquality.org.au/factsheets/take-all-disease-nsw

9.2.1 Varietal resistance

Cereal rye's resistance and tolerance to take-all (which is also known as haydie) makes it a useful break crop for sowing before susceptible wheat, triticale or barley crops. It can also be sown in situations where take-all is expected, e.g. following grassy pasture on soils that are unsuitable for oats. [19]

Cereal rye: a host for take-all?

One study from New Zealand suggests that rye may increase take-all inoculum, even though it is regarded as resistant to the disease. [20] The Foundation for Arable Research reported that:

- Wheat and barley roots are both infected by take-all. Triticale, depending on the parentage of the cultivar, ranges from being almost as susceptible as wheat to as resistant as rye.
- The effects on wheat are usually more serious than for barley. A field trial confirmed that wheat is more susceptible to take-all than rye, triticale and barley. The triticale cultivar (cv.) Kortego was more resistant than barley (tested using cv. Quench), while rye had no visible infection by take-all. The results support the selection of rye, triticale and barley over wheat for growing in fields known to have *G. graminis* var. *tritici (Ggt*).
- Although barley, triticale and rye do not become heavily infected by take-all, levels of *Ggt* in the soil after these cereals can be high. The large root systems of these species may provide more material for infection and *Ggt* inoculum build-up.

Growers are keen to keep cropping rotations flexible. This research shows that the risk to take-all in wheat cannot be reduced by using barley, triticale and rye as break crops between wheat crops. [21]

The cereal rye variety Bevy, which was developed from a composite of nine predominantly semi-dwarf spring rye types, is a host for take-all, and should be monitored carefully. [22]

9.2.2 Symptoms

Initial indications of take-all in a crop are the appearance of indistinct patches of poor growth in the crop; these may be from a few metres across to significant areas of crop. Closer inspection of individual plants will indicate discolouration of the crown, roots and stem base. Blackening of the centre of the roots (stele) is symptomatic of an early take-all infection. Severely infected plants will have a blackened crown and stem base, and be easy to pull from the soil because they will no longer have an attached root system. Any remaining roots are brittle and break off with a 'square end'.

The appearance of whiteheads later in the season is another indicator of a take-all (although frost and micronutrient deficiencies can also cause whiteheads), with severe infections causing the crop to hay-off early. Infected plants will produce pinched grain, with severe infections yielding little harvestable seed in the head (hence 'take-all'); in some cases infected areas may not be worth harvesting. [23]

19 Wrightson Seeds (2010) Forage focus—Southern Green forage ryecorn. Wrightson Seeds, http://www.pggwrightsonseeds.com.au/assets/FTP-Uploads/Forage_Focus/Cereals/FF_Southern-Green-Forage-Ryecorn.pdf

20 Foundation for Arable Research (2009) High take-all inoculum levels can follow resistant cereals. Arable Update No. 194. FAR, https://www.far.org.nz/assets/files/uploads/C194Take-all.pdf

21 Foundation for Arable Research (2009) High take-all inoculum levels can follow resistant cereals. Arable Update No. 194. FAR, https://www.far.org.nz/assets/files/uploads/C194Take-all.pdf

22 Agriculture Victoria (2013) Growing cereal rye. Note AG0403. Updated. Agriculture Victoria, http://agriculture.vic.gov.au/agriculture/grains-and-other-crops/crop-production/growing-cereal-rye

23 A Wherrett and B MacLeod (2016) Take-all disease: New South Wales. Fact sheet. Soilquality, http://www.soilquality.org.au/factsheets/take-all-disease-nsw

What to look for in the paddock

- Patches (up to several metres in diameter and with indistinct and irregular edges) of white-coloured tillers and heads containing shrivelled grain or no grain (Figure 5). [24]
- Affected plants can be individuals scattered among healthy plants, or entire populations of plants over a large area.

Photo 5: *Patches with irregular edges of white-coloured tillers and heads containing shrivelled grain or no grain.*

Photo: DAFWA

What to look for in the plant

- The first obvious signs of infection are seen after flowering, with the development of whiteheads.
- Roots of affected plants are blackened to the core (not just on the surface) and are brittle and break easily (Figure 6).
- Severely affected plants can also have blackened crowns and lower stems.

24 DAFWA (2015) Diagnosing take-all in cereals. DAFWA, https://www.agric.wa.gov.au/mycrop/diagnosing-take-all-cereals

Photo 6: *Roots of affected plants are blackened and brittle (left). Severely affected plants can have blackened crowns and lower stems (right).*

Photos: DAFWA

9.2.3 Conditions favouring development

Gaeumannomyces graminis survives the Australian summer in the residue of the previous season's grass host (Figure 1). The arrival of cooler temperatures and rainfall in the autumn triggers the fungus into action. The fungus infects the roots of the emerging crop during this period. Higher rainfall in winter is likely to increase take-all disease pressure. For this reason, the southern regions of New South Wales are most likely to suffer yield loss in cereal crops due to take-all. While lower soil moisture will decrease the chance of a severe outbreak of take-all, plants that are already infected will find it difficult to cope due to water stress.

Soil at field capacity (i.e. is fully wet) encourages early-season infection of seedlings by both *G. graminis* var. *tritici* and *G. graminis* var. *avenae*. Greatest yield loss occurs on infected plants when moisture is limiting post-anthesis.

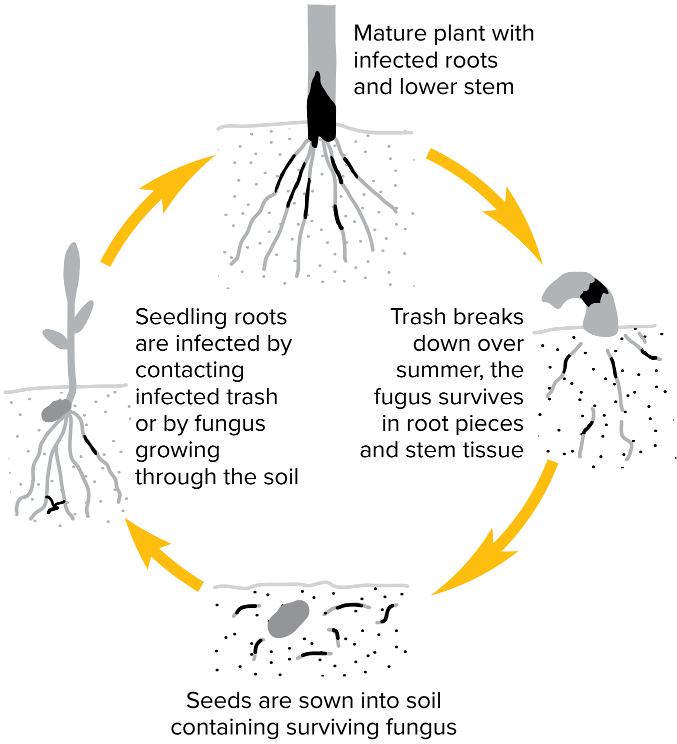


Figure 1: *Common life cycle of the take-all fungus in Western Australian cropping regions.*

Source: Soilquality

Hosts

All annual grasses can be infected by *G. graminis*, although some species are more susceptible than others. While wheat, barley and triticale are the most susceptible crops to take-all, barley grass is also an effective host to the disease. Oats are the only cereal crop to offer resistance, although evidence of *G. graminis* strains capable of causing yield loss has been reported in areas where continual oat cropping occurs. Brome grass, silver grass and ryegrass are all viable host species for take-all. All non-cereal crops (e.g. lupins, canola and clover) are non-hosts to take-all. [25]

9.2.4 Managing take-all

- By far the most effective method of reducing take-all is to remove grasses in the year before you plant the susceptible crop, and replace grasses with a grass-free pasture or break crop.
- Cereal rye's resistance and tolerance to take-all makes it a useful break crop for sowing before susceptible wheat, triticale or barley crops. [26] However, research from New Zealand suggests that cereal rye can be a host for take-all disease. [27]
- There are fungicides to be applied with seeding, fertiliser and in-furrow that are registered for take-all control.
- Acidifying fertilisers can slightly reduce disease severity; conversely, take-all severity may increase following liming.

25 A Wherrett and B MacLeod (2016) Take-all disease: New South Wales. Fact sheet. Soilquality, http://www.soilquality.org.au/factsheets/take-all-disease-nsw

26 Wrightson Seeds (2010) Forage Focus – Southern Green forage ryecorn. Wrightson Seeds, http://www.pggwrightsonseeds.com.au/assets/FTP-Uploads/Forage_Focus/Cereals/FF_Southern-Green-Forage-Ryecorn.pdf

27 Foundation for Arable Research (2009) High take-all inoculum levels can follow resistant cereals. Arable Update No. 194. FAR, https://www.far.org.nz/assets/files/uploads/C194Take-all.pdf

- Control volunteer grasses and cereals.
- Delay sowing following the opening rains by implementing a short chemical fallow. [28]

The most effective management strategy for take-all is to deny the fungus the ability to survive in the paddock, through the elimination of hosts. This is most effectively done through the use of a non-cereal break crop (e.g. lupins, canola, field peas, faba beans, chickpeas, or sorghum) and by controlling grass weeds during autumn. Pastures containing low levels of grass species will also have reduced take-all carryover the following season. Where minimum tillage is practiced the time taken for residues to break down is increased, allowing the disease to stay viable for longer. The use of break crops and activities to hasten residue breakdown may be beneficial. While burning does decrease the amount of surface residue infected with the fungus, the fire is generally not hot enough to affect the infected material below ground.

Registered fungicides applied as either fertiliser or seed treatments are generally only economically viable where severe outbreaks have occurred. In many cases it is more practical to sow non-cereal crops or pasture to reduce take-all carryover.

Competition from other soil organisms decreases the survival of *G. graminis* in the soil. Summer rains or an early break in the season allows for such conditions to develop. The effect of this can be negated by poor weed control during this period, because:

- Cereal weeds become infected, thus enabling *G. graminis* to survive until crop establishment.
- Rapid drying of the topsoil due to weeds decreases the survival of competitive soil organisms, therefore slowing the decline of *G. graminis*.

Decline of take-all

Take-all decline is the apparent waning of the extent of the occurrence of take-all following many years of continuous cereal cropping, and has been shown to occur in South Australia. This has been attributed to the build-up of antagonistic microorganisms in the soil. Although this process may occur, it is not a viable way to deal with take-all, as the economic losses incurred during the build-up appear to be unacceptable. There have, however, been examples of a reduction in take-all incidence due to gradual acidification of soil; this decline is reversed when lime is applied to increase soil pH. [29]

9.3 Rusts

Stem and leaf rusts are seen on cereal rye in most years, but they are only occasionally a serious problem. [30] All commercial cereal rye varieties have resistance to the current pathotypes of stripe rust. However, the outcrossing nature of the species means that under high disease pressure, 15–20% of the crop may show evidence of the disease. Other diseases are usually insignificant. Be wary that varietal resistance can change with the outbreak of new strains.

In Queensland and New South Wales, there are three rust diseases of rye and wheat:

- stripe rust
- stem rust
- leaf rust.

They are caused by three closely related fungi all belonging to the genus *Puccinia*.

The rusts are so named because the powdery mass of spores which erupt through the plant's epidermis have the appearance of rusty metal. The spores can be

28 DAFWA (2015) Diagnosing take-all in cereals. DAFWA, https://www.agric.wa.gov.au/mycrop/diagnosing-take-all-cereals

29 A Wherrett and B MacLeod (2016) Take-all disease: New South Wales. Fact sheet. Soilquality, http://www.soilquality.org.au/factsheets/take-all-disease-nsw

30 Agriculture Victoria (2013) Growing cereal rye. Note AG0403. Agriculture Victoria, http://agriculture.vic.gov.au/agriculture/grains-and-other-crops/crop-production/growing-cereal-rye

spread over considerable distances by wind, and may also be spread via clothing and equipment.

The three rusts that affect rye have a number of features in common. They can only infect a limited number of specific host plants (mostly volunteer wheat, triticale and barley) and can only survive on green, growing plant tissue. Biotrophic (parasitic) pathogens including stem rust, stripe rust and leaf rust require a living plant host and cannot survive on soil, seed or dead tissue. They therefore need a green bridge of grassy weeds or overlapping crops to persist. These plants facilitate the survival of rust fungi through the summer. [31]

Rust diseases occur throughout the Northern grain region, frequently causing economic damage. In Queensland stripe rust has recently been the more prevalent rust disease. Stripe rust reached epidemic levels in eastern Australia during 2009, and resulted in widespread fungicidal spraying.

The most recent cereal rust report, of September 2016, reports that a sample of rye leaf rust was received from Borrika in South Australia in late July, 2016.

In the Northern region, samples of leaf rust were received from the Queensland districts of Millmerran in mid-August and Mirabooka late August. Identification of the pathotypes (variants that also cause disease) for these two samples were under way at the time of publication. Samples subsequently received from Warwick, Gatton and Emerald were also scheduled for pathotype identification. Samples of stripe rust had been received from Boree Creek in NSW, and from Gatton in Queensland, sampled off a susceptible wheat spreader. [32]

The three rusts are relatively easy to differentiate (Table 1). [33]

9.3.1 Symptoms

Table 1: *Diagnosing leaf diseases in cereals.*

Disease	Spore colour	Symptoms	Plant part affected
Stripe rust	Yellow–orange	Small closely packed circular pustules during the vegetative stage, becoming stripes along leaves of older plants	Upper surface of leaf, leaf sheaths, awns and inside glumes
Leaf rust	Orange or brown	Random, circular to oval pustules	Upper surface of leaf and leaf sheaths
Stem rust	Reddish brown	Random, oblong pustules with torn margins	Both sides of leaf, leaf sheaths, stems and outside of head
Yellow spot	Small tan oval spots with a yellow margin	Spots up to 10 mm, varied shapes and may coalesce	Both sides of leaf, leaf sheaths, stems and outside of head

Source: DAF Qld

Stripe rust

Stripe rust (also known as yellow rust) is caused by the fungus *Puccinia striiformis*. It is easily distinguished from other wheat rusts by the yellow–orange spores, which produce small, closely packed pustules that develop into stripes along the length of the leaf veins. The spores occur on the upper surface of the leaves, the leaf sheaths, awns and inside of the glumes (Photo 7, Table 1).

31 DAF Queensland (2015) Wheat: diseases, physiological disorders and frost. DAF Qld, https://www.daf.qld.gov.au/plants/field-crops-and-pastures/broadacre-field-crops/wheat/diseases

32 W Cuddy, R Park, and D Singh (2016) Cereal rust situation. Cereal Rust Report. 19 September 2016. University of Sydney. 14 (7), http://sydney.edu.au/agriculture/documents/pbi/cereal_rust_report_2016_14_7.pdf

33 DAF Queensland (2015) Integrated disease management of wheat rusts and yellow spot. DAF Qld, https://www.daf.qld.gov.au/plants/field-crops-and-pastures/broadacre-field-crops/wheat/wheat-rusts

VIDEOS

WATCH: GRDC (2010) Cereal rust. GCTV1, GRDC.

Stripe rust requires cool and wet conditions to infect a crop. Free moisture on the leaves and an optimal temperature of 10–15°C are required. Pustules erupt within 10–14 days of infection.

If the weather is conducive to stripe rust, the disease can cause up to 25% yield loss on varieties scored as moderately susceptible, i.e. 5 (MR–MS) or lower. This is provided there is inoculum from a neglected green bridge or from an infected crop.

There are several fungicides recommended for the control of stripe rust. They can be incorporated with the fertiliser or applied as seed dressings to delay the onset of disease (Table 2). Later on, if 'money' leaves require protection, foliar fungicides (Table 3) can be applied.

In Queensland, stripe rust pathotypes 134 E16 A+ and 134 E16 A+ 17+ were prevalent during 2011. Grain growers should refer to the wheat varieties guide when selecting stripe rust-resistant varieties, as there is a threat from additional stripe rust pathotypes 134 E16 A+ J+ and 134 E16 A+ J+ T+, which have also been identified in Queensland.

Photo 7: *Stripe rust in cereals.*

Photo: DAF Qld

Leaf rust

Leaf rust (also known as brown rust) is caused by the fungus *Puccinia triticinia* (previously called *Puccinia recondite* f. sp. *tritici*). The disease infects rye, wheat and triticale.

Leaf rust produces reddish-orange-coloured spores which occur in small, 1.5 mm, circular to oval-shaped pustules. These are found on the top surface of the leaves; this distinguishes leaf rust from stem rust, which is found on both surfaces of the leaf (Photo 8).

Queensland wheat varieties mostly have reasonable resistance (rating of MR-MS, or 5 or higher) and so leaf rust is currently not of major concern to Queensland cereal growers.

The spores require temperatures of 15–20°C and free moisture (dew, rain, or irrigation water) on the leaves to successfully infect wheat. The first signs of the disease, at sporulation, occur 10–14 days after infection. Removal of volunteer wheat plants, which form a green bridge for the fungus through the summer, can eliminate or delay the onset of leaf rust. [34]

One fungicide is available to treat leaf rust when seeding or fertilising (Table 2), and several are available as foliar fungicides in established crops (Table 3).

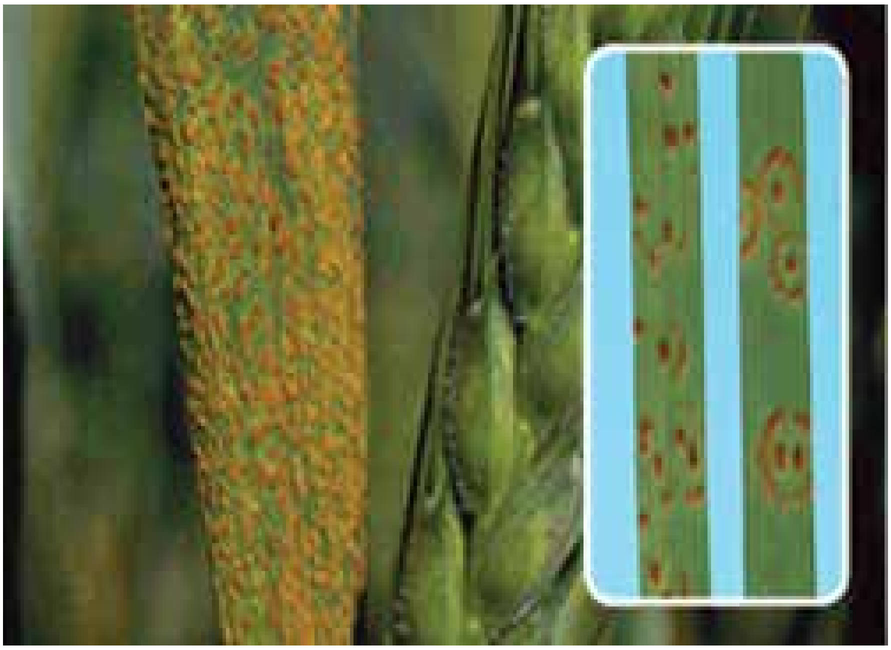


Photo 8: *Leaf rust in cereals.*

Photo: DAF Qld

Stem rust

Stem rust (or black rust) is caused by the fungus *Puccinia graminis* f. sp. *tritici*. In addition to rye, it also attacks wheat, barley and triticale.

Stem rust produces reddish-brown spore masses in oval, elongated or spindle-shaped pustules on the stems and leaves. Unlike leaf rust, pustules erupt through both sides of the leaves (Figure 10). When the pustules rupture they release masses of stem rust spores, which are disseminated by wind and other carriers.

Stem rust develops at higher temperatures than the other wheat rusts, within the range of 18–30°C. Spores require free moisture (dew, rain or irrigation water) and take up to six hours to infect the plant. The pustules can be seen 10–20 days after infection.

Queensland wheat varieties have reasonable resistance to stem rust (a rating 5 or higher). However, in the past, stem rust has caused significant economic damage, from 50–100% of yield. This has happened when conditions conducive for the disease occur when susceptible varieties were grown, or when a new stem rust pathotype has developed and overcome the wheat's resistance.

Inoculum must be present for the disease to develop. Practising crop hygiene by removing volunteer wheat, which forms a green bridge for the fungus through the summer, can eliminate or delay the onset of stem rust. [35]

There are no fungicides registered for use at seeding or with fertiliser for stem rust (Table 2), but several foliar fungicides are available (Table 3).

VIDEOS

WATCH: GRDC (2012) Green bridge control for less stem rust. GCTV5. GRDC.

34 DAF Queensland (2015) Integrated disease management of wheat rusts and yellow spot. DAF Qld, https://www.daf.qld.gov.au/plants/field-crops-and-pastures/broadacre-field-crops/wheat/wheat-rusts

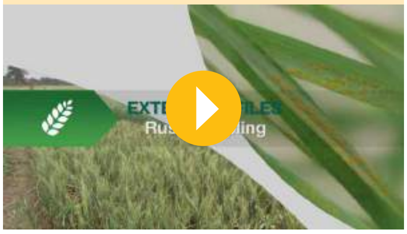
35 DAF Queensland (2015) Integrated disease management of wheat rusts and yellow spot. DAF Qld, https://www.daf.qld.gov.au/plants/field-crops-and-pastures/broadacre-field-crops/wheat/wheat-rusts

Figure 2: *Stem rust in cereals.*

Photo: DAF Qld

VIDEOS

WATCH: GRDC (2015) GCTV: Extension files: rust sampling.



9.3.2 Managing rust

Rust diseases of wheat can be eliminated or significantly reduced by removing any green bridges. This should be done well before the new crop is sown, to allow time for any herbicide to work and for the fungus to stop producing spores.

Rust fungi continually change, producing new pathotypes. The pathotypes are detected when disease is found on a previously resistant variety. Therefore, even if a resistant variety has been sown, the crop should be monitored regularly for foliar diseases. This should start no later than growth stage 31, the second-node stage on the main stem, and continue to at least growth stage 39, the flag-leaf stage. This is because the flag leaf and the two leaves below it are the main factories that contribute to yield and quality. It is very important that these leaves are protected from diseases. [36]

Integrated disease management of rusts and yellow spot

- Destroy volunteer wheat plants by March, as they can provide a green bridge for rust carryover.
- Community efforts are required to eradicate volunteers from roadsides, railway lines, bridges, paddocks and around silos.
- Crop rotation is very important in the cases of yellow spot and *Fusarium* head blight.
- Growing resistant varieties is an economical and environmentally friendly way of reducing the incidence of disease.
- Seed or fertiliser treatment can control stripe rust up to four weeks after sowing, and suppress it thereafter.
- During the growing season active crop monitoring is very important for early detection of diseases.
- Correct disease identification is very important: consult agricultural department fact sheets, charts and websites, and consult experts.

36 DAF Queensland (2015) Wheat: diseases, physiological disorders and frost. DAF Qld, https://www.daf.qld.gov.au/plants/field-crops-and-pastures/broadacre-field-crops/wheat/diseases

- When deciding if a fungicide spray is needed, consider crop stage and potential yield loss.
- Select a recommended and cost-effective fungicide.
- For effective coverage, the use of the right spray equipment and nozzles is very important.
- Read the label and follow instructions on it, and wear protective gear to protect yourself and the environment.
- Avoid the repeated use of fungicides with the same active ingredient in the same season.
- Always check for withholding periods before grazing or harvesting a crop that has had fungicide applied.
- If you suspect a severe disease outbreak, especially on resistant varieties, contact DAF Queensland or DPI NSW.

Wherever possible, sow resistant cereal varieties that have been rated MR (moderately resistant, or 6) and above. All commercial varieties of rye have stripe rust resistance to the current pathotypes although out-crossing can occur.

There are a number of fungicides recommended for the control of foliar diseases of wheat (Table 2 and Table 3).

Table 2: *Fungicides recommended for seed and fertiliser treatment.*

Disease	Fungicide	
	Fluquinconazole (167 g/L)	**Flutriafol (250 g/L)**
Stripe rust (yellow rust)	Rate: 450 mL/100 kg seed	Rate: 200 or 400 mL/ha fertiliser
Leaf rust (brown rust)	Rate: 450 mL/100 kg seed	–
Stem rust (black rust)	–	–
Yellow spot (tan spot)	–	–
Withholding period after treatment	12 weeks for grazing and harvest	4 weeks for grazing and harvest

Source: DAF Qld

Table 3: *Rate of fungicide (product formulation) recommended as foliar sprays for the control of rust diseases and yellow spot of wheat.*

Disease	Foliar fungicide (rate of application)							
	Epoxi-conazole (125 g/L)	Flutriafol (250 g/L)	Propi-conazole (250 g/L)	Triadimefon (125 g/L)	Tebu-conazole (430 g/L)	Prothio-conazole (210 g/L) + Tebu-conazole (210 g/L)	Azoxy-strobin (200 g/L) + Cypro-conazole (80 g/L)	Propi-conazole (250 g/L) + Cypro-conazole (80 g/L)
Stripe rust (yellow rust)	250–500 mL/ha	250–500 mL/ha	250–500 mL/ha	500 or 1000 mL/ha	145 or 290 mL/ha	150–300 mL/ha + Hasten 1% v/v	400 or 800 mL/ha	250–500 mL/ha
Leaf rust (brown rust)	500 mL/ha	250–500 mL/ha	150–500 mL/ha	–	145 or 290 mL/ha	150–300 mL/ha + Hasten 1% v/v	400 or 800 mL/ha	150–500 mL/ha
Stem rust (black rust)	–	–	500 mL/ha	–	145 or 290 mL/ha	150–300 mL/ha + Hasten 1% v/v	–	500 mL/ha
Yellow spot (tan spot)	–	–	250–500 mL/ha	–	145 or 290 mL/ha	150–300 mL/ha	400 or 800 mL/ha	250–500 mL/ha
Withholding period after treatment	6 weeks for grazing and harvest	7 weeks for grazing and harvest	4 weeks for harvest, 7 days for grazing	4 weeks for grazing and harvest	5 weeks for harvest, 14 days for grazing	5 weeks for harvest, 14 days for grazing	6 weeks for harvest, 21 days for grazing	6 weeks for harvest, 21 days for grazing

Source: DAF Qld

MORE INFORMATION

CSIRO (2016) Cereal rusts.

Rust Bust. (2015) How to manage rust.

IN FOCUS

Breeding cereals for rust resistance in Australia

Rust diseases have caused significant losses to Australian cereal crops, and continue to pose a serious threat. Because Australian cereal crop yields are generally low, genetic resistance remains the most economical means of controlling rust. Resistant cultivars also contribute significantly to reducing rust survival over summer.

A policy of releasing only rust-resistant wheats in northern New South Wales and Queensland resulted in industry-wide protection from rust in the northern grains region for the 40 years up to the early 2000s. The Australian Cereal Rust Control Program conducts annual pathogenicity surveys for all cereal rust pathogens, undertakes genetic research to identify and characterise new sources of resistance, and provides a germ-plasm screening and enhancement service to all Australian cereal breeding groups. These three activities are interdependent, and are closely integrated, with particular emphasis on linking pathology and genetics to ensure breeding outcomes that continue to offer protection to domestic crops from rust.

In a paper published in 2008, a researcher discusses the rise of recent changes in the wheat-rust pathogens that have made the protection of crops more difficult. Changes include the development of virulence for the disease-resistance genes *Yr17*, *Lr24*, *Lr37* and *Sr38 (which had been incorporated into several wheat cultivars)*, and the evolution of a new pathotype of the wheat stripe-rust pathogen. They have provided

VIDEOS

WATCH: GRDC (2015) Adult plant resistance – revisited. GCTV18.

WATCH: GRDC (2012) Cereal rust – adult plant resistance. GCTV9.

GRDC (2015) Triple rust resistance. GCTV18.

WATCH: GRDC (2010) Yellow or tan spot. GCTV2.

significant challenges for wheat rust resistance breeding. Similar challenges exist in breeding barley and oats for rust resistance.

The author also discusses the opportunities that arise from the evolution of new pathotypes: new virulence can inform observant researchers how they might approach breeding for resistance in new ways. Examples are discussed to illustrate the ways in which rust isolates are providing information that can be used in breeding for rust resistance. In future, as more markers linked to durable sources of rust resistance become available, it is likely that the use of marker-assisted selection will become more common-place in rust resistance breeding. [37]

9.4 Yellow spot

Yellow spot (which is also known as yellow leaf spot and tan spot) is caused by the fungus *Pyrenophora tritici-repentis*. It survives in wheat and, occasionally, triticale stubble. In rare cases, the fungus may survive in barley stubble. Wet spores (ascospores) develop in fungal fruiting bodies on wheat stubble, spread during wet conditions, and infect growing cereal plants.

As the crop develops, masses of a second type of spore (conidia) are produced on old lesions and dead tissues. Conidia result in the rapid development of a yellow-spot epidemic in a crop, and in the spread of the disease to other crops and areas. Again, wet conditions are necessary for conidia spore production and infection. Strong winds are needed to spread the disease any great distance. [38]

9.4.1 Varietal resistance

Cereal rye is partially susceptible to yellow spot. [39]

9.4.2 Damage caused by disease

Grain yield can be substantially reduced and losses of more than 50% may occur in extreme situations. Pink grain that is reduced in value is also a frequent result of severe yellow-spot epidemics. In continuous cereal cropping and where some stubble is left on the soil surface, losses may be 10–15%, and up to 30% in wet seasons.

9.4.3 Symptoms

Yellow spot shows up as tan-brown flecks that turn into yellow-brown oval-shaped spots or lesions with yellow margins. They may expand to 10–12 mm in diameter. Large lesions coalesce, and have dark brown centres. Spot develops on both sides of leaves (Photo 9). Severe yellow spot may result in short, spindly plants with reduced tillering and root development. Where conditions are favourable, plants may be fully defoliated soon after flowering. [40]

37 RF Park (2008) Breeding cereals for rust resistance in Australia. Plant Pathology, 57 (4), 591–602, http://onlinelibrary.wiley.com/doi/10.1111/j.1365-3059.2008.01836.x/abstract

38 DAF Queensland (2015) Wheat: diseases, physiological disorders and frost. DAF Qld, https://www.daf.qld.gov.au/plants/field-crops-and-pastures/broadacre-field-crops/wheat/diseases

39 HerbiGuide. Yellow spot of wheat. HerbiGuide, http://www.herbiguide.com.au/Descriptions/hg_Yellow_Spot_of_Wheat.htm

40 DAF Queensland (2015) Wheat: diseases, physiological disorders and frost. DAF Qld, https://www.daf.qld.gov.au/plants/field-crops-and-pastures/broadacre-field-crops/wheat/diseases

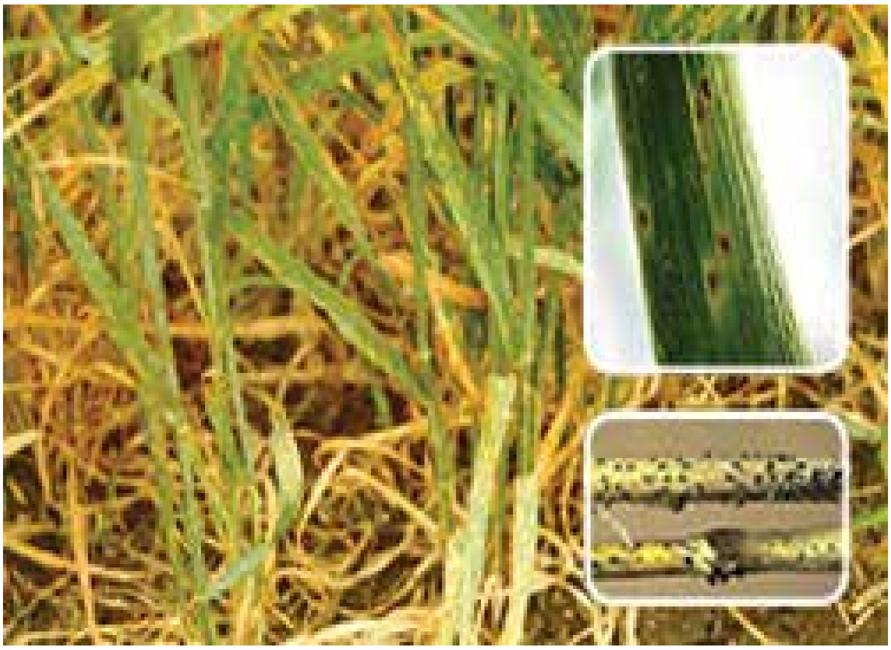


Photo 9: *Yellow spot in cereals.*

Photo: DAF Qld

9.4.4 Conditions favouring development

Yellow spot is likely to develop in wet years in fields where wheat residues remain on the soil surface. Temperatures from 20–30°C and free moisture (dew, rain, or irrigation water) favour disease development.

9.4.5 Managing yellow spot

The impact of the disease can be reduced by:

- planting partially resistant varieties
- rotating with resistant crops such as barley, oats or chickpeas
- incorporating stubble into the soil
- grazing or burning the stubble late in the fallow period.

Incorporation or burning stubble is not recommended unless infestation levels are very high. Correct identification of the yellow spot fungus in infected stubble should be carried out before the stubble is removed. Varieties partially resistant to yellow spot offer the only long-term solution and should be considered for planting where yellow spot could be a problem. [41]

If you do not want to be concerned by yellow spot (including at seedling stages) then:

- *Do not* sow wheat on wheat.
- If you are going to sow wheat on wheat consider a late (autumn) stubble burn and/or select a wheat variety with some level of resistance to yellow spot (noting also tolerance and resistance to other diseases).
- Primary management decisions for yellow spot need to be made before sowing or at sowing. Fungicides are a poor last resort for controlling yellow spot as they control but do not kill the lesions. Yellow spot is very different to stripe rust! [42]

MORE INFORMATION

Management of yellow spot in wheat: decide before you sow.

41 DAF Queensland (2015) Wheat: diseases, physiological disorders and frost. DAF Qld, https://www.daf.qld.gov.au/plants/field-crops-and-pastures/broadacre-field-crops/wheat/diseases

42 S Simpfendorfer (2013) Management of yellow spot in wheat: decide before you sow. GRDC Update Papers. GRDC, https://grdc.com.au/Research-and-Development/GRDC-Update-Papers/2013/03/Management-of-yellow-spot-in-wheat-decide-before-you-sow

In-crop fungicides and timing

Fungicides used against yellow spot in Australia include:

- propiconazole
- tebuconazole
- azoxystrobin with cyproconazole
- propiconazole with cyproconazole

Timing for applying the chosen fungicide is crucial. The most effective time of application is at 90% flag-leaf emergence with disease levels of less than 10% on the flag leaf. Table 3 (section 9.3.2) gives rates of application for the different fungicides.

The higher rate of application has been shown to provide longer protection during periods of high disease pressure. Fungicide is more effective on susceptible varieties, and effectiveness reduces with increasing levels of resistance, at least in irrigated field trials. The economic viability of such applications during the extreme pressure of large-scale epidemics is another question, and the grower must consider all factors when deciding whether to apply fungicide. [43]

Search the APVMA's database of registered chemical products and permits for fungicide updates.

MORE INFORMATION

Management to reduce the risk of yellow leaf spot.

9.5 Crown rot and Fusarium head blight

- *Fusarium* species are responsible for causing two distinctly different diseases in winter cereal crops: crown rot and Fusarium head blight.
- Crown rot survives on infected stubble, from where it is passed onto the following crop.
- Use non-host crops (e.g. pulses, oilseeds and broad-leaf pasture species) in rotation sequences to reduce inoculum levels.
- Control grass-weed hosts to reduce opportunities for *Fusarium* spp. to survive fallow or non-host rotations.
- Sow varieties with partial resistance or improved tolerance where available.
- The approximate order of increasing yield loss from crown rot is cereal rye, oats, barley, bread wheat, triticale and durum wheat. [44]

The frequency of crown rot has increased in recent years due to the continuous cropping of wheat and other cereals. Some of the current options for managing the disease are to control grass hosts prior to cropping, rotate susceptible cereals with non-host break crops, burn infected stubble, and grow tolerant varieties.

There are two types of *Fusarium* disease that affect Northern region crops: Fusarium head blight (FHB) and crown rot (CR).

Fusarium head blight is usually caused by the fungus *Fusarium graminearum,* but the crown rot fungus *Fusarium pseudograminearum* may also cause FNB in wet years if rain splash distributes the fungus from nodes on the lower stem into the grain heads. Crown rot is generally caused by *Fusarium pseudograminearum.*

While all winter cereals host the crown-rot fungus, yield loss due to infection varies with cereal type. The approximate order of increasing yield loss is cereal rye, oats, barley, bread wheat, triticale and durum wheat. [45]

43 DAF Queensland (2015) Wheat: diseases, physiological disorders and frost. DAF Qld, https://www.daf.qld.gov.au/plants/field-crops-and-pastures/broadacre-field-crops/wheat/diseases

44 GRDC (2016) Crown rot in winter cereals—southern region. Tips and Tactics. GRDC, https://grdc.com.au/resources-and-publications/all-publications/factsheets/2016/02/tt-crownrotwintercereals

45 GRDC (2016) Crown rot in winter cereals—southern region. Tips and Tactics. GRDC, https://grdc.com.au/resources-and-publications/all-publications/factsheets/2016/02/tt-crownrotwintercereals

Crown rot is a major disease in the Northern grains region. Infection requires moist soil, and the past few years have caused problems for growers by increasing the disease's prevalence. [46]

Both CR and FHB become apparent after flowering; however FHB requires prolonged wet weather during flowering and grain fill to occur, and crown rot expresses as whiteheads following periods of moisture and/or heat stress. (Whiteheads are dead heads that contain shrivelled grain or none at all.) Crown rot is sometimes first seen in patches or in wheel tracks, but is often not obvious until after heading, when whiteheads become apparent. It is important to note that yield loss can occur even without the formation of whiteheads.

Update on the latest research on crown rot

Key points:

- The impact of crown rot on yield and quality is a balance between inoculum levels and soil water.
- The balance is heavily tipped towards soil water, yet most management strategies focus on combating inoculum, sometimes to the detriment of considering soil water.
- Cultivation, even when shallow, distributes infected residue more evenly across paddocks and into the infection zones below ground for crown rot.
- Some of the newer wheat varieties appear to be promising in that they provide improved tolerance to crown rot.
- PreDicta B (see section 1.5.3, Managing crown rot) is a good technique for identifying the level of risk for crown rot (and other soil-borne pathogens) prior to sowing. However, this requires a dedicated sampling strategy and is *not* a simple add-on to a soil-nutrition test.

Crown rot is a significant disease of winter cereals in the northern region. Infection is characterised by a light honey-brown to dark brown discolouration of the base of infected tillers, although major yield loss, from the production of whiteheads, is related to moisture stress after flowering. It is critical that growers understand that there are three distinct and separate phases of crown rot: *survival, infection* and *expression*. Management strategies can affect each phase in distinctive ways.

Survival: the crown-rot fungus survives as mycelium (cottony growth) inside infected residues of winter cereals (wheat, barley, durum, triticale and oats) and grass weeds. The fungus will survive as inoculum inside the stubble for as long as the stubble remains intact. This varies greatly with soil and weather conditions, although decomposition generally is a *very slow* process.

Infection: given some level of soil moisture the crown-rot fungus grows out of stubble residues and infects new winter cereal plants through the coleoptile, sub-crown internode or crown tissue, which are all below the soil surface. The fungus can also infect plants above ground level *right at* the soil surface through the outer leaf sheathes. However, with all points of infection, direct contact with the previously infected residues is required and infections can occur throughout the whole season, if there is moisture. Hence, wet seasons favour increased infection by crown rot, especially when combined with the production of greater stubble loads, which significantly builds up inoculum levels.

46 T Dixon (2013) Balancing crown rot and nematodes in wheat. Ground Cover. Issue 104, May–June 2013. GRDC, https://grdc.com.au/Media-Centre/Ground-Cover/Ground-Cover-Issue-104-May-June-2013/Balancing-crown-rot-and-nematodes-in-wheat

Expression: Yield loss is related to moisture or temperature stress around flowering and through grain-fill. Stress is believed to trigger the fungus to proliferate in the base of infected tillers, which restricts water movement from the roots and through the stems, and results in whiteheads that contain either no grain or lightweight shrivelled grain. The expression of whiteheads in plants infected with crown rot (i.e. still have basal browning) is restricted in wet seasons and increases greatly with increasing moisture and temperature stress during grain-fill. Focus attention on crops around trees in a paddock or along tree lines. Even in good years (of little infection) whiteheads associated with crown-rot infection are likely to be seen around trees. This is due to the extra competition for water.

9.5.1 Varietal resistance or tolerance

While all winter cereals host the crown-rot fungus, yield loss due to infection varies with cereal type. The approximate order of increasing yield loss is cereal rye, oats, barley, bread wheat, triticale and durum wheat. [47] Variety choice is not a total solution to crown rot, because all cereal grains are susceptible to crown rot to varying degrees.

9.5.2 Damage caused by crown rot

The presence of crown rot within the plant stem limits water movement, which can result in the premature death of the tiller and the presence of white (dead) heads (Photo 10; see also Figure 14). Crown rot survives from one season to the next on infected stubble, from where it is passed onto the following crop. The impact of a bad crown-rot season can make or break a crop, with bread wheat yield losses of up to 55% being possible when there are high levels of inoculum; losses in durum may be up to 90%.

Photo 10: *Scattered whiteheads lead to large yield losses in cereal crops.*

Photo: DAFWA

47 GRDC (2016) Crown rot in winter cereals—southern region. Tips and Tactics. GRDC, https://grdc.com.au/resources-and-publications/all-publications/factsheets/2016/02/tt-crownrotwintercereals

9.5.3 Symptoms of crown rot

If the leaf bases are removed from the crowns of diseased plants, a honey-brown to dark-brown discolouration will be seen (Photo 11). In moist weather, a pink–purple fungal growth forms inside the lower leaf sheaths and on the lower nodes (Photo 13).

The infection of plants with crown rot occurs at the base of the plant and spreads up the stem during the growing season. The onset of crown rot is often not obvious until after heading, when whiteheads appear with the onset of water stress. Plants infected with crown rot display a number of symptoms, including:

- Brown tiller bases, often extending up 2–4 nodes (Photo 11). This is the most reliable indicator of crown rot, with browning often becoming more pronounced from mid to late grain filling through to harvest.
- Whitehead formation, particularly in seasons with a wet start and dry finish (Photos 10 and 12). These are usually scattered throughout the crop, and do not appear in distinct patches. These may first appear in wheel tracks where crop-available moisture is more limited.
- A cottony fungal growth that may be found around the inside of tillers, and a pinkish fungal growth that may form on the lower nodes, especially during moist weather (Photo 13).
- Pinched grain at harvest. [48]

Photo 11: *Honey-brown discolouration of stem bases.*

Photo: DAFWA

48 Soilquality (2016) Crown rot: Queensland. Fact sheet. Soilquality, http://www.soilquality.org.au/factsheets/crown-rot-queensland

Photo 12: *Scattered single tillers and whiteheads.*

Photo: DAFWA

Photo 13: *Pink discolouration often forms around or in the crown or under leaf sheaths.*

Photo: DAFWA

9.5.4 Managing crown rot

- Rotate crops. This is the most important management option. A grass-free break from winter cereals is the best way to lower crown rot inoculum levels.
- Observe: check plants for browning at the base of infected tillers, as this is the most reliable indicator of crown rot. Don't rely solely on whiteheads as an indicator (see Figure 3).
- Test using a pre-sowing PreDicta B soil test to identify paddocks at risk of crown rot.
- Sow winter cereals into paddocks where the risk is lowest.
- Choosing more resistant crop varieties can help, but this still need to be combined with effective management.
- Keeping crown rot inoculum at low levels is the most effective way to reduce yield loss from this disease. [49]

Figure 3: *The GRDC's 'Stop the crown rot' campaign.*

Source: GRDC

49 GRDC (2016) Crown rot in winter cereals—northern region. Tips and Tactics. GRDC, https://grdc.com.au/Resources/Factsheets/2016/02/Crown-rot-in-winter-cereals

Crop rotation

> *The disease may be controlled through planting partially resistant varieties or crop rotation. If the disease is severe, rotation to a non-susceptible crop for at least two and preferably three years is recommended. A winter crop such as chickpeas, oats or any summer crop may be used as a disease-free rotation crop.* [50]

Agronomist's view

The most effective way to reduce crown-rot inoculum is to include non-susceptible crops in the rotation sequence. As the fungus can survive for two to three years in stubble and soil, growing a non-host crop for at least two seasons is recommended to reduce inoculum levels. This allows time for decomposition of winter-cereal residues that host the fungus. Stubble decomposition varies with the type of break crop grown, and is influenced by canopy density and rate of the canopy closure, as well as row spacing, the amount of soil water the break crop uses, and seasonal rainfall. Trials in the northern region have indicated that faba beans and canola are better break crops for crown rot than chickpeas.

Because crown rot survives from one season to the next on infected stubble, the use of break crops can give stubble a chance to decompose and thus reduce soil inoculum levels. The use of break crops with dense canopies, such as canola and sorghum, can be particularly effective, as these help to maintain a moist soil surface, which encourages the breakdown of cereal residues.

The number or break crops required to sufficiently reduce crown rot levels will vary, depending on rainfall in the break year. In dry years, when residue breakdown is slower, a two-year break crop may be required to reduce crown rot to acceptable levels. In wetter seasons a one-year break may be sufficient.

It should be noted that incorporating plant residues into the soil by cultivation during the break period can increase the rate of residue decay. However, cultivation also spreads infected residue, which may increase plant infection rates in following crops, thus counteracting any benefits from increased residue breakdown.

Baling, grazing and/or burning crop residues are not effective solutions for the removal of crown rot, either. Most of the inoculum is below ground and in the bottom 7 cm of the stem, so the fungus can still survive even if above ground material is removed.

Cereal crop and variety choice

All winter cereal crops host the crow-rot fungus. Yield losses vary between crops and the approximate order of increasing loss is oats, barley, triticale, bread wheat and durum.

Bread-wheat varieties appear to differ significantly in their level of yield loss to crown rot. Newer varieties in the Northern region appear to maintain greater yields compared to the widely grown EGA GREGORY⟑. NSW DPI trials at 23 sites across the Northern region in 2013–14 indicate that this can represent a yield benefit of around 0.5 t/ha in the presence of high levels of crown-rot infection.

All current durum varieties are very susceptible to crown rot and should be avoided in medium and high risk situations.

Variety choice alone is not a solution to crown rot, with even the best varieties still yielding up to 40% less when crown rot is bad and the season finishes dry and hot.

The Queensland Government has been working to develop winter cereals with resistance to crown rot. Growers need to be aware of the levels of crown rot in their

50 DAF Queensland (2015) Wheat: diseases, physiological disorders and frost. DAF Qld, https://www.daf.qld.gov.au/plants/field-crops-and-pastures/broadacre-field-crops/wheat/diseases

VIDEOS

WATCH: GRDC (2015) Crown rot tolerance in new cereal varieties.

paddocks, as even the most resistant crops can suffer yield loss when there are high levels of the disease. In this case, a break crop may be required. At intermediate levels, the grower can make a calculated risk of returns versus yield loss by growing only resistant varieties.

Cultivation

Growers cultivate their stubble for a number of reasons. However, cultivation may increase the likelihood of spreading crown rot, and have an impact on all three phases of the disease cycle. Like all farming practices, cultivation is a balancing act between benefits and costs, and all these need to be weighed up when deciding how to manage farming land to minimise crown rot.

Survival: stubble decomposition is a microbial process driven by temperature and moisture. Cultivating stubble in theory increases the rate of decomposition as it reduces the particle size of stubble, buries the particles in the soil where microbial activity is greater, and puts the stubble in greater contact with the soil environment, which maintains more optimal moisture and temperature conditions for breakdown. However, in practice, cultivation also dries out the soil in the cultivation layer, and this immediately limits the potential for decomposition of the incorporated stubble. Decomposition of cereal stubbles is a *very slow* process that requires adequate moisture for an extended period to occur completely: a summer fallow (even if extremely wet and stubble has been cultivated) is *not* long enough!

Infection: as most infection sites are below ground and the plant must make physical contact with infected residue to initiate infection, the cultivation of winter-cereal stubble that harbours the fungus in effect breaks the inoculum into smaller pieces and spreads them more evenly through the paddock. Consequently, as the next winter cereal crop germinates and develops, the crown-rot fungus is been given a much greater chance of coming into contact with the major infection sites below ground. In a no-till system the crown rot fungus becomes confined to the previous cereal rows and is more reliant on infection through the outer leaf sheathes at the soil surface. This is why inter-row sowing with GPS guidance has been shown to provide around a 50% reduction in the number of plants infected with crown rot when used in no-till cropping. Cultivation or harrowing negates the option of inter-row sowing as a crown-rot management strategy.

Expression: extensive research has shown that cultivation dries out the soil to the depth of the cultivation and reduces the rate of water infiltration due to the loss of soil structure (macropores, etc.). The lack of cereal-stubble cover can also increase soil evaporation. With poorer infiltration and higher evaporation, the efficiency of fallow is reduced for cultivated systems compared to a no-till stubble-retention system. Greater moisture availability has the potential to provide buffering against the expression of crown rot late in the season.

Stubble burning

Stubble burning is not a 'quick fix' for high-inoculum situations, because although it removes the above-ground portion of crown-rot inoculum, the fungus will still survive in infected crown tissue below ground. Removal of stubble through burning will increase evaporation from the soil surface and make the fallow less efficient. A cooler autumn burn is preferable to an earlier hotter burn, as it minimises the negative impacts on soil-moisture storage while still reducing inoculum levels.

Crop management

Stressed plants are the most susceptible to the effects of crown rot. Management practices that optimise soil water and ensure good crop nutrition can help reduce the impacts of crown rot. Effective strategies can include:

- Reducing moisture stress in plants through good fallow management and avoiding excessively high sowing rates.
- Matching nitrogen fertiliser inputs to available soil water to avoid excessive early crop growth.

- Ensuring good crop nutrition. Zinc nutrition can be particularly important as the expression of whiteheads can be more severe in zinc-deficient crops.

Reducing water loss

Inoculum level is important in limiting the potential loss of yield from crown rot, but the overriding factor that dictates the extent of yield loss is moisture or temperature stress during grain-fill. Any management strategy that limits the storage of soil water or creates constraints that reduce the ability of the roots to access soil water will increase the probability and/or severity of moisture stress during grain-fill, and exacerbate the impact of crown rot.

Managing grass weeds

Grass weeds should be controlled in fallow periods and in-crop, especially in break crops, as they host the crown rot fungus and can also significantly reduce soil moisture storage. In pasture situations grasses need to be cleaned out well in advance of a following cereal crop as they serve as a host for the crown rot fungus.

Row placement

In a no-till system, the crown-rot fungus becomes confined to the previous cereal rows and is more reliant on infection spreading through the outer leaf sheathes at the soil surface. This is why inter-row sowing with GPS guidance has been shown to provide around a 50% reduction in the number of plants infected with crown rot when used in no-till cropping. Research conducted by NSW DPI has also demonstrated that it is beneficial to use inter-row sowing in combination with crop rotation and the relative placement of break crop rows and winter cereal rows within the sequence in order to limit disease and maximise yield. [51] Sowing break crops between standing wheat rows which are kept intact, then sowing the following wheat crop directly over the row of the previous year's break crop, ensures four years between wheat being sown in the same row. This substantially reduces the incidence of crown rot in wheat crops. It also improves the establishment of break crops (especially canola), and chickpeas will benefit from reduced incidence of viruses in standing wheat stubble.

Soil type

Soil type in itself does not affect the survival or infection phases of crown rot. However, the inherent water-holding capacity of each soil type influences the expression of crown rot by the degree to which it provides buffering against moisture stress late in the season. Hence yield loss can be worse on red soils compared to black soils due to their generally lower water-holding capacities. Any other sub-soil constraint, e.g. sodicity, salinity or shallower soil depth, effectively reduces the level of water available to the plant, and this may increase the expression of crown rot.

Sowing time

Earlier sowing within the recommended window of a given variety for a region can bring the grain-fill period forward and reduce the probability of moisture and temperature stress during grain-fill. Earlier sowing can increase root length and depth, which provides the plant with greater access to deeper soil water later in the season. This buffers the plant against crown rot, and has been shown in NSW DPI research across seasons to reduce yield loss from this disease.

However, earlier sowing can place a crop at risk of frost damage during its most susceptible age. Sowing time in the northern region is a balancing act between the risk of frost and the risk of heat stress. However, when it comes to crown rot, increased disease expression with delayed sowing can have as big an impact on yield as frost. The big difference that was observed in NSW DPI trials is the additional detrimental impact of later sowing on grain size in the presence of crown rot.

51 GRDC Grains Research Update paper (July 2014) on Managing crown-rot through crop sequencing and row placement, Andrew Verrell, NSW DPI

VIDEOS

WATCH: GRDC (2014) Does variety choice matter with crown rot? Northern region.

MORE INFORMATION

Crown rot in winter cereals—Northern region.

Interaction with root-lesion nematodes

Root-lesion nematodes (RLNs) are also a widespread constraint to wheat production across the region. Two important species of RLN, *Pratylenchus thornei* (*Pt*) and *P. neglectus* (*Pn*), exist throughout the northern region. Surveys in the northern NSW have revealed that *Pt* is more widespread and generally at higher populations than *Pn*. RLNs feed inside the root systems of susceptible winter cereals, creating lesions and reducing lateral branching. This reduces the efficacy of the root system to extract soil water and nutrients, which subsequently can exacerbate the expression of crown rot. if both of these pathogens are present in a paddock, varieties with reduced tolerance of *Pt* can have significantly greater yield loss.

How do I know my level of risk for crown rot and RLN?

PreDicta B is a DNA-based soil test which detects levels of a number of cereal pathogens. It is commercially available to growers through the South Australian Research and Development Institute (SARDI). Because the crown-rot fungus is stubble-borne, normal soil samples are unreliable. This means that detection of the disease is highly sensitive to the sampling technique used. Follow the specific protocols for how to collect samples for crown-rot testing. [52]

Soil testing

To work out the best option for your situation, it is important to know if crown rot is present in the paddock, and how severe it is. Testing involves carrying out a visual assessment on stubble followed by a precise plating test. This is the only way of accurately testing for the disease. Results are provided to the grower and consultant within approximately four weeks of receiving the sample.

In addition to visual symptoms, the DNA-based soil test PreDicta B, which was developed specifically to identify soil-borne pathogens in Northern Australian cropping regions, can be used to assess the level of crown rot in the paddock. [53] (The B stands for broadacre.) Soil samples that include plant residues should be tested early in late summer to allow results to be returned before seeding. This test is particularly useful when sowing susceptible wheat varieties, and for assessing the risk after a non-cereal crop. [54] It is also useful for testing before sowing to oats which, although not susceptible to crown rot itself, does host it. Other diseases that can be tested for are:

- cereal cyst nematode (CCN)
- take-all (*Gaeumannomyces graminis* var. *tritici* (Ggt) and *G. graminis* var. *avenae* (Gga))
- rhizoctonia barepatch (*Rhizoctonia solani* AG8)
- root lesion nematode (*Pratylenchus neglectus* and *P. thornei*)
- stem nematode (*Ditylenchus dipsaci*)

Figure 4:

Photo: GRDC

PreDicta B samples are processed weekly from February to mid-May (prior to crops being sown) to assist with planning the cropping program. The test is not intended for in-crop diagnosis: that is best achieved by sending samples of affected plants

52 S Simpfendorfer (2015). Crown rot: an update on latest research. GRDC Update Paper. GRDC. https://grdc.com.au/Research-and-Development/GRDC-Update-Papers/2015/07/Crown-rot-an-update-on-latest-research

53 Access PreDicta B information and testing service at http://pir.sa.gov.au/research/services/molecular_diagnostics/predicta_b

54 Soilquality (2016) Crown rot: Queensland. Fact sheet. Soilquality, http://www.soilquality.org.au/factsheets/crown-rot-queensland

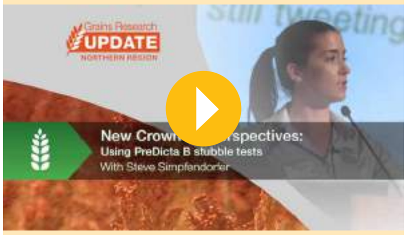
MORE INFORMATION

PIRSA, PreDicta B website

Crown Analytical Services

VIDEOS

WATCH: GRDC (2015) Crown rot: Improving PreDicta B.



WATCH: GRDC (2013) Over the Fence north: Drew Penberthy.

to your local plant pathology laboratory. It should be used in conjunction with other management options. [55]

Crown Analytical Services also has a test for crown rot that is based on five years of laboratory research. The company's website includes its testing protocols. [56]

9.5.5 Symptoms of Fusarium head blight

Fusarium head blight is an infection of the head of the plant rather than root or crown as with CR. In cereals, FHB appears as premature bleaching of spikelets within a head. Frequently only part of the head (usually the upper half) is affected (Photo 5). [57] Salmon pink to orange spore masses (sporodochia) at the bases of infected spikelets can also be apparent during prolonged warm, humid weather. Infected wheat grains have a chalky white appearance and are usually shrivelled and lightweight; they may sometimes have pink staining, too. In barley, infected spikelets have a brown or a water-soaked appearance, rather than bleaching. The grains have an orange or black encrustation on their surfaces, rather than being chalky.

Figure 5: *Heads are partly or fully bleached with FHB.*

Photo: DAFWA

55 D Lush (2014) PreDicta B sampling strategy. GRDC, https://grdc.com.au/Media-Centre/Media-News/South/2014/04/PreDicta-B-sampling-strategy

56 Crown Analytical Services (n.d.) Protocol. Crown Analytical Services, https://sites.google.com/site/crownanalyticalservices/home/testing-process

57 DAFWA (2015) Diagnosing fusarium head blight in cereals. DAFWA, https://www.agric.wa.gov.au/mycrop/diagnosing-fusarium-head-blight-cereals

9.5.6 Conditions favouring FHB development

Crown rot is a fungal disease that affects cereals. It survives from one season to the next in the stubble remains of infected plants. The disease is more common on heavy clay soils.

Infection is favoured by high soil moisture in the two months after planting. Drought stress during elongation and flowering will lead to the production of whiteheads (or deadheads) in the crop.

The effects of crown rot on yield tend to be most severe when there are good crop conditions in the first part of the season followed by a dry finish. This is because the moist conditions earlier enable the fungus to grow from infected stubble to an adjacent seedling, while the dry conditions during flowering and grain filling cause moisture stress, which allows for the rapid growth of the pathogen within the plant. A wet finish to the season can reduce the damage caused by crown rot, but will not prevent yield loss in all cases. [58]

Soil water is by far the biggest factor in the impact of crown rot on profitability. The effect of moisture on crown rot yield losses is huge.

Cultivation can also have a huge impact. Crown rot is a stubble-borne disease and for a plant to become infected it must come into contact with inoculum from previous winter cereal crops. So by cultivating soil, growers help to spread the crown rot inoculum to next year's crop. The best thing a grower can do with infected stubble is leave it alone. [59]

9.6 Common root rot

Common root rot (*Bipolaris sorokiniana*) is a soil-borne fungal disease which attacks wheat, barley and triticale. It survives from one season to the next through fungal spores, which remain in the cultivated layer of the soil. The disease increases in severity with continuous wheat or wheat-barley sequences. Common symptoms are:

- a dark-brown to black discolouration of the stem just below the soil surface
- black streaks on the base of stems
- slight root rotting

9.6.1 Damage caused by disease

Common root rot can cause yield losses of 10–15% in susceptible varieties.

9.6.2 Symptoms

What to look for in the paddock

- Affected plants tend to be scattered over a paddock, and they may be slightly stunted, have fewer tillers and produce smaller heads. [60]

What to look for in the plant

- Browning of roots and sub-crown internode (the piece of stem emerging from the seed to the crown).
- Blackening of sub-crown internode in extreme cases (Photo 14).

58 Soilquality (2016) Crown rot: Queensland. Fact sheet. Soilquality, http://www.soilquality.org.au/factsheets/crown-rot-queensland

59 T Dixon (2013) Balancing crown rot and nematodes in wheat. Ground Cover. Issue 104, May–June 2013. GRDC, https://grdc.com.au/Media-Centre/Ground-Cover/Ground-Cover-Issue-104-May-June-2013/Balancing-crown-rot-and-nematodes-in-wheat

60 DAFWA (2015) Diagnosing common root rot of cereals. DAFWA, https://www.agric.wa.gov.au/mycrop/diagnosing-common-root-rot-cereals

Photo 14: *Blackening of sub-crown internode in extreme cases.*

Photo: DAFWA

9.6.3 Conditions favouring development

- Common root rot can occur from tillering onwards, and is most obvious after flowering.
- There are no distinct paddock symptoms, although the crop may lack vigour.
- Severe infections can lead to the stunting of plants.
- It appears more prevalent in paddocks that are deficient in nitrogen (N). When N is not limiting, yield loss occurs through a reduction in tillering due to poor N-use efficiency.
- Affected plants are usually scattered through the crop.
- This form of rot is widespread through the grain belt, and is often found in association with crown rot.
- The fungus that causes common root rot survives on the roots of grasses and as dormant spores in the soil. It can build up to damaging levels in continuous wheat rotations. [61]

Infection is favoured by high soil moisture for six to eight weeks after planting.

9.6.4 Managing common root rot

The disease may be controlled by planting partially resistant varieties or by crop rotation. Where the disease is severe, rotation to non-susceptible crops for at least two years is recommended. Summer crops such as sorghum, sunflower, or white French millet can be used for this purpose. [62]

61 K Moore, B Manning, S Simpfendorfer, and A Verrell. (n.d.) Root and crown diseases of wheat and barley in northern NSW. NSW DPI, http://www.dpi.nsw.gov.au/__data/assets/pdf_file/0019/159031/root-crown-rot-diseases.pdf

62 DAF Queensland (2015) Wheat: diseases, physiological disorders and frost. DAF Qld, https://www.daf.qld.gov.au/plants/field-crops-and-pastures/broadacre-field-crops/wheat/diseases

- Reduce levels of the fungus in your paddocks by rotating with crops such as field peas, faba beans, canola, mustard, mungbeans, sorghum and sunflower.
- Weak crops or pasture must be grass-free.
- Sow partly resistant wheat or barley varieties.
- If moisture permits, reduce sowing depth to limit the length of the sub-crown internode (SCI).
- Ensure adequate nutrition, especially of phosphorus, which reduces the severity of common root rot.
- Burning does not decrease the number of spores in the soil. [63]

9.7 Smuts

9.7.1 Bunt or stinking smut

Bunt, or stinking smut, is caused by the fungi *Tilletia laevis* and *Tilletia caries*. Bunt affects mature wheat ears in which a mass of black fungal spores replaces the interior of the grain and forms a bunt ball. Infected plants are shorter than healthy plants, and have darker green ears and gaping glumes (Photo 15). [64] Bunt is usually only noticed at harvest ,when bunt balls and fragments can be seen in the grain. Grain deliveries with traces of bunt balls are not accepted by AWB Limited.

Photo 15: *Common bunt in cereal head showing glumes containing bunt balls.*

Photo: DAFWA

If a bunt ball is crushed, a putrid fish-like odour is released.

Spores released during harvest contaminate sound grain. The spores germinate with the seed when planted and infect the young seedling. The fungus then grows inside the developing wheat plant, finally replacing each normal grain with a mass of spores.

Bunt has not been recorded in commercial wheat crops in Queensland for more than 30 years. This is probably because of the widespread use of fungicidal seed dressings.

63 K Moore, B Manning, S Simpfendorfer, and A Verrell. (n.d.) Root and crown diseases of wheat and barley in northern NSW. NSW DPI, http://www.dpi.nsw.gov.au/__data/assets/pdf_file/0019/159031/root-crown-rot-diseases.pdf

64 DAFWA (2016) Smut and bunt diseases of cereal: biology, identification and management. DAFWA, https://www.agric.wa.gov.au/autumn/smut-and-bunt-diseases-cereal-biology-identification-and-management?page=0,1

9.7.2 Managing bunt

- Seed that is sown to provide the following season's wheat seed should be treated with a fungicidal seed dressing.
- Seed obtained from plants grown from untreated seed should be treated with a fungicidal seed dressing before planting.
- All seed entering Queensland should be treated with a fungicidal seed dressing which will control bunt.
- Grain from a crop with bunt should not be used for seed.
- On farms where a crop has been affected by bunt, all wheat seed should be treated with fungicidal seed dressing for at least six years.

These recommendations could be adopted in one of two ways:

1. Treat all wheat seed with a fungicidal seed dressing every second year.
2. Treat a small quantity of seed of each variety with a fungicidal seed dressing every year, and use the grain from this as planting seed in the following year. [65]

9.7.3 Loose smut

Loose smut is a fungal disease that becomes evident at head emergence. A loose, powdery mass of fungal spores is formed in the head; these spores are readily blown away leaving a bare, ragged stalk (Photo 16).

Photo 16: *Barley heads affected with loose smut.*

Photo: DAFWA

If the spores settle on healthy flowers, they may germinate and infect the embryo of the developing seed. When the seed is planted, the smut grows inside the plant until flowering when the disease appears externally. Because loose smut is carried inside the seed, systemic seed dressings are needed to control it. These are more expensive than other fungicides and should be used only when a high incidence of loose smut is expected. [66]

65 DAF Queensland (2015) Wheat: diseases, physiological disorders and frost. DAF Qld, https://www.daf.qld.gov.au/plants/field-crops-and-pastures/broadacre-field-crops/wheat/diseases

66 DAF Queensland (2015) Wheat: diseases, physiological disorders and frost. DAF Qld, https://www.daf.qld.gov.au/plants/field-crops-and-pastures/broadacre-field-crops/wheat/diseases

9.7.4 Managing loose smut

The disease is controlled by pickling seed with a systemic fungicide which penetrates the developing seedling to kill the internal infection. Cereal seed-dressing fungicides differ in their efficacy for smut management, with trial research demonstrating that some seed dressings can reduce the incidence of loose smut in heavily infected seed to nearly zero. The correct application of seed dressings is critical to ensuring adequate control. In-furrow and foliar fungicide applications are not effective. [67]

9.8 Rhizoctonia root rot

- Rhizoctonia root rot is most evident as bare patches in a young crop. Close inspection of infected seedlings shows brown discolouration or rotting of the roots and evidence of 'spear tips'.
- Adequate nutrition during crop emergence gives the crop better chance of getting ahead of the disease.
- Fast growing roots will push past the infected topsoil before *Rhizoctonia* infects the root tip.
- Poor weed management prior to seeding allows *Rhizoctonia solani* to 'prime' itself for infection of the upcoming crop.
- In severe paddock infections cultivation following late summer – early autumn rains can help to reduce infection by the fungus.

Rhizoctonia root rot (*Rhizoctonia solani* Kuhn) is a fungal disease that affects a wide range of crops and has become more prevalent in light soils in recent years following the introduction of minimum-tillage practices. The previous practice of tillage prior to seeding encouraged the breakdown of the fungus in the soil prior to emergence. Minimum tillage decreases the rate of organic-matter breakdown, thereby providing a habitat for the *Rhizoctonia* sp. over summer. Bare patch and root rot of cereals, and damping off and hypocotyl rot of oilseeds and legumes are all caused by different strains of *R. solani*. [68]

9.8.1 Symptoms

The characteristic symptom of *Rhizoctonia* is clearly defined bare patches in the crop (figure 1). The reason these patches are clearly defined relates to the susceptibility of young seedlings, and the placement of the fungus within the soil profile. *Rhizoctonia solani* tends to reside in the upper layers of soil but not in the surface and only infects seedlings through the root tip soon after germination. Older plants have a more developed root epidermis that does not allow the penetration of hyphae into the root. For this reason, once the crop is fully established, plants have either perished due to seedling infection or reasonably healthy. Some yield loss may be associated with plants on the margins of the bare patch. Roots of a plant infected with *R. solani* will typically be shortened with a brown 'spear tip' where they have rotted. Plants within a patch remain stunted with stiff, rolled leaves and can be darker green than those outside the patch. [69]

What to look for in the paddock

- Severely stunted plants occur in patches with a distinct edge between diseased and healthy plants. [70]
- Patches vary in size from less than half a metre to several metres in diameter.
- Patches of uneven growth occur from mid-winter, when seminal roots have established (Photo 17).

67 DAFWA (2016) Smut and bunt diseases for cereal: biology, identification and management. DAFWA, https://www.agric.wa.gov.au/autumn/smut-and-bunt-diseases-cereal-biology-identification-and-management?page=0%2C0

68 Soilquality (2016) Rhizoctonia: New South Wales. Fact sheet. Soilquality, http://www.soilquality.org.au/factsheets/rhizoctonia-nsw

69 Soilquality (2016) Rhizoctonia: New South Wales. Fact sheet. Soilquality, http://www.soilquality.org.au/factsheets/rhizoctonia-nsw

70 DAFWA (2016) Diagnosing rhizoctonia root rot in cereals. DAFWA, https://www.agric.wa.gov.au/mycrop/diagnosing-rhizoctonia-root-rot-cereals

Photo 17: *Patches have a distinct edge, and vary in size from less than a metre to several metres in diameter.*

Photo: DAFWA

What to look for in the plant

- Affected plants are stunted with stiff, rolled leaves that are sometimes darker green than in healthy plants (Photo 18).
- The roots of affected plants are short with characteristic pinched ends called 'spear tips' (Photo 19).

Photo 18: *Affected plants are stunted with stiff, rolled leaves which are sometimes darker than those of healthy plants.*

Photo: DAFWA

Photo 19: *Roots of affected plants are short with characteristic pinched ends or 'spear tips'.*

Photo: DAFWA

9.8.2 Conditions favouring development

Rhizoctonia solani survives best in organic matter just below the surface of an undisturbed soil. The fungus benefits from summer rainfall by infecting weeds and multiplying on them, and has a limited ability to survive on the residue of the previous season's crops. The break of season initiates the development of the fungus in soil, which primes itself to infect germinating seeds.

Infection by the pathogen is encouraged by factors that restrict root growth, such as low soil fertility and the prior use of sulfonylurea herbicides. If there is a delay between the season break and seeding, it is imperative that weeds are controlled to minimise proliferation of the fungus. Good nitrogen nutrition helps to minimise the effects of the disease: bare patches are smaller and less severe.

In general, *Rhizoctonia* root rot is most likely to be a severe problem where plants are stressed from factors other than the disease, e.g. low rainfall or poor nutrition.

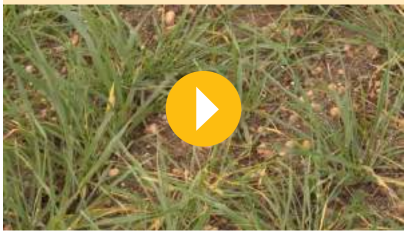
Some soil conditions favour the development of *Rhizoctonia* root rot during and after seeding.

Soil nutrition

The disease is most common in soils of poor fertility. Crops with access to sufficient nutrients for growth have a better ability to get ahead of *Rhizoctonia* sp. infections.

VIDEOS

WATCH: DAFWA (2014) How to diagnose Rhizoctonia root rot. DAFWA



Soil disturbance

Rhizoctonia root rot is sensitive to cultivation, with cultivation after rain and before sowing being the most effective means of reducing infection. By disturbing the soil, the grower prevents the fungus from priming itself to infect the emerging crop.

Soil moisture

When it is moisture stressed the crop becomes more susceptible to *R. solani* infection, and has a decreased ability to get ahead of the disease.

Weeds

Poor weed management following late summer and early autumn rain allows *Rhizoctonia solani* to infect grass weeds, thereby allowing the fungus to multiply and be able to take advantage of the crop.

Herbicides

Sulfonylurea herbicides can sometimes worsen *Rhizoctonia solani infections*, and this is attributed to minor herbicidal effects on the crop. [71]

9.8.3 Managing Rhizoctonia root rot

Where reduced tillage is practiced, bare patch caused by *Rhizoctonia* root rot is best controlled by killing weeds and maintaining adequate nutrition for the establishing crop. Spraying weeds with a fast-acting knockdown herbicide will minimise the development of the fungus in the ground prior to seeding, and good nutrition gives the crop a better chance of getting ahead of the disease.

The best tillage practices for this disease are deep cultivation and shallow sowing, with minimal time between the two. In no-till systems the use of modified sowing points that provide some soil disturbance 5–10 cm below the seed can be useful in controlling the disease.

In the past, tillage was the most effective method of reducing the impact of *Rhizoctonia solani*. The establishment of *the fungus* in the topsoil late in autumn was negated as cultivation broke the network of fungal hyphae. The fungus did not have time to recover before seedling establishment. In severely infected paddocks, cultivation may be an important management strategy.

Currently there are no resistant crop varieties, but there are products on the market for *Rhizoctonia* root rot control in NSW. Consult your local adviser for specific information.

In areas where the disease is known or suspected it is best practice to clean knife points once the seeding is complete, thereby eliminating movement of the fungus from one paddock to the next. In general, maintaining adequate nutrition (especially nitrogen) during crop establishment is the best way to reduce the chance of *R. solani* infection. [72]

9.9 Cereal fungicides

All of the diseases addressed so far are caused by different fungi. Fungal disease is a major disease threat to all Australian crops, and is treated using a number of complementary tactics.

- Fungicides are only one component of a good management strategy.
- Correct identification of the cause of plant symptoms is essential, as is an understanding of the growth and spread of any pathogen, as these will assist in decision-making.

71 Soilquality (2016) Rhizoctonia: New South Wales. Fact sheet. Soilquality, http://www.soilquality.org.au/factsheets/rhizoctonia-nsw

72 Soilquality (2016) Rhizoctonia: New South Wales. Fact sheet. Soilquality, http://www.soilquality.org.au/factsheets/rhizoctonia-nsw

- Cultivar resistance is the best protection against fungal diseases. Ideally, when agronomically suitable varieties are available, opt for moderately resistant (MR) to resistant (R) varieties in disease-prone environments.
- Disease control using fungicides is an economic decision.
- Understand the role of the season and have a plan in place before planting, and if growing susceptible varieties have on hand the right chemicals to support crop health and combat pests.
- For cereal rusts and mildew, remove the green bridge between crops to prevent rusts from over-seasoning.
- Monitor crops throughout the season.
- Spray if disease threatens key plant parts (flag to flag-2) of varieties that are moderately susceptible (MS) or susceptible (S).
- Fungicides do not increase yield; they protect yield potential and cannot retrieve lost yield if applied after infection is established.
- Fungicide resistance is a major emerging issue. Do not use tebuconazole-based products on barley if there is any chance of powdery mildew occurring, and select varieties that are resistant to powdery mildew (Table 4). [73]

Table 4: *Modes of action registered for the control of foliar diseases in Australian cereals.*

Group	Active Ingredient	Example Product Name	Foliar (F), seed (S) or in-furrow (IF)
3 - DMI	Triadimefon	Triad®	F and IF
	Propiconazole	Tilt®	F
	Propiconazole + cyproconazole	Tilt® Xtra	F
	Tebuconazole	Folicur®	F and S
	Flutriafol	Impact®	F and IF
	Tebuconazole + flutriafol	Impact® Topguard	F
	Tebuconazole + prothioconazole	Prosaro®	F
	Epoxiconazole	Opus®	F
	Triadimenol	Baytan®	S
	Fluquinconazole	Jockey®	S
3 + 11 (Strobilurins)	Azoxystrobin + cyproconazole	Amistar® Xtra	F
	Pyraclostrobin + epoxiconazole	Opera®	F

Source: GRDC

VIDEOS

WATCH: GRDC (2012) Banding Fungicide in Cereals. GCTV9. GRDC.

9.9.1 Fungicide stewardship

There have been a number of pathogens such as Septoria tritici blotch (STB) which have recently developed a level of fungicide resistance in Australia. Their occurrence highlights the important role all growers play in fungicide-resistance management.

To help minimise the development of resistance to fungicides and to minimise the occurrence of disease, there are three important steps growers need to implement.

1. Remove the source of infection.

73 GRDC (2013) Cereal fungicides—northern region. Fact sheet. GRDC, https://grdc.com.au/Resources/Factsheets/2013/05/Cereal-fungicides

- For many pathogens, stubble is the source of the infection each year. By removing stubble before sowing, there is a substantial reduction of pathogen population size.
- Removing stubble reduces all forms of the pathogen irrespective of resistance, and reduces the initial establishment of disease.
- To avoid rapid disease build-up, do not sow wheat on wheat or barley on barley.

2. Variety choice.

- Under high disease pressure, a variety rated MR–MS can substantially reduce the leaf-area loss. Where possible, choose a more resistant variety.
- Host resistance reduces all forms of the pathogen irrespective of resistance, and reduces the need for multiple applications of canopy fungicides.
- Resistance ratings do change, so crops must always be monitored during the season for higher than expected reactions. Check each year for updates to disease ratings.

3. Fungicide choice and use.

- Do not use the same triazole-active ingredient more than once in a season. Do not use a strobilurin or succinate dehydrogenase inhibitors (SDHIs) more than once in a season.
- Aim for early control of necrotrophic diseases in high-rainfall years. Reducing the disease in the lower canopy slows the upward movement of disease and ultimately the leaf area lost.
- Follow label instructions at all times.

The timing of the application in the disease epidemic is critical to getting the most out of chemical products. [74]

MORE INFORMATION

GRDC Cereal fungicides fact sheet

9.10 Disease following extreme weather events

9.10.1 Cereal disease after drought

Drought reduces the breakdown of plant residues. This means that the inoculum of some diseases, such as crown rot. does not decrease as quickly as expected, and will carry over for more than one growing season. The expected benefits of crop rotation may not occur, or may be limited. Inversely, bacterial numbers decline in dry soil. Some bacteria are important antagonists of soil-borne fungal diseases such as common root rot. These diseases can be more severe after drought.

During the drought year, the inoculum of some diseases favoured by a wet season may not increase as expected.

Large amounts of seed produced in abandoned crops, or pinched seed from drought stress, will fall to the ground. If there are summer rains, large numbers of volunteers will provide a summer green bridge and autumn green ramp for rusts, viruses and virus vectors, and many other pathogens.

Low stock numbers make it difficult to control volunteers.

Weeds that harbour diseases are harder to kill.

Soil water and nitrogen may be unbalanced and these are likely to impact on diseases. [75]

9.10.2 Cereal disease after flood

For disease to occur, the pathogen must have virulence to the particular variety, inoculum must be available and easily transported, and there must be favourable conditions for infection and disease development.

74 A Milgate (2016) Cereal disease update and risks for southern NSW crops in 2016. GRDC Update Paper. GRDC, https://grdc.com.au/Research-and-Development/GRDC-Update-Papers/2016/07/Cereal-disease-update-and-risks-for-southern-NSW-crops-in-2016

75 G Murray, T Hind-Lanoiselet, K Moore, S Simpfendorfer, and J Edwards (2006) Crop diseases after drought. Primefact 408. NSW DPI.

One of the legacies of floods and much rain is the transport of inoculum (e.g. in crown rot, nematodes and leaf spots through the movement of infected stubble and soil) (Photo 20). Other effects are the development of sexual stages (in leaf spots and head blights), the survival of volunteers (unharvested material and self-sown plants in double-crop situations), and weather-damaged seed. [76]

Photo 20: *Tan spot-infected stubble following flood.*

Photo: Rachel Bowman, Seedbed Media

76 DAF Queensland (2013) Winter cereals pathology. DAF Qld, https://www.daf.qld.gov.au/plants/field-crops-and-pastures/broadacre-field-crops/prepare-for-winter-crops-following-floods/winter-cereals-pathology

Plant growth regulators and canopy management

Key messages

- In Australian cereal production, plant growth regulators (PGRs) are mostly used with the intention of producing a smaller plant that is resistant to lodging, or with the intention of reducing excessive growth in irrigated broadacre crops.
- Trials have revealed mixed responses in crop yield to the application of PGRs.
- Canopy management includes a range tools to help manage crop growth and development with the aim of maintaining canopy size and duration to optimise photosynthetic capacity and grain production.
- Canopy management starts at seeding: sowing date, variety, plant population and row spacing are fundamental. There is more to it than delaying the application of nitrogen.
- So far the best results for canopy management in the northern region have been seen in early sown, long-season varieties with high yield potential and which are very responsive to N with high N-fertiliser inputs. [1]

10.1 Plant growth regulators

A plant growth regulator (PGR) is an organic compound, either natural or synthetic, that modifies or controls one or more physiological processes within a plant. They include many agricultural and horticultural chemicals that influence plant growth and development . PGRs are intended to accelerate or retard the rate of growth or maturation, or otherwise alter the behaviour of plants or their produce. [2] This influence can be positive, e.g. larger fruit or more pasture growth, or negative, e.g. shorter stems or smaller plant canopies. [3]

The use of PGR products in Australia has generally been relatively low. The principle reason for this is simply that crop responses are viewed as variable, and growers have not seen enough benefit in incorporating them into their cropping programs.

The most widely used PGRs in Australia have a negative influence on plant growth; i.e. they are applied with the intention of producing a smaller plant that is resistant to lodging or with the intention of reducing excessive growth in irrigated broadacre crops. Currently, there are four broad groups of PGRs in use in Australian crops. They are:
Ethephon, e.g. Ethrel®.

1. Onium-type PGRs, e.g. Cycocel®, the active ingredient of which is chlormequat (and Pix®, which is registered only for cotton).
2. Triazoles, e.g. propiconazole (which is registered as a fungicide, and not for use as a PGR).
3. Trinexapac-ethyl, e.g. Moddus®, Moddus® Evo.

The four groups of PGRs act by reducing plant cell expansion, resulting in, among other things, shorter and possibly thicker stems. If the stems are stronger and shorter, the crop is less likely to lodge.

Ethephon is applied from the stage of the flag leaf emerging (Z37) to booting (Z45), and reduces stem elongation through the increase in concentration of ethylene gas in the expanding cells.

1 G McMullen (2009) Canopy management in the northern grains region: the research view. NSW DPI. http://www.nga.org.au/results-and-publications/download/31/australian-grain-articles/general-1/canopy-management-tactical-nitrogen-in-winter-cereals-july-2009-.pdf

2 PG Lemaux (1999) Plant growth regulators and biotechnology. Presentation, Western Plant Growth Regulator Society, http://ucbiotech.org/resources/biotech/talks/misc/regulat.html

3 D Jones (2014) Plant growth regulators. GRDC Update Paper. GRDC, https://grdc.com.au/Research-and-Development/GRDC-Update-Papers/2014/07/Plant-growth-regulators

The PGRs in groups two to four reduce crop height by reducing the effect of the plant hormone gibberellin. These are applied at early stem elongation (Z30–32).

The manufacturers of these products claim other benefits, too, including:

- Better root development that allows for increased root anchorage.
- Better root development that provides greater opportunity for water and nutrient scavenging.
- Possible improved grain quality.
- Reduction in shedding in barley.
- Increased harvest index (HI), the ratio between grain and total dry matter.
- Faster harvest speeds and reduced stress at harvest.

A combination of trinexapac-ethyl and chlormequat applied at growth stage 31 has been found to provide significant and consistent yield gains in wheat (11%) and barley (9%) under dry spring conditions. They also significantly reduced plant height, lessening the possibility of lodging in wetter seasons. [4] Overseas, chlormequat chloride has been found to inhibit gibberellin production, and has been recommended in winter and spring rye, wheat, oats, triticale and winter barley. [5]

Moddus® is registered for ryegrass seed crops, poppies and sugar cane. Moddus Evo®, an enhanced dispersion concentrate of Moddus®, is not currently registered but has been submitted to the Australian Pesticides and Veterinary Medicines Authority (APVMA) for registration to be used in Australian cereals.

An alternative to the chemical PGRs is grazing. It was demonstrated in the Grain and Graze project, which had study sites at a number of mixed-farming locations, that grazed treatments were regularly shorter than the non-grazed treatments, and grazed crops were less prone to lodging. [6]

MORE INFORMATION

Plant growth regulators

Plant growth regulators in broad acre crops

Plant growth regulators and their agronomic and economic benefits to high yield potential cereal, pulse and oilseed crops

10.1.1 Considering mixed results

In Australia there have been mixed results in the ability of PGRs to increase yield, and therefore profits.

The most important things to remember about PGRs are:

- Crop responses to the use of plant growth regulators (PGRs) can be inconsistent.
- In general, yield responses, if any, are produced by the reduction in lodging rather than as a direct effect of the PGRs.
- Plant growth regulators must be applied at the correct crop growth stage, according to product directions, which may be well before any lodging issues become apparent.

Attempting to grow high-yielding irrigated crops requires high levels of inputs, including water and fertiliser, which can promote large vegetative crops that increase the risk of lodging. Lodging is considered one of the biggest barriers to reliably achieving high yields in intensive cereal production in Australia. It can result in reduced yields and a difficult harvest. Plant growth regulators have been used for many years, but results can be variable, even having negative effects on yield. The ICC conducted trials in 2003 and 2004 in which there was some reduction in lodging but little yield gain. At the same time, trials on nitrogen (N) management in cereals demonstrated that, to achieve high yields, crops do not necessarily need to be sown at heavy rates and with large amounts of nitrogen, which give a correspondingly lush crop early in the season, but one that is prone to lodging. This has seen many growers adopt a topdressing tactic that supplies the crop with N when it needs it, i.e. from stem elongation onwards. Less vegetation at stem elongation promotes stronger stems, which can support a crop that yields 8 t/ha.

4 W Long (2005) AC0003: Plant growth regulators and their agronomic and economic benefits to high yield potential cereal, pulse and oilseed crops. Final Report. Project ACC00003. GRDC, http://finalreports.grdc.com.au/ACC00003

5 BASF. How do PGR's work? http://www.agricentre.basf.co.uk/agroportal/uk/en/crop_solutions/cereals_5/lodging___canopy_managememt/canopy_management_in_cereals.html

6 D Jones (2014) Plant growth regulators. GRDC Update Paper. GRDC, https://grdc.com.au/Research-and-Development/GRDC-Update-Papers/2014/07/Plant-growth-regulators

MORE INFORMATION

Mixed bag: dual purpose crops, PGRs and other local research

A trial conducted at the ICC trial block in 2012 which aimed to grow 10 t/ha of wheat and barley was deliberately sown heavily and fertilised early, and sprayed with the plant growth regulator, Moddus® Evo, as lodging was likely to occur. The effect of the PGR was mixed: barley yields increased, but wheat yields did not, despite the crops not actually lodging. A repeat trial sown in 2013 saw some lodging control and, once again, a yield increase in barley.

Conclusions: The value of PGRs

PGRs may have a place in the management of high-yielding crops. Unfortunately, their effects are not consistent and the decision whether to apply a PGR has to be made at approximately three months before the lodging would be expected.

Other chemicals that have a PGR effect are available but are not yet registered for use on all crops or at rates and timings that would have a regulatory effect on growth.

The yield improvements seen in barley in the ICC trials need further investigation, as the reason behind the yield increase is not clear. [7]

10.1.2 Case study: using Moddus® Evo

Key points:

- Moddus® Evo reduces lodging and can increase yields.
- Application, timing and concentration are critical.
- Moddus® Evo should not be applied to stressed plants.
- Moddus® Evo has better formulation stability and plant uptake

Lodging is considered one of the biggest barriers to reliably achieving high yields in intensive cereal production in Australia. Cereal rye can be prone to lodging. When favourable season conditions combine with traditional management practices in high input cereal production systems, lodging can result in significant reductions in yield and grain quality.

Moddus® (250 g/L trinexapac-ethyl) is used by cereal growers in a number of other countries, including New Zealand, UK and Germany, to reduce the incidence and severity of lodging and to optimise the yield and quality of high-yielding cereal crops. Moddus® Evo is a formulation with an enhanced dispersion concentrate (DC) which has been developed to provide greater formulation stability and more effective uptake in the plant. With improved mixing characteristics and the potential to provide better consistency of performance Moddus® Evo is currently before the APVMA for registration for use in Australian cereals.

GRDC and Syngenta, the manufacturer of Moddus®, undertook research to investigate the value of Moddus® applications to Australian cereals to reduce lodging and improve yields. [8]

Methods

The researchers conducted field trials across Australia from 2004 to 2011. They used a number of varieties, climatic conditions and geographical locations. They established small plots, typically 20–120 m^2 using a randomised complete block design, and incorporating three to six replicates.

They measured the effect of Moddus® application on plant growth, stem strength, stem-wall thickness, lodging, lodging score, and yield, and took grain-quality measurements.

7 D Jones (2014) Plant growth regulators. GRDC Update Paper. GRDC, https://grdc.com.au/Research-and-Development/GRDC-Update-Papers/2014/07/Plant-growth-regulators

8 LM Forsyth and K McKee (2013) Moddus Evo: controlling plant growth for reduced lodging and improved cereal yields. GRDC Update Paper. GRDC, https://grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2013/03/moddus-evo-controlling-plant-growth-for-reduced-lodging-and-improved-cereal-yields

MORE INFORMATION

Moddus Evo: Controlling plant growth for reduced lodging and improved cereal yields

Results

In the trials, overall improvements in yield were often correlated with a reduction in stem height, irrespective of whether lodging had occurred. Yield improvements through the reduction of lodging are well documented. What is less understood is the often-positive impact on yields with the use of Moddus® Evo in the absence of lodging.

Conversely during the course of the evaluation of Moddus® Evo on the yield enhancement and reduction in lodging, a few trials gave anomalous results, in which the application of Moddus® Evo did not improve yield. When the researchers examined these trials, they found that either environmental conditions during the lead-up to the application of the chemical were poor—with extensive frosting, drought, poor subsoil moisture,—or there were nutrient deficiencies in the crop. As a result, they recommended that Moddus® Evo should only be applied to healthy crops with optimum yield potential. As well, the timing and concentration of Moddus® Evo applications is critical to produce the optimal yield improvements.

Moddus® Evo offers growers in environments conducive to lodging an in-season option to reduce the impact of lodging while allowing them to manage crops for maximal yields.

10.2 Canopy management

Key points:

- Canopy management starts at seeding, and involves sowing date, variety, plant population and row spacing are fundamental, not just delaying the application of nitrogen.
- The correct identification of the key growth stages for input application is essential, particularly during early stem elongation when the most important leaves of the crop canopy emerge.
- Knowledge of soil-moisture status and the reserve and supply of soil nitrogen need to be taken into account in order to match canopy size to environmental conditions.
- Crop models can help growers and advisers to integrate information on crop development, environmental conditions and nutrient status so they can make better canopy management decisions. [9]

10.2.1 What does canopy management entail?

The concept of canopy management has been developed primarily in Europe and New Zealand, both distinct production environments to those typically found in the grain-producing regions of Australia, and especially the northern grains region. Canopy management incorporates the use of a number of tools to manage crop growth and development—sowing date, choice of variety, density of plant population, row spacing, and aspects of nitrogen (N) application—so as to maintain canopy size and duration in order to optimise photosynthetic capacity and grain production (Photo 1). [10]

One of the main tools growers use to manage the crop canopy is the rate and timing of the application of nitrogen (N) fertiliser. The main difference between canopy management and previous N topdressing is that, in the canopy management all or part of the N inputs are tactically delayed until later in the growing season. The delay tends to reduce early crop canopy size, but the canopy is maintained for longer, as measured by green-leaf retention during the grain-filling period, and tends to give higher yields. [11]

9 GRDC (2009) Cereal canopy management more than delayed nitrogen. Fact sheet. GRDC, https://grdc.com.au/__data/assets/pdf_file/0014/202523/canopy-management.pdf.pdf

10 N Poole (2005) Cereal growth stages. GRDC, https://www.researchgate.net/file.PostFileLoader.html?id=5780fa6bf7b67e860b4def31&assetKey=AS%3A381929540079624%401468070506798

11 G McMullen (2009) Canopy management in the northern grains region: the research view. NSW DPI, http://www.nga.org.au/results-and-publications/download/31/australian-grain-articles/general-1/canopy-management-tactical-nitrogen-in-winter-cereals-july-2009-.pdf

Photo 1: *Examples of controlled canopy cover. Left: with thinner crop canopy, yield = 6.18 t/ha and 12% protein. Right: with thicker crop canopy, yield = 6.20 t/ha and 10.6% protein. Plots sown to Kellalac wheat 11 June 2009 in Gnarwarre (Geelong region), in high rainfall zone, and treated with same level of nitrogen.*

Photos: GRDC

By adopting canopy-management principles and avoiding excessively vegetative crops, growers may be able to realise a better match of canopy size with yield potential, as defined by the water available.

However, canopy management is not about a delayed N strategy: it starts at seeding, by determining the correct plant establishment for the chosen seeding date and row spacing. This must take into account available soil moisture and nutrients (Figure 1). [12]

Other than sowing date, plant population is the first point at which the grower can influence the size and duration of the crop canopy. [13] One of the main tools for growers to use is the rate and timing of applied fertiliser N.

If the canopy becomes too big, it competes with the growing heads for resources, especially during the critical 30-day period before flowering. This is when the main yield component, grain number per unit area, is set. Increased competition from the canopy with the head may reduce yield by reducing the number of grains that survive for grainfill.

After flowering, temperature and evaporative demand increase rapidly. If there is not enough soil moisture, the canopy dies faster than the grain develops, and results in small grain. Excessive N application and high seeding rates are the main causes of excessive vegetative production. Unfortunately, optimum N and seeding rates are season-dependent. Under drought conditions, N application and seeding rates that would be regarded as inadequate under normal conditions may maximise yield, whereas higher input rates may result in progressively lower yields. Alternatively, in years of above-average rainfall, yield may be compromised with normal input rates. At the extreme, excessive early growth results in haying-off. In this situation, a large amount of biomass is produced using a lot of water and resources, then later in the season, there is insufficient moisture to keep the canopy photosynthesising and there are not enough stored water-soluble carbohydrates to fill the grain. Therefore, grain size and yield decrease.

To attain maximum yield, it is important to achieve a balance between biomass and resources. The main factors that can be managed are:

- plant population
- row spacing
- inputs of N

12 GRDC (2009) Cereal canopy management more than delayed nitrogen. Fact sheet. GRDC, https://grdc.com.au/__data/assets/pdf_file/0014/202523/canopy-management.pdf.pdf

13 N Poole (2005) Cereal growth stages. GRDC, https://www.researchgate.net/file.PostFileLoader.html?id=5780fa6bf7b67e860b4def31&assetKey=AS%3A381929540079624%401468070506798

- sowing date
- weed, pest and disease control
- plant growth regulation with grazing or specific plant growth regulator products

Of these, the most important to canopy management are N, row spacing and plant population. [14]

Applying N or fungicide at stem elongation increases the opportunity to match input costs to the potential yield for that season. While seeding applications may still be required for healthy establishment, crop models help support decisions on application timing. Models such as APSIM and Yield Prophet® simulate growth stage and season.

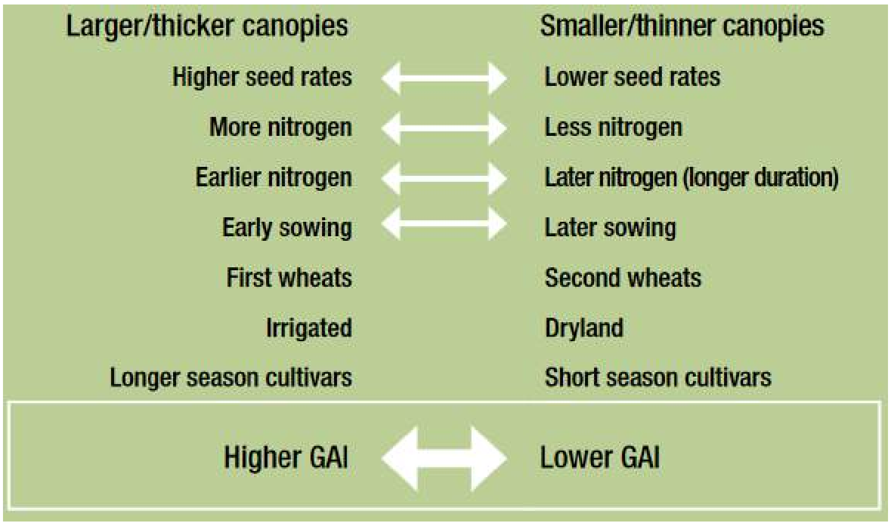


Figure 1: *Factors under grower control that influence canopy density, size and duration. (GAI = green area index, the amount of green surface area.)*

Source: GRDC.

The timing and rate of N application should also be considered in conjunction with the inter-related factors of:

- soil moisture
- soil-nitrogen reserves
- seeding date
- seed rate and variety

To practice canopy management it is important to understand the principal interactions between plant-growth stages, available water and nutrients, and disease pressure. These interactions are complex but tools from simple visual indicators through to crop models can assist.

Cereal canopy management in a nutshell

1. Select a target head density for your environment (350 to 400 heads per square metre should be sufficient to achieve optimum yield, even for yield potential of 7 t/ha).
2. Adjust canopy management based on paddock nutrition, history and seeding time to achieve target head density.
3. Established plant populations for cereals of between 80 and 200 plants/m^2 would cover most scenarios.
4. Lower end of range, 80–100 plants/m^2—for earlier sowings and high fertility and/or low yield potential low-rainfall environments.

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

5. Higher end of the range, 150–200 plants/m^2—for later sowings, lower fertility situations and/or higher-rainfall regions.
6. During stem elongation (GS30–39), provide the crop with necessary nutrition (particularly N at GS30–33 pseudo-stem erect – third node), matched to water supply and fungicides to:
7. maximise potential grain size and grain number per head;
8. maximise transpiration efficiency;
9. ensure complete radiation interception from when the flag leaf has emerged (GS39); and
10. keep the canopy green for as long as possible following anthesis.

Keeping tiller numbers just high enough to achieve potential yield will help preserve water for filling the grain and increase the proportion of water-soluble carbohydrates (WSCs). The timing of the applied N during the GS30–33 window can be adjusted to take account of the targeted head number; applications earlier in the window (GS30) can be employed where tiller numbers and soil nitrogen seems deficient for desired head numbers. Conversely, where tiller numbers are high and crops are still regarded as too thick, N can be delayed further until the second or third node (GS32–33), which will result in fewer tillers surviving to produce a head. Much of the research on topdressing N has focused on the role of in-crop N to respond to seasons in which yield potentials have increased significantly due to above-average rainfall. In these situations, research has shown that positive responses can be achieved, especially when good rainfall is received after N application. [15]

10.2.2 Setting up the canopy

Research has shown that extra tillers produced by more plants per unit area are more strongly correlated to yield than are extra shoots stimulated by increased nitrogen at seeding.

Boosting tiller numbers with seeding N results in greater tiller loss between stem elongation and grain fill. This occurs specifically in two situations: in low-rainfall, short-season environments; and when soil moisture is limited. In these situations, moisture and nutrient resources are used before the stems lengthen to produce biomass that fails to contribute to grain yield. Indeed, diverting these resources to unsuccessful tillers limits the potential of surviving tillers.

Therefore, identifying the correct population for a particular sowing date, soil-nitrogen reserve and region is the basis for setting up the crop canopy.

10.2.3 Soil-moisture status

Under Australian conditions, soil moisture has been identified as the biggest driver of the size and the duration of the cereal-crop canopy. Therefore, an understanding of how much water a soil can hold, and how much water a soil is holding at seeding and stem elongation, are central to canopy management.

See, the Bureau of Meteorology's Australian landscape water balance map for updates on local soil moisture.

The start of stem elongation (GS30) is the pivotal point for deciding on inputs, as from this point canopy expansion is rapid, and nitrogen and water reserves in the soil can be quickly used up.

If soil moisture is limited at the start of stem elongation, the ability to manipulate the crop canopy with nitrogen is limited. In many cases, the best canopy management is not to apply inputs such as nitrogen and fungicides.

Modelling demonstrates that by setting up a smaller crop canopy, growers can reserve limited stored soil moisture for use at grain fill, rather than have it depleted

15 N Poole and J Hunt (2014) Advancing the management of crop canopies. GRDC, https://grdc.com.au/resources-and-publications/all-publications/publications/2014/01/gc105-canopymanagement

by excessive early growth. However, in higher-rainfall regions and in good seasons, setting up a small canopy may result in yields falling below potential.

Calculating potential yield and then plotting actual rainfall against decile readings for the region provides a broad picture of whether there will be sufficient soil moisture to consider additional nitrogen inputs at stem elongation.

The decision-support tool Yield Prophet® offers simple tools to record and assess multiple options that cover the relationship between growing plants and the environment, including available water and nutrients.

10.2.4 Soil nitrogen

It is important to have an understanding of soil-N reserves to the depth of the rooting zone. Generally, 40 to 50 kilograms of N per hectare of soil-available N is required to feed a crop to stem elongation (GS30). Higher soil-nitrogen reserves provide much more flexibility in managing the canopy with tactical nitrogen applied during stem elongation.

The timing of deep-soil tests is important. Those carried out in summer, several months before seeding, may reveal less soil nitrogen than tests carried out after the autumn rains, when greater mineralisation will have occurred.

Providing soil moisture has not been limited or the crop has not been subject to waterlogging over winter, crop appearance at GS30–31 gives a reasonable indication of nitrogen reserves, and the justification for nitrogen application at this stage.

However, it is difficult to use visual appearance unless you have a benchmark; this has led to the concept of the N-rich strip (Photo 2). A useful guide that requires no sophisticated equipment is to apply an excess of nitrogen at sowing, e.g. 50–100 kg N/ha, to a small area of the paddock, approximately 2 m by 10 m, and use that as a benchmark. [16]

Photo 2: *vA large difference in visual appearance: N-Rich strip (110 kg N/ha at seeding) viewed at GS31 on low soil-N reserve (25 kg N/ha 0–90 cm). Left: 443 tillers/m^2 in N-rich soil. Right: 266 tillers/m^2 in soil with no extra N enrichment.*

Photos: GRDC

During winter and spring by comparing crop vigour (tiller number) and greenness in these small N-rich areas with the rest of the crop, an indication of N supply can be obtained. The advantage of using the plant rather than depending totally on a soil test is that the plant directly registers soil-N supply, whereas the soil test measures the soil-nitrogen reserve, which crop roots may not always be able to access.

This visual difference can be quantified by using crop sensors that measure the light reflectance from the crop canopy. By measuring the reflectance at the red and near-infrared wavelengths, it is possible to quantify canopy greenness using a number of vegetative indices, the most common of which is termed the Normalised Difference

16 GRDC (2009) Cereal canopy management more than delayed nitrogen. Fact sheet. GRDC, https://grdc.com.au/__data/assets/pdf_file/0014/202523/canopy-management.pdf.pdf

Vegetative Index (NDVI). This index gives an indication of both biomass present and the greenness of that biomass. Canopy sensing can be done remotely from aircraft or satellites, or with a hand-held or vehicle-mounted sensor.

10.2.5 Seeding rate and date

Achieving the correct plant population is fundamental if sufficient tillers are to be set. Seeding rates need to be adjusted for seed size and planting date; if this does not occur the first step in controlling the canopy is lost.

How many plants are targeted depends on:

- region—as a general guide, drier regions sustain lower plant populations than wetter environments; and
- sowing date—earlier sowings require lower plant populations compared to later sowings, as the tillering window is longer and more tillers are produced per plant.

Overall, earlier planting provides greater opportunities to manipulate the crop canopy during the stem-elongation period: the plant's development periods are extended along with the earlier tillering period.

Row spacing

Increased interest in no-till farming has created a trend for wider spacing of crop rows (Figure 2).

- In general, increasing row spacing up to 50 cm has minimal effect on cereal yield when yield potential is less than 2 t/ha.
- In higher-rainfall areas, where cereal crops have higher potential yields, significant yield decreases have been recorded with row spacing greater than 25 cm.
- The yields of broadleaf crops vary in response to wider row spacing.
- Precision agriculture allows for easier inter-row sowing and fertiliser applications at wider row spacing. [17]

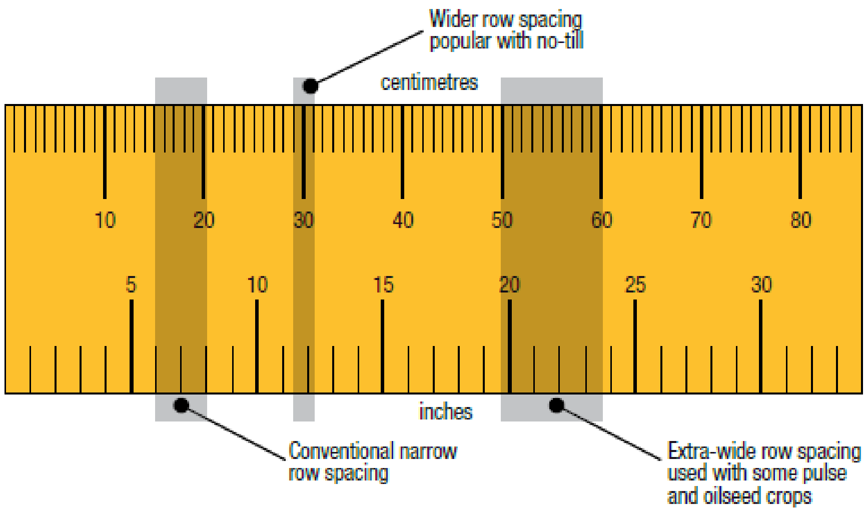


Figure 2: *Common row spacings in metric and imperial measurements.*

Source: GRDC.

17 GRDC (2011) Crop placement and row spacing: northern region. Fact sheet. GRDC, https://grdc.com.au/resources-and-publications/all-publications/factsheets/2011/02/crop-placement-and-row-spacing-northern-fact-sheet

Row orientation

The competitive ability of cereal crops can be increased by orientating crop rows at a right angle to the sun light direction, i.e. sow crops in an east-west direction. East-west crops more effectively shade weeds in the inter-row space than north-south crops. The shaded weeds have reduced biomass and seed set. The advantage of this technique is that it's free!

Consider the weed species in the field. Broadleaf weeds can alter the angle of their leaves to 'track' the sun throughout the day. So while a cereal crop can shade broadleaf weeds, the weeds will still be able to get maximum benefit from any sunlight that reaches them through the crop canopy. Further, any weeds that grow taller than the crop will not be effectively shaded by the crop canopy.

Consider the layout of the paddock. It may not be possible to sow a paddock in an east-west direction, depending of the shape of individual fields.

Consider the location of the paddock. The sun angle in winter is highest at the equator (where the sun is close to being directly overhead at midday). Sun angle becomes lower south of the equator. A low sun angle in winter will cause an east-west crop to cast shade on the inter-row space for a great proportion of the day. Therefore, a crop orientation will have a greater impact in southern Australia, compared to northern Australia.

Using an east-west orientation may be more practical with auto-steer. Without auto-steer, driving directly into the sunrise/sunset for seeding/spraying/harvest of an east-west crop will be unpleasant and potentially dangerous.

Increased shading by an east-west crop reduces the soil surface temperature in the inter-row space and reduces evaporation, leading to increased soil moisture. This increased moisture occasionally increases crop yield where moisture is limited. However, the cool, moist environment of the inter-row space may influence the development of crop disease in some locations (although altered levels of disease have not been noted in previous trials). [18]

Yield

- There are a number of reasons why growers might wish to pursue wider row spacing in cereals, e.g. residue flow, and inter-row weed and disease control. However, in canopy-management trials (2007–10) in a wide range of rainfall scenarios, increasing row width reduced yield. [19]
- The yield reduction was particularly significant when row width exceeded 30 cm.
- Crop row spacing is an important factor in managing weed competition (Photo 3). [20]
- At row widths of 30 cm, the reduction in yield compared to narrower 20–22.5 cm row spacing was dependent on overall yield potential.
- At yields of 2–3 t/ha the yield reduction was negligible.
- At yields of 5 t/ha the yield reduction was 5–7%, and averaged about 6%.
- Data from a single site suggest that rotation position may influence the yield response in wider row spacing. Continuous cereal plantings suffered less yield reduction with wider rows than an equivalent trial at the same site which including wheat after canola. [21]

18 Borger C. (2016). East-west orientation for improved crop competition. DAFWA. https://www.agric.wa.gov.au/grains-research-development/east-west-orientation-improved-crop-competition

19 N Poole and J Hunt (2014) Advancing the management of crop canopies. GRDC, https://grdc.com.au/resources-and-publications/all-publications/publications/2014/01/gc105-canopymanagement

20 Weedsmart (2015) Narrow row spacing: is it worth going back? Weedsmart, http://weedsmart.org.au/narrow-row-spacing/

21 N Poole and J Hunt (2014) Advancing the management of crop canopies. GRDC, https://grdc.com.au/resources-and-publications/all-publications/publications/2014/01/gc105-canopymanagement

Photo 3: *Narrow row spacing (left) and wide row spacing (right). The higher the yield potential, the greater the negative impact of wider rows on crop yields.*

Photos: Weedsmart

Plant spacing

- Increasing row width decreases the plant-to-plant spacing within the row, leading to more competition within the row and reduced seedling establishment (for reasons that are not clearly understood).
- Increasing plant populations when using wider rows can be counterproductive with regard to yield, particularly where plant populations exceed 100 plants per square metre as a starting point.
- Limited data indicate that increasing seeding rates so that the average plant-to-plant spacing in the row drops below 2.5 cm are either negative or neutral in terms of grain yield.
- Planting seed in a band (as opposed to a row) will increase plant-to-plant spacing but may also increase weed germination and moisture loss through greater soil disturbance. [22]

Dry matter

- Wider row spacing (30 cm and over) reduced harvest dry matter relative to narrower rows (22.5 cm and under), with differences growing steadily (in kilograms per hectare) from crop emergence to harvest, by which time differences were in the order of 1–3 t/ha depending on row width and growing-season rainfall.
- The reduction in dry matter in wide rows was also significant at flowering (GS60–69), frequently 1 t/ha reduction when row spacing increased 10 cm or more over a 20 cm row-spacing base. This could be important when considering harvesting for hay rather than grain. [23]

Grain quality

- The most noticeable effect of row width on grain quality was on protein: wider rows reduced yield and increased grain protein.
- Differences in grain quality were typically small in terms of test weights and screenings, with very small benefits to wider rows over narrow rows on some occasions. [24]

Nitrogen management

Nitrogen management has not been found to interact with row spacing, so optimum N regimes for narrow row spacing (22.5 cm or less) can be the same as for wider row spacing (30 cm or more). The greater nitrogen efficiency observed with N applied

22 GRDC. (2014). Advancing the management of crop canopies. https://grdc.com.au/resources-and-publications/all-publications/publications/2014/01/gc105-canopymanagement

23 N Poole and J Hunt (2014) Advancing the management of crop canopies. GRDC, https://grdc.com.au/resources-and-publications/all-publications/publications/2014/01/gc105-canopymanagement

24 N Poole and J Hunt (2014) Advancing the management of crop canopies. GRDC, https://grdc.com.au/resources-and-publications/all-publications/publications/2014/01/gc105-canopymanagement

at stem elongation was more important with narrow row spacing, since higher yields lead to a tendency for lower protein. [25]

10.2.6 In-crop nitrogen

Delaying N inputs from seeding to stem elongation (GS30–31) means they can be better matched to the season. So, in a dry spring, no application may be warranted. In spring, with adequate rainfall to justify N application, project trials have shown stem-elongation N to give yields equal to or better than wheat crops grown with seeding N. However, applying N in advance of a rain front to ensure good incorporation has been found to be more important than applying it at an exact growth stage. While GS31 should be the target growth stage for in-crop N application, the window can be expanded from GS25–31 in order to take advantage of rainfall. Even applications delayed until flag leaf can be successful where starting soil nitrogen is not too low (Figure 3). [26]

Figure 3 presents the results from winter cereal cropping trials across Australia that investigated the use of in-crop solid nitrogen at stem elongation. The trials showed that where soil nitrogen reserves are low, N applied at stem elongation is not always the most appropriate strategy if yield is to be optimised. Stem-elongation N applications were found to be less appropriate with shorter-season varieties and late-sown crops. Drought conditions during the trial period (2006 to 2008) limited the results of these trials. These trials assessed stem elongation N use in cereals grown on wider-row spacings 30–35 cm compared to 17.5–20 cm. However, at the same seeding rate, moving to wider rows was found to reduce tillers per unit area, and final ear population and yield, the latter by approximately 6% in the high-rainfall zone (HRZ).

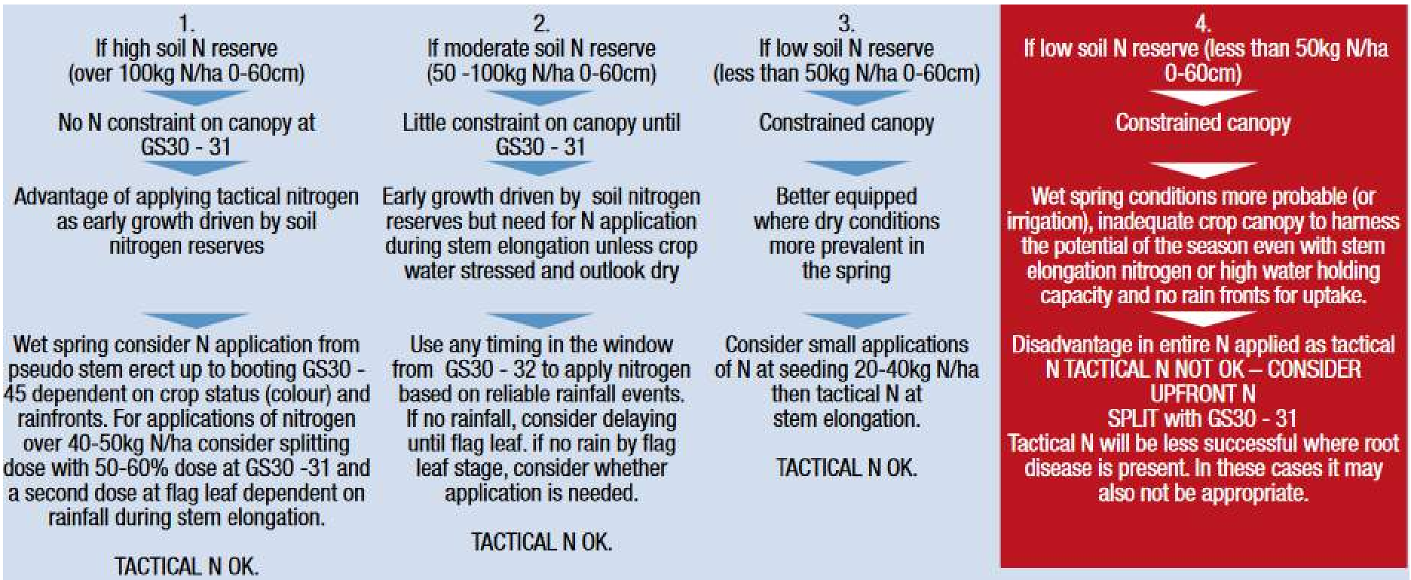


Figure 3: *Broad scenarios based on soil nitrogen level.*

Source: GRDC

10.2.7 Limitations of tactical nitrogen application

The main limitation to tactical N application in the Northern region is the ability to reliably apply N before a rain event, when it would be applied to enable roots to access soluble N in the root-zone. Predicted rain fronts may pass without yielding anything; therefore, dependably applying N throughout the season is risky.

25 N Poole and J Hunt (2014) Advancing the management of crop canopies. GRDC, https://grdc.com.au/resources-and-publications/all-publications/publications/2014/01/gc105-canopymanagement

26 GRDC (2009) Cereal canopy management more than delayed nitrogen. Fact sheet. GRDC, https://grdc.com.au/__data/assets/pdf_file/0014/202523/canopy-management.pdf.pdf

Foliar N application is gaining popularity; however, this is only suitable for relatively low rates of N addition. Where higher N input is required, an efficient system to apply N into the wet soil profile, after a rainfall event, needs to be devised.

As technologies such as NDVI imaging and paddock management in zones become prevalent, the addition of N later in the crop cycle will become more relevant and will force the development of equipment to make such a system work.

By combing knowledge gained from the results of trials and from paddock experience, the aim of improving the economic outcome of the season by manipulating the most costly input in a sophisticated way is becoming a reality. Adoption of these techniques throughout the northern cropping zone would be further aided by the development of efficient, in-soil N-application equipment.

The question is, can canopy management work under Australian conditions—especially the shorter growing season of northern NSW?
Results from southern regions have showed some potential to be applied in the Northern region. This is especially so in areas with high yield potential (although this also means higher N inputs) but further research is required to test and validate the principles in the Northern region. [27]

10.3 The future of canopy management in the Northern grains region

In the past much of the research on topdressing nitrogen (N) in northern NSW has focussed on the role of in-crop N to respond to seasons in which yield potentials have increased significantly after above-average rainfall. In these situations research has shown that good responses can be achieved, especially when good rainfall is received after N application.

Recently, though, there has been significant interest in the role of canopy-management principles for crop production in the northern grains region. To increase knowledge about the response of cereal crops to these principles, a research group that includes NSW DPI, the Northern Grower Alliance, AgVance Farming, and Nick Poole from the Foundation for Arable Research in New Zealand, have been conducting trials since 2006. This work is funded by GRDC, and has focussed on the interaction between delayed N applications in high-yielding crops on the Liverpool Plains.

Results from three years of supplementary irrigated research have provided important pointers for the use of canopy management principles in northern NSW. Tactically delaying N is a management system that gives growers the flexibility to respond to seasonal conditions and to manage climate variability. Research has shown that N fertiliser has been able to be delayed until stem elongation (GS31) without yield loss and usually with increased grain protein when conditions are suitable. This means that growers are able to apply a portion of the expected N requirement, and then assess yield potential, as influenced by soil water and seasonal forecasts, later in the season, and respond accordingly. To date, the best results with this approach have been seen in early sown, long-season varieties with high yield potential, as they are very N responsive with high N fertiliser inputs. [28]

Though the trials do not test the effect on cereal rye specifically, recommendations may be applicable to cereals more broadly. Make sure to consult with your local agronomist.

MORE INFORMATION

For details on the trials, see Canopy management in the northern grains region: the research view

Defining guidelines for canopy management in barley for the different climatic regions of Australia

Cereal canopy management more than delayed nitrogen

Cereal growth stages

Advancing the management of crop canopies

27 McMullen G. (2009) Canopy management in the Northern Grains region. NSW DPI. http://www.nga.org.au/results-and-publications/download/31/australian-grain-articles/general-1/canopy-management-tactical-nitrogen-in-winter-cereals-july-2009-.pdf

28 G McMullen (2009). Canopy management in the northern grains region: the research view. NSW DPI, http://www.nga.org.au/results-and-publications/download/31/australian-grain-articles/general-1/canopy-management-tactical-nitrogen-in-winter-cereals-july-2009-.pdf

Crop desiccation/spray out

Not applicable for this crop.

Harvest

Key messages

- Rye is ready to harvest when the leaves are dead and the stems have turned yellow-brown.
- Rye is susceptible to head shatter making it difficult to harvest and results in many volunteer plants emerging in the field next season.
- Because cereal rye matures earlier than other small grains, strict harvest and grazing management procedures are important to prevent it from becoming a weed.
- The limited information available on cereal rye suggests that the preferred growth stage to harvest for silage is the boot stage. Feed quality of cereal rye deteriorates more quickly with maturity compared to other cereals.
- Ensure that all equipment is clean and work to avoid blockages so that fire risk is minimised.

Although rye comes into ear earlier than wheat, the grain takes much longer to mature. Rye is ready to harvest when the leaves are dead and the stems have turned yellow-brown [1], and the crop should be harvested as soon as the grain is thoroughly dry and hard. However, rye grain shatters very easily when ripe, and seed losses from shattering can occur soon after it ripens (Photo 1). Rye is harvested with a conventional header. The grain is lighter and longer than wheat, so the machine will require minor adjustments from normal wheat settings. [2] The grain threshes very easily.
Under dry threshing conditions care must be taken to adjust the concave setting and/or cylinder speed to minimise cracking. [3]

Photo 1: *Shattered seed head in mature rye: about ¾ of the head has broken off and fallen to the ground.*

Photo: Joseph Lofthouse

1 Plant Village (n.d.) Rye Secale cereale. Plant Village, https://www.plantvillage.org/en/topics/rye/diseases_and_pests_description_uses_propagation

2 Agriculture Victoria (2013) Growing cereal rye. Note AG0403. Updated. Agriculture Victoria, http://agriculture.vic.gov.au/agriculture/grains-and-other-crops/crop-production/growing-cereal-rye

3 Alberta Agriculture and Forestry (2016) Fall rye production. Revised. AgDex 117/20-1. Alberta Agriculture and Forestry,

12.1 Windrowing

Rye shatters very easily when ripe. For this reason, common practice in the North America is to windrow cereal rye. In North America, waiting for the rye crop moisture to dry down for straight combining results in substantial shattering, and leads to volunteer crop problems in following years. [4]

Windrowing or swathing involves cutting the crop and placing it in rows held together by interlaced straws, supported above the ground by the remaining stubble (Photo 2). It can be considered as an option where:

- the crop is uneven in maturity, or the climate does not allow for rapid drying of the grain naturally
- there is a risk of crop losses from shedding and lodging

High yielding crops may gain more from windrowing than low yielding crops. Generally, crops expected to yield less than 2 t/ha should not be windrowed. Picking up windrowed cereals is significantly slower than direct heading because of the large volume of material.

If the crop is too thin or the stubble too short to support the windrow above the ground, the crop should not be windrowed. Heads on the ground may sprout and attempts to pick up heads that are lying close to the soil surface will pick up soil. [5]

Photo 2: *Directing chaff into a narrow windrow using a custom-made chute.*

Source: GRDC

12.1.1 Timing

Windrowing can begin when grain moisture content is below 35%—when grain is at the medium dough stage, hard but can still be dented with the thumbnail.

- It is better to windrow early to prevent losses from shedding and lodging, but not when the ground is wet after rain.
- Avoid windrowing too early as the grain is not fully developed and will result in small pinched grain.

4 Alberta Agriculture and Forestry (2016) Fall rye production. Revised. AgDex 117/20-1. Alberta Agriculture and Forestry, http://www1.agric.gov.ab.ca/$department/deptdocs.nsf/all/agdex1269/$file/117_20-1.pdf

5 G Troup (2016) Oats: harvesting, swathing and grain storage, Swathing. DAFWA, https://www.agric.wa.gov.au/oats/oats-harvesting-swathing-and-grain-storage?page=0%2C1

- Although it may be easier to windrow later, the windrows of a ripe crop may not interlock well enough to withstand disturbance from strong wind. [6]

12.1.2 Cutting

- Cut across the sowing direction, or at 45 degrees for crops with wider row spacing, so the windrow sits-up on the stubble. Windrowing is not recommended for paddocks where the crop row spacing is over 25 cm.
- Avoid placing windrows in the same location each year so nutrients are not concentrated in one place.
- Windrow size or width of cut should match header capacity. A double-up attachment to the windrower or placing two windrows side by side requires a larger capacity header and concentrates the residue in a narrow band within the paddock.
- Cutting height should be adjusted to keep sufficient straw on the head to hold the windrow together (minimum 30 cm) and sufficient stubble height to support the windrow.
- Start the cutting height at 10–20 cm above the ground (one-third crop height) and adjust to produce an even windrow with well-interlaced straws that sit above the ground. This allows good air circulation and rapid drying should rain occur. [7]

12.1.3 Harvesting the windrow

Harvesting of the windrowed crop must be completed as soon as possible, ideally within 10 days of windrowing.

- If left too long and subjected to long periods of wetting (more than 25 mm of rain over 4–8 days), grain may sprout and become stained. The windrow may also become contaminated with bronze field beetle.
- When the windrow is picked up, the reel should be rotating slightly faster than ground speed, but not fast enough to knock the heads off the stems.
- The conveyor canvas should be revolving sufficiently fast to prevent the crop material banking up.
- Rows pick up best when the header follows the direction of the windrow (heads first).

One of the major sources of contamination in windrowed cereals is the stubble being torn out during the windrowing operation. This generally occurs when the windrower is operated at too high a ground speed or when trying to windrow when the straw is tough due to it being cool or damp. [8]

MORE INFORMATION

Setting up at harvest for narrow windrow burning

12.2 Harvest timing

Cereal rye is harvested at about the same time as wheat. Harvest as soon as the grain dries and hardens. Ripe crops that are left to stand are likely to shed grain. Maturity is often uneven, so inspect the whole paddock before harvesting.

One way to determine whether rye is ripe for harvest is to use your fingernail to test its strength: the nail, when pressed firmly into the kernel, should make only a very light indent, this is called the soft-dough stage, (Photo 3, top). When kernel moisture content has dropped to 13–14%, the grain is harvest ripe. The surface cannot be dented with a thumbnail (Photo 3, bottom). [9]

6 G Troup (2016) Oats: harvesting, swathing and grain storage, Swathing. DAFWA, https://www.agric.wa.gov.au/oats/oats-harvesting-swathing-and-grain-storage?page=0%2C1

7 G Troup (2016) Oats: harvesting, swathing and grain storage, Swathing. DAFWA,https://www.agric.wa.gov.au/oats/oats-harvesting-swathing-and-grain-storage?page=0%2C1

8 G Troup (2016) Oats: harvesting, swathing and grain storage, Swathing. DAFWA,https://www.agric.wa.gov.au/oats/oats-harvesting-swathing-and-grain-storage?page=0%2C1

9 JacksonL, Williams J (2006) Small grain production part 2: Growth and developments of small grains. University of California, http://anrcatalog.ucanr.edu/pdf/8165.pdf

Photo 3: *Stages of cereal-grain ripening from the milk stage (top) to the harvest-ripe stage (bottom).*

Source: Jackson and Williams 2006

The moisture level in rye should be about 12% at harvest (Photo 4). Only harvest in dry conditions. When harvesting with a combine, growers may need to cut the straw high in order to avoid clogging the equipment, since rye is tall and produces a large quantity of straw. This will obviously leave taller stubble in the paddock. [10]

Photo 4: *Rye ripening.*

Photo: Plant Village

10 UVM Extension Crops and Soils Team (2011) Cereal rye, http://northerngraingrowers.org/wp-content/uploads/RYE.pdf

12.2.1 Harvesting after lodging

Lodging is when portions of the crop fall over due to strong wind, and occasionally in very high-yielding crops (which have heavy heads) or in varieties with weak stems.

The lodged plants will begin to lose nutritive value, and the grain may even begin to sprout if it is advanced enough in its formation; i.e. at the hard-dough stage.

If possible, harvest a lodged crop within days of it lodging, before its nutritive value deteriorates too much, and before mould and deleterious bacteria build up. Travelling in the opposite direction to the lodged plants will ensure less difficulty in the harvest operation and minimal losses.

Crops that have lodged for some time can be a problem. If the harvester travels in the opposite direction to that in which the plants have lodged the nutritive value of the seed will be decreased, due to harvesting decaying plants. Decaying plant material will also adversely affect fermentation. [11]

12.2.2 Harvesting forage cereals

Cereals suitable for ensiling are cereal rye, oats, barley, wheat and triticale. The limited information available on cereal rye suggests that the preferred growth stage to harvest it for silage is the boot stage. This is because the feed quality of cereal rye deteriorates more quickly with maturity compared to other cereals. [12]

When to cut for silage

The timing of harvest should take into consideration the following:

- The end use of the silage; i.e. for animal production or maintenance rations
- Weather conditions at harvest.
- Soil type and soil-moisture conditions at harvest.
- If double cropping, when the following crop needs to be sown.
- The availability of suitable harvesting machinery.

Harvesting at the correct percentage of dry matter (DM) is important to ensure optimal yield, minimal loss of nutritive value, and a desirable fermentation process.

Dry matter levels for ensiling

If cutting at the flag-leaf or boot stages, the recommended DM levels are 33–40% for forage, and 38–50% DM for baling. The recommended ranges for cutting at the soft-dough stage are 35–42% DM for forage, and 38–45% DM for silage that is baled.

In the later stages of growth, cereal plants contain large stems, with leaves ranging from green (alive) to yellowing (dying) and grain heads in various stages of formation. This makes the estimation of the DM content difficult. Therefore, it is essential that a representative sample of the whole crop to be silage is obtained for estimating the DM content.

Mowing

The stage of growth of the crop at harvest will determine whether it is mown and wilted before harvesting or direct-cut and ensiled as a standing crop. However, the height of cutting can have some bearing on how the product is stored.

Cutting height is usually 7–10 cm above ground level. Cutting higher will result in a slight increase in nutritive value, but at the cost of reduced yields.

If cut when mown and wilted, the higher cutting height will tend to keep the mown windrow higher off the ground, thereby allowing more airflow under the crop and a

11 F Mickan (2008) Harvesting forage cereals. Note Ag1244. Updated. Agriculture Victoria, http://agriculture.vic.gov.au/agriculture/grains-and-other-crops/crop-production/harvesting-forage-cereals

12 NW Griffiths, FJ Mickan and AG Kasier (2004) Chapter 5: Crops and by-products for silage. In Successful silage. 2nd edn. NSW DPI, https://www.dpi.nsw.gov.au/__data/assets/pdf_file/0005/294053/successful-silage-topfodder.pdf

slightly faster wilting rate. It will also reduce the risk of soil contamination by other equipment, e.g. in operations such as raking.

However, cutting at greater heights will mean leaving behind more stubble, which creates a problem of future removal and preparation for the next forage crop. [13]

12.2.3 Equipment

Cereal rye is tall and the bulky straw makes harvesting slow, due to the large volume of material going through the harvester.

Clean out all machinery and equipment before and after harvest to prevent cross-contamination between cereal grains (Photo 5). [14]

Photo 5: *Cereal harvest under way. It is important to clean all equipment prior to and after harvesting.*

Photo: Agency Brazil

Standard headers

A standard wheat header is suitable for harvesting cereal rye. Adjustments need to be made to the harvester settings to avoid grain losses and damage, because the grain is lighter and longer than wheat. [15]

Tall crops are likely to lean or lodge, so crop lifters might be necessary.

In trials in 2014 in the southern high-rainfall zone (HRZ), researchers found that there is a 10% lift in header efficiency for every 10-centimetre increase in harvest height. They compared three harvest heights—15 cm, 30 cm and 50 cm—in wheat and barley (Note that cereal rye grows taller than wheat).

The trials also showed how much slower harvesting is at a height of 15 cm; as well as time costs, fuel consumption goes up, too. When they increased the height from 30 cm to 50 cm, harvesting was around 25% faster. A rule of thumb is that there is a 10% efficiency increase for every 10 cm of harvest height. If a 100 ha crop is harvested at 15 cm it will take about 20% more time to harvest than a crop cut at 30 cm, and 38% more time than if it had been harvested at 50 cm. [16]

13 F Mickan (2008) Harvesting forage cereals. Note Ag1244. Updated. Agriculture Victoria, http://agriculture.vic.gov.au/agriculture/grains-and-other-crops/crop-production/harvesting-forage-cereals

14 P Matthews, D McCaffery and L Jenkins. (2016).Winter crop variety sowing guide 2016. DPI NSW, https://www.dpi.nsw.gov.au/agriculture/broadacre-crops/guides/publications/winter-crop-variety-sowing-guide

15 Agriculture Victoria (2013) Growing cereal rye. Note AG0403. Updated. Agriculture Victoria, http://agriculture.vic.gov.au/agriculture/grains-and-other-crops/crop-production/growing-cereal-rye

16 A Lawson (2015) Header efficiency increases with harvest height. Ground Cover. Issue 118, September–October 2015. GRDC, https://grdc.com.au/Media-Centre/Ground-Cover/Ground-Cover-Issue-118-Sep-Oct-2015/Header-efficiency-increases-with-harvest-height

However, there are reasons for harvesting low: it is done to reduce stubble loads to manageable levels, which is achieved by baling the stubble or burning the windrows, or spreading trash and straw as evenly as possible across the header swathe.

Treating weed seeds while harvesting low may help to reduce the weed seedbank in the soil over time, and this can assist with weed control and the management of herbicide resistance.

Forage harvesters

Cereals for whole-crop silage (WCS) should ideally be harvested using a precision-chopping forage harvester to ensure a short chop length (20–50 mm). This ensures that the material can be well compacted in the stack or pit to minimise the amount of air trapped, and thereby minimise losses of nutritive value and DM. Losses are due to continued plant and microbial respiration during the early phases of fermentation.

Most other forage-harvesting machines, e.g. self-loading wagons, cut the material to varying lengths, often over 200 mm, making adequate compaction very difficult.

The drier the crop DM content at harvest, the shorter the chop length required. Chopping the material short also ensures a thorough mixing of the high nutritive heads with the much lower nutritive stems and leaves.

Increased density also reduces the rate of aerobic spoilage at stack opening, a common although not insurmountable problem with cereal silages. Less wastage also occurs, as animals cannot easily select the heads and leave the stem material when fed.

Forage cereals being direct-harvested at the later growth stage is increasingly being carried out with forage harvesters that have a cutter bar instead of the typical rotary-disc mowers to reduce grain loss. Grain loss from the gaps in the housing of the chopping and feeding mechanisms can be minimised by fitting blanking plates.

Grain loss may be slightly higher in pre-mown crops due to the rotary-disc action of the mower and, particularly if raked before harvesting, DM yield and nutritive value will also be slightly lower.

If the crop is harvested after the soft-dough stage, the grain will be hardening as it matures. Forage harvesters, which are fitted with rollers specifically for cracking grain (often referred to as primary processing), will be essential.

Balers

Harvesting the whole crop using balers is not recommended, as dense compaction is often not achieved and vermin damage to the bales in storage can be a serious problem. If whole-crop cereals are to be harvested with round or square balers, the material needs to be wilted to slightly higher DM contents to ensure a lactic-acid fermentation occurs.

If using a baler, those with chopping mechanisms are highly recommended to aid compaction. The fermentation process and animal intakes of WCS will also benefit substantially from chopping. Once past the ideal stage for harvesting, cereal stems become more lignified (stiffer) and the stems are hollow, i.e. contain more internal air. Drier stems allow more air to be trapped within and between the stems in the bale. In this situation a chopping baler, with all knives in operation, is highly recommended. An alternative is to bale at the moister end of the DM range recommended for baling. Baling with some dew on the material will also be useful if DM levels are above those recommended.

Baling at a slower forward speed will also allow most balers to produce a denser bale. Baling material that is too dry, or not tightly compacted, results in large volumes of air being trapped in the bale thus reducing nutritive value and increased risk of puncturing by the stalks.

Anecdotal feedback from some machinery operators is that, if a mower only is used for the later growth stages of the crop, particularly when baling, the baler should travel in the opposite direction to the mower. The heads of the crop are picked up first, and this results in much less trouble in the picking up and feeding in of the forage into the machine. However, one piece of research has indicated that friction from the rolling mechanisms in some balers induces heavier grain loss than that from forage harvesters. More research is needed to quantify losses at all stages of WCS harvesting and storage.

Applying net-wrap instead of twine will also reduce the amount of air trapped between the plastic and the bale as the twine, especially in slightly loose bales, will pull into the bale. This allows air to travel around the twine once plastic is applied, and the feed may become mouldy, particularly if the plastic is holed. Applying net-wrap will also minimise straw stalks protruding from the bales and puncturing the stretch-wrap plastic seal, thereby allowing air to enter. [17]

12.3 Fire prevention

Grain growers must take precautions during the harvest season, as operating machinery in extreme fire conditions is dangerous. They should take all possible measures to minimise the risk of fire. Fires are regularly experienced during harvest in stubble as well as standing crops. The main cause is hot machinery combining with combustible material. This is exacerbated on hot, dry, windy days. Seasonal conditions can also contribute to lower moisture content in grain and therefore a greater risk of fires.

Harvester fire reduction checklist

1. Recognise the big four factors that contribute to fires: relative humidity, ambient temperature, wind and crop type and conditions. Stop harvest when the danger is extreme.
2. Focus on service, maintenance and machine hygiene at harvest on the days more hazardous for fire. Follow systematic preparation and prevention procedures.
3. Use every means possible to avoid the accumulation of flammable material on the manifold, turbocharger or the exhaust system. Be aware of side and tailwinds that can disrupt the radiator fan airblast that normally keeps the exhaust area clean.
4. Be on the lookout for places where chaffing can occur, such as fuel lines, battery cables, wiring looms, tyres and drive belts.
5. Avoid overloading electrical circuits. Do not replace a blown fuse with a higher amperage fuse. It is your only protection against wiring damage from shorts and overloading.
6. Periodically check bearings around the harvester front and the machine. Use a hand-held digital heat-measuring gun for temperature diagnostics on bearings and brakes.
7. Maintain fire extinguishers on the harvester and consider adding a water-type extinguisher for residue fires. Keep a well maintained fire fighting unit close-by to the harvesting operation ready to respond.
8. Static will not start a fire but may contribute to dust accumulation. Drag chains or cables may help dissipate electrical charge but are not universally successful in all conditions. There are some machine mounted fire-suppression options on the market.
9. If fitted, use the battery isolation switch when the harvester is parked. Use vermin deterrents in the cab and elsewhere, as vermin chew some types of electrical insulation.
10. Observe the Grassland Fire Danger Index (GFDI) protocol on high fire risk days.

17 F Mickan (2008) Harvesting forage cereals. Note Ag1244. Updated. Agriculture Victoria, http://agriculture.vic.gov.au/agriculture/grains-and-other-crops/crop-production/harvesting-forage-cereals

11. Maintain two-way or mobile phone contact with base and others and establish a plan with the harvest team to respond to fires if one occurs. [18]

Using machinery

To preventing machinery fires, it is imperative that all headers, chaser bins, tractors and augers be regularly cleaned and maintained. All machinery and vehicles must have an effective spark arrester fitted to the exhaust system. To prevent overheating of tractors, motorcycles, off-road vehicles and other mechanical equipment, all machinery needs to be properly serviced and maintained. Fire-fighting equipment must be available and maintained—it is not just common sense; it is a legal requirement.

Take great care when using this equipment outdoors:

Be extremely careful when using cutters and welders to repair plant equipment; this includes angle grinders, welders and cutting equipment,

Ensure that machinery components including brakes and bearings do not overheat, as these components can drop hot metal onto the ground, starting a fire.

Use machinery correctly, as incorrect usage can cause it to overheat and ignite.

Be aware that when blades of slashers, mowers and similar equipment hit rocks or metal, they can cause sparks to ignite dry grass.

Avoid using machinery during inappropriate weather conditions of high temperatures, low humidity and high wind.

Do repairs and maintenance in a hazard-free, clean working area such as on bare ground, concrete or in a workshop, rather than in the field.

Keep machinery clean and as free from fine debris as possible, as this can reduce onboard ignitions. [19]

Harvester fire research

With research showing an average of 12 harvesters burnt to the ground every year in Australia (Photo 6), agricultural engineers encourage care in keeping headers clean to reduce the potential for crop and machinery losses.

Key findings:

- Most harvester fires start in the engine or engine bay.
- Other fires are caused by failed bearings, brakes and electricals, and rock strikes. [20]

18 Barr R. (2015). Plant of attack needed for harvester fires. https://grdc.com.au/Media-Centre/Media-News/South/2015/10/Plan-of-attack-needed-for-harvester-fires

19 NSW Rural fire Service. Farm firewise. NSW Government, http://www.rfs.nsw.gov.au/plan-and-prepare/farm-fire-safety

20 GRDC (2012) A few steps to preventing header fires. GRDC Ground Cover Issue 101, http://www.grdc.com.au/Media-Centre/Ground-Cover/Ground-Cover-Issue-101/A-few-steps-to-preventing-header-fires

Photo 6: *GRDC figures show that there are 1000 combine harvester fires in Australia each year.*

Source: Weekly Times

12.3.1 Harvesting in low-risk conditions

Growers can use the Grassland Fire Danger Index guide to assess the wind speed at which harvest must cease (a GFDI of 35), depending on the temperature and relative humidity (Figure 1).

Step 1: Read the temperature on the left hand side.

Step 2: Move across to the relative humidity.

Step 3: Read the wind speed at the intersection. In the worked example, the temperature is 35°C and the relative humidity is 10% so the wind speed limit is 26kph.

TEMP °C	5	10	15	20	25	30	40	50	60	65	RH%*
15	31	35	38	40	43	45	49	53	56	58	AVERAGE WIND SPEED (KPH)†
20	29	33	36	38	40	43	46	50	53	55	
25	27	30	33	36	38	40	44	47	50	52	
30	25	28	31	33	35	37	41	44	47	49	
35	23	26	28	31	33	35	38	41	44	46	
40	21	24	26	28	30	32	35	39	41	43	
45	19	22	24	26	28	30	33	36	39	40	
TEMP °C	5	10	15	20	25	30	40	50	60	65	RH%*

*RH% (Relative Humidity rounded down)
†Wind speed averaged over 10 minutes

Figure 1: *Grassland fire danger index guide.*

Source: CFS South Australia

PODCAST

GRDC Podcasts: Harvester Fires.

MORE INFORMATION

GRDC Reducing Harvester Fire Risk: The Back Pocket Guide

An investigation into harvester fires

Plan of attack needed for harvester fires

12.4 Receival standards

Cereal-rye standards are to be applied on individual truck loads, and must not be averaged over a number of loads (Table 1). [21]

Table 1: *Grain Trade Australia receival standards for cereal rye.*

Category	Standard
Moisture Max (%)	12.0
Description	Clean, sound mature whole grain, amber–light brown colour, free of genetic modification. The seller warrants the rye is fit for human consumption and complies with the standards laid down under the Food Standard Code.
General	Rye tendered for delivery shall be free of any uncharacteristic odour, infestation, objectionable material and any nominated commercially unacceptable contaminant.
Specific allergens	Nil presence of peanuts or biological material of any kind derived from the peanut plant in rye tendered for delivery.
Chemical treatment	No chemical treatments are to be used on harvested rye unless authorised in writing by Allied Mills, and any other chemical treatments must be declared at the time of receival. It is illegal to deliver grains containing above 0.3 ppm of phosphine.

Source: Grain Flow

MORE INFORMATION

AWB receival standards for cereal rye in 2016–2017

Grain Trade Australia, Cereal rye and triticale trading standards 2015–16

Cereal rye standards 2015–2016

12.5 Harvest weed-seed management

There are several ways of utilising harvest to lessen the numbers of viable weed seeds, to prevent weed seed returning to the seedbank and then proliferate during the next season. Techniques include harvest weed-seed control (HWSC), windrow burning, and the use of chaff carts, direct baling the Harrington Seed Destructor. It has been shown that these systems have similar effectiveness. [22]

12.5.1 Harvest weed-seed control

Many Northern grain growers have been a little sceptical about introducing harvest weed-seed control (HWSC) as a tool for combating herbicide resistance. Although few growers in Queensland and New South Wales incorporate HWSC into their management practices at the moment, this is likely to change. Nationally, HWSC is proven to reduce the weed seedbank, and some weeds of the northern grains region are suited to this method of control, particularly in a farming environment of increasing herbicide resistance.

Weed-seed capture and control at harvest can add to the effectiveness of other tactics to put the weed seedbank into decline. Up to 95% of annual ryegrass seeds that enter the harvester exit in the chaff fraction. If these can be captured, they can be destroyed or removed.

Western Australian farmers and researchers have developed several systems to effectively reduce the return of annual ryegrass and wild radish seed into the seed bank, and help put weed populations into decline.

A key tactic for all harvest weed-seed control operations is to maximise the percentage of weed seeds that enter the header. This means harvesting as early as possible before weed seed is shed, and harvesting as low as is practical, e.g. at 'beer-can height'.

21 Grain Flow (2016) Cereal rye standards 2015–16. Grain Flow, http://www.grainflow.com.au/NR/rdonlyres/A655AD52-F1D1-43B6-92A0-60226BE6FDB5/0/GFCerealRyeStandards201516.pdf

22 M Street and G Shepherd (2013) Windrow burning for weed control: WA fad or a viable option for the east? GRDC Update Paper. GRDC, https://grdc.com.au/Research-and-Development/GRDC-Update-Papers/2013/02/Windrow-burning-for-weed-control-WA-fad-or-viable-option-for-the-east

MORE INFORMATION

GRDC's [Tactics for managing weed populations]

Section on narrow-windrow burning in GRDC's [Tactics for managing weed populations]

[Windrow burning for weed control: WA fad or a viable option for the east?]

Northern weeds suited to HWSC

- Definitely—turnip weed and African turnip weed are potentially very good candidates for HWSC, although these species are not yet resistant.
- Definitely in winter crops—annual ryegrass and wild oats. Wild oats shed seed at about 2% per day and ryegrass at 1% a day, but it is still worth using HWSC at the start of harvest.
- Possibly in winter crops—barnyard grass and feathertop Rhodes grass are known to shed their seed in summer crops, but where they germinate in spring in winter crops they may be suitable candidates for HWSC.
- Possibly in summer crops—feathertop Rhodes grass provides an opportunity for HWSC in summer crops where there is a high percentage of seed retention at the start of harvest. [23]

12.5.2 Burning in narrow windrows

During traditional whole-paddock stubble burning, the very high temperatures needed to destroy weed seeds are not sustained for long enough to kill most weed seeds. However, by concentrating harvest residues, which includes weed seeds, into a narrow windrow, the fuel load is increased and the period of high temperatures extends to several minutes, improving the kill of weed seeds.

Windrow burning: the WA experience

Windrow burning has been widely adopted in Western Australia as an option for dealing with weed seeds that are resistant to herbicides. It is used as part of an integrated harvest weed-management strategy that includes these considerations:

- Continued reliance on herbicides alone is not sustainable in continuous-cropping systems. Rotating herbicides alone will not prevent the development of resistance.
- The early implementation of windrow burning will prolong the usefulness of herbicides, not replace them.
- Windrow burning is the cheapest non-chemical technique for managing weed seeds present at harvest.
- Even with higher summer rainfall, windrow burning is a viable option for NSW cropping systems.
- Windrow burning is an effective weed-management strategy, even in the absence of resistance.
- Growers need to begin experimenting now on small areas to gain the experience needed to successfully implement the strategy. [24]

12.5.3 Chaff carts

Chaff carts are towed behind headers during harvest to collect the chaff fraction (Photo 7). The chaff that is collected is dumped into piles and then burnt the following autumn or used as a source of stock feed.

23 T Somes (2016) Can harvest weed-seed control work for the North? Ground Cover. Issue 124, September–October 2016. GRDC, https://grdc.com.au/Media-Centre/Ground-Cover/Ground-Cover-Issue-124-SeptemberOctober-2016/Can-harvest-weedseed-control-work-in-the-north

24 M Street and G Shepherd (2013) Windrow burning for weed control: WA fad or a viable option for the east? GRDC Update Paper. GRDC, https://grdc.com.au/Research-and-Development/GRDC-Update-Papers/2013/02/Windrow-burning-for-weed-control-WA-fad-or-viable-option-for-the-east

MORE INFORMATION

Section on chaff carts in GRDC's Tactics for managing weed populations

Section on bale-direct systems in GRDC's Tactics for managing weed populations

Small and large baler projects of the Shields family

Section on the Harrington Seed Destructor in GRDC's Tactics for managing weed populations

Chaff deck concentrates weeds in controlled traffic

VIDEOS

WATCH: A beginner's guide to harvest weed seed control

Photo 7: *Chaff cart in action*

Photo: A. Storrie

12.5.4 Bale-direct system

The bale-direct system uses a baler attached to the harvester to collect all chaff and straw material. This system requires a large baler to be attached to the back of the harvester. As well as removing weed seeds, the baled material has an economic value as a livestock feed. Header-towed bailing systems were developed in Western Australia by the Shields family.

12.5.5 Harrington Seed Destructor

The integrated Harrington Seed Destructor (iHSD) is the invention of Ray Harrington, a progressive farmer from Darkan, WA. Developed as a trail-behind unit, the iHSD comprises a chaff-processing cage mill, and chaff and straw delivery systems. The retention of all harvest residues in the field reduces the loss and/or banding of nutrients and maintains all organic matter to protect the soil from wind and water erosion, as well as reducing evaporation loss compared to the use of windrow burning, chaff carts and baling. [25]

The chaff deck places the chaff exiting the sieves of the harvester on to permanent wheel tracks. Growers using chaff decks have observed that few weeds germinate from the chaff fraction and believe that many weed seeds rot in it. A permanent tramline farming system is necessary to be able to implement the chaff deck system. [26]

25 GRDC (n.d.) Section 6. Managing weeds at harvest. GRDC, https://grdc.com.au/Resources/IWMhub/Section-6-Managing-weeds-at-harvest

26 Roberts P. (2014). New systems broaden harvest weed control options. GRDC. https://grdc.com.au/Media-Centre/Media-News/West/2014/11/New-systems-broaden-harvest-weed-control-options

Storage

Key messages

- Rye is considered to be dry and safe for storage at 12% or lower kernel moisture. At this moisture content, loss of condition due to moulds or mites is unlikely.
- Rye that goes for milling and baking has to meet specified commercial and hygienic standards. Therefore, early harvesting and proper drying before storage are necessary.
- Cereal rye grain does not store well unless frequently treated for insect contamination.
- Seed germination drops rapidly when cereal rye is stored longer than a year.
- Moisture content and temperature of the grain during harvest determine how long rye can be stored safely. Drying and cooling of freshly harvested, moist, warm grain is an important operation that must occur before rye goes for processing or storage.

Drying and storage of cereal rye is similar to wheat. Rye that goes for milling and baking has to meet specified commercial and hygienic standards. Therefore, early harvesting and proper drying before storage are necessary. [1]

Rye should have 12% or less moisture content (MC) when stored.

It is important to follow guidelines on the safe storage to avoid grain deterioration. The MC and temperature of the grain at harvest determine how long it can be stored safely; i.e. without loss in quality or quantity. It is important to dry and cool freshly harvested, moist, warm grain before it goes for processing or storage.

Seed germination drops rapidly when cereal rye is stored longer than a year. [2]

IN FOCUS

Storing rye safely

Rye samples with moisture contents of 10.0%, 12.5%, 15.0% and 17.5% (wet basis) were stored for 16 weeks, with samples at each degree of moisture kept at 10°C, 20°C, 30°C and 40°C. Once a week, the researchers measured the germination rate and moisture content, and monitored visible mould on all samples. Every two weeks, they checked free fatty acid values (FAV). Every four weeks, they tested all samples for invisible microflora.

The germination rate decreased significantly as moisture content, temperature and storage period increased. The moisture content of the samples stored at 10°C increased with time, whereas that of samples stored at 30°C and 40°C decreased. Visible mould appeared in all the samples with 17.5% MC, and in all the samples stored at 40°C. The predominant fungi in almost all the samples in the study were *Penicillium* spp. and *Aspergillus glaucus*. Fat acidity value increased with increasing moisture content, temperature, and storage time.

The researchers determined that germination was the most sensitive, effective, and simple method of determining the condition of a grain bulk on the farm, as it proved to be a good indicator in its own right, and because it can be determined with no special training and expensive equipment. They developed safe storage guidelines for MC and

1 G Sathya, DS Jayas and NDG White (2008) Safe storage guidelines for rye. Canadian Biosystems Engineering, 50, 3.1–3.8, http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.498.6611&rep=rep1&type=pdf

2 Alberta Agriculture and Forestry (2016) Fall rye production. Revised. AgDex 117/20-1. Alberta Agriculture and Forestry http://www1.agric.gov.ab.ca/$department/deptdocs.nsf/all/agdex1269/$file/117_20-1.pdf

temperature were developed based on the drop in germination and the appearance of visible mould.

On this basis, rye with less than 12.5% MC stored at less than 20°C is safe for at least 15 weeks, whereas with rye with over 15% MC stored at 40°C growers have less than a week to complete drying and cooling (Figure 1). [3]

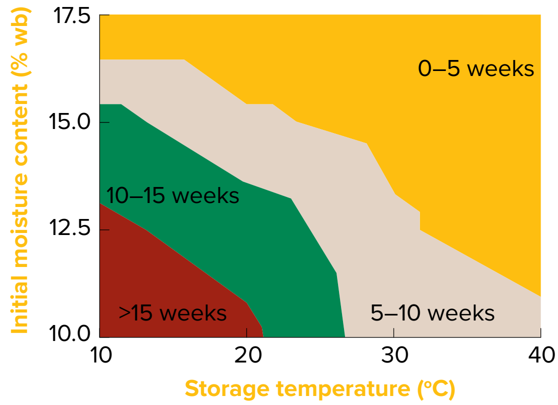


Figure 1: *Estimated safe storage life of rye based on 20% decrease in the initial germination and no visible mould. Periods of safe storage are indicated.*

Source: Satha, Jayas and White 2008

GRDC Stored grain information hub

Following the work already done through the Grain Storage Extension Project, the GRDC have funded another three years allowing grain storage extension to continue through to 2018.

The project aims to provide a stored grain information hub and equip growers with the skills and knowledge to enable best management practices of on-farm grain storage. Some exciting new resources to keep an eye out for under the new project will be an eLearning Manual, a smart phone App and an extension community of practice.

For more information on the grain storage extension project or to arrange a workshop in your area contact a member of the team.

- National Hotline 1800 weevil (1800 933 845)
- QLD and northern NSW, Philip Burrill philip.burrill@daff.qld.gov.au
- Southern NSW, VIC, SA and TAS, Peter Botta pbotta@bigpond.com
- WA, Ben White ben@storedgrain.com.au
- Project coordinator Chris Warrick info@storedgrain.com.au

MORE INFORMATION

Stored grain information hub

13.1 How to store product on-farm

On-farm grain storage takes a significant investment. Although many farms have older storage facilities that cannot be sealed for grain fumigation, replacing them with sealable silos may not be economically viable.

3 G Sathya, DS Jayas and NDG White (2008) Safe storage guidelines for rye. Canadian Biosystems Engineering, 50, 3.1–3.8, http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.498.6611&rep=rep1&type=pdf

Growers might only plan to store grain on-farm for a short time, but markets can change, so investing in gas-tight sealable structures means you can treat pests reliably and safely and leave your business open to a range of markets.

Growers should approach storage as they would purchasing machinery: Growers spend a lot of time researching a header purchase to make sure it is fit-for-purpose. Grain storage can also be a significant investment, and a permanent one, so it pays to have a plan that adds value to your enterprise into the future.

> *Decide what you want to achieve with storage, critique any existing infrastructure and be prepared for future changes: A good storage plan can remove a lot of stress at harvest – growers need a system that works so they capture a better return in their system.* [4]

Agronomist's view

Mixed storage could be the solution. The strategy is to purchase a small number of sealable silos and use them to batch-fumigate grain prior to sale. This works because grain silos in the northern region are aeration-cooled for most of the time and only sealed for the purpose of fumigation.

There are several reason why growers might consider storing grain on the farm, including:

- improving harvest logistics
- taking advantage of higher grain prices sometime after harvest
- supplying a local market (e.g. feedlot, dairy, etc.)
- avoiding high freight costs at peak time
- adding value by through cleaning, drying or blending grain
- retaining planting seed [5]

In most cases, for on-farm storage to be economical, it will need to deliver on more than one of these benefits, and the benefits need to outweigh the disadvantages (Table 1). Under very favourable circumstances grain storage facilities can pay for themselves within a few years, but it is also possible for an investment in on-farm storage to be very unprofitable. GRDC's Stored Grain Information Hub has a cost–benefit analysis tool that can help growers decide what type of grain storage to have on the farm. [6]

VIDEOS

WATCH: Over the Fence: On-farm storage pays in wet harvest

4 GRDC. (2015). Ground cover issue 119 – Grain storage. Extension tailored for regional challenges. https://grdc.com.au/Media-Centre/Ground-Cover-Supplements/Ground-Cover-Issue-119--Grain-storage/Extension-tailored-for-regional-challenges

5 GRDC (2015) Grain storage strategies in the northern region. GRDC, https://grdc.com.au/archive/key-issues/grain-storage-strategies-in-the-northern-region

6 Stored Grain Information Hub (n.d.) Grain storage cost benefit analysis template. GRDC, http://storedgrain.com.au/cost-benefit-template/

Table 1: *Advantages and disadvantages of grain-storage options.*

Storage type	Advantages	Disadvantages
Gas-tight, sealable silo	Gas-tight, sealable status allows phosphine and controlled atmospheres to control insects Easily aerated with fans Fabricated on-site, or off-site and transported Capacity from 15 t to 3,000 t 25 years or more of service life Simple in-loading and out-loading Easily administered hygiene (cone-based silos particularly) Can be used multiple times in a season	Requires foundation to be constructed Relatively high initial investment required Seals must be maintained regularly Access requires safety equipment and infrastructure Requires and annual test to check gas-tight sealing
Unsealed silo	Easily aerated with fans 7–10% cheaper than sealed silos Capacity from 15 t to 3,000 t Up to 25 year service life Can be used multiple times in a season	Requires foundation to be constructed Silo cannot be used for fumigation Insect control limited to protectants in eastern states and Dryacide® in WA Access requires safety equipment and infrastructure
Grain-storage bags	Low initial cost Can be laid on a prepared pad in the paddock Provide harvest logistics support Can provide segregation options Are ground operated	Requires purchase or lease of loader and unloader Increased risk of damage to grain beyond short-term storage (typically three months) Limited insect control options, with fumigation possible only under specific protocols Requires regular inspection and maintenance, which need to be budgeted for Aeration of grain bags currently limited to research trials only Must be fenced off Prone to attack by mice, birds, foxes, etc. Limited wet-weather access if stored in paddock Need to dispose of bag after use Single-use only

MORE INFORMATION

Grain storage cost–benefit analysis template

Saving weather-damaged grain for seed

Prepare on-farm storage early to protect your harvest

Storage checklist

Grain storage – invest today for the system of tomorrow

Storage type	Advantages	Disadvantages
Grain-storage sheds	Can be used for dual purposes 30 years or more of service life Low cost per stored tonne	Aeration systems require specific design Risk of contamination from dual purpose use Difficult to seal for fumigation Vermin control is difficult Limited insect control options without sealing Difficult to unload

Source: Kondinin Group

13.1.1 Silos

Cereal rye grain does not store well unless it is frequently treated for insect contamination. To minimise insect attack, the grain should be stored at less than 12% MC, preferably in sealed silos (Photo 1). [7] Treat the grain as it enters the silo and then check every 2–3 months for reinfestation by grain insects.

Photo 1: *It is important to pressure test all silos used on the farm, even those that are labelled as 'sealed'.*

Source: GRDC

Sealed silos offer a longer-term grain-storage option than grain-storage bags. Depending on the amount of storage required, silos will be more expensive to install than storage bags: as stored tonnage increases the capital cost of storage increases. Silos are depreciated over a longer time frame than the machinery required for the grain bags.

Among the advantages of using sealed silos to store grain storage are improved harvest management, reduced harvest stress, reduced harvest freight requirements, minimal insecticide exposure, and the opportunity to segregate and blend grain.

7 Stored Grain Information Hub (2014) Pressure-testing sealable silos. Revised. Fact sheet. GRDC, http://storedgrain.com.au/pressure-testing/

VIDEOS

WATCH: GCTV2: Pressure testing sealed silos

MORE INFORMATION

Pressure testing sealable silos fact sheet

GRDC Silo buyer's guide

Disadvantages include the initial capital outlay, the outlay required to meet occupational health and safety requirements, the additional on-farm handling required, and the additional site-maintenance requirements. [8]

Pressure testing

- A silo sold as a sealed silo needs to be pressure tested to be sure it's gas-tight.
- It is strongly recommended that growers ask the manufacturer or reseller to quote the AS2628 on the invoice as a means of legal reference to the quality of the silo being paid for.
- Pressure-test sealed silos upon erection, annually and before fumigating by using a five-minute half-life pressure test.
- Maintenance is the key to ensuring a silo purchased as sealable can be sealed and kept gas-tight.

In order to kill grain pests at all stages of their life cycle (egg, larvae, pupae, adult), phosphine gas concentration levels need to reach and remain at 300 parts per million (ppm) for seven days or 200 ppm for 10 days. This can only occur if the gas cannot leak out of the grain-storage space. The only way to determine if the space seals is to conduct a pressure test.

A silo is only truly sealed if it passes a five-minute half-life pressure test according to the Australian Standard AS2628. Often silos are sold as sealed but are not gas-tight—rendering them unsuitable for fumigation.

Even if a silo is sold as 'sealed' it is not sealed until it is proven to be gas-tight with a pressure test.

The term 'sealed' has been used loosely during the past and, in fact, some silos may not have been gas-tight from the day they were constructed.

However, even a silo that was gas-tight to the Australian Standard on construction will deteriorate over time, so it needs annual maintenance to remain gas-tight.

The importance of a gas-tight silo

The Kondinin Group 2009 National Agricultural survey revealed that 85% of respondents had used phosphine at least once during the previous five years and that, of those users, 37% had used phosphine every year for the past five years. A Grains Research and Development Corporation survey during 2010 revealed that only 36% of growers using phosphine applied it correctly, i.e. in a gas-tight, sealed silo (Figure 2). Research shows that fumigating in a storage that does not meet the industry standard does not achieve a high enough concentration of fumigant for long enough to kill pests at all life-cycle stages (Figure 3). For effective phosphine fumigation, a minimum of 300 parts per million (ppm) gas concentration for seven days, or 200 ppm for 10 days, is required. Fumigation trials in silos with small leaks demonstrated that phosphine levels are as low as 3 ppm close to the leaks. In the rest of the silo, gas concentrations are also reduced. [9]

8 J Francis (2006) An analysis of grain storage bags, sealed grain silos and warehousing for storing grain. Holmes Sackett and Associates

9 P Botta, P Burrill and C Newman (2014) Pressure testing sealable silos. Fact sheet. Updated. GRDC, http://storedgrain.com.au/pressure-testing/

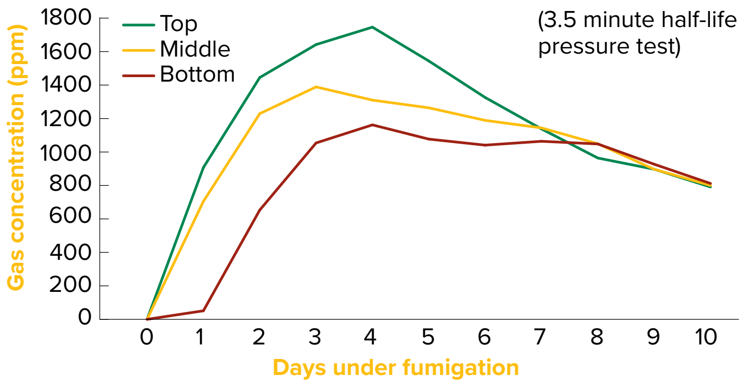


Figure 2: *Gas concentration in gas-tight silo is maintained for long enough to kill pests at all life stages.*

Source: GRDC

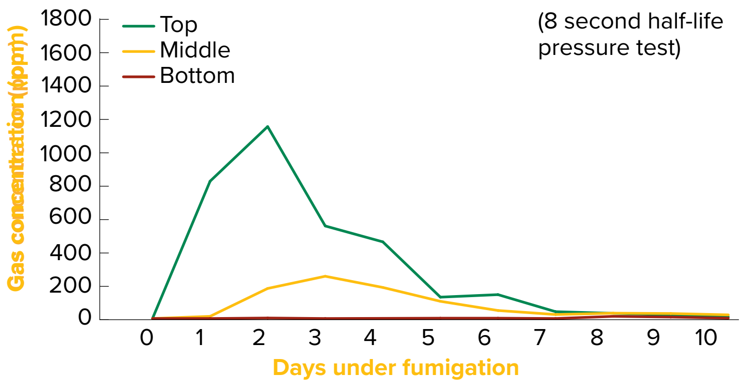


Figure 3: *In a silo that can't be sealed, gas concentration drops quickly and not all insects are killed.*

Source: GRDC

It is recommended that sealable silos be pressure-tested once a year to check for damaged seals on openings.

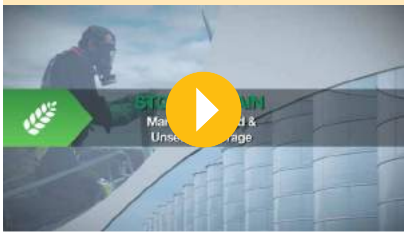
There is no compulsory manufacturing standard for sealed silos in Australia. A voluntary industry standard was adopted in 2010, but not all silo manufacturers have adopted the standard. [10] Watch this GRDC Ground Cover TV clip to find out more.

13.1.2 Grain bags

Grain-storage bags are relatively new technology, and offer a low-cost alternative for the temporary storage of grain. They are made of a multilayer polyethylene material similar to that used in silage-fodder systems. Bags typically store between 200 and 220 tonnes of wheat, and are filled and emptied using specialised machinery (Phot 2). The bags are sealed after filling, creating a relatively airtight environment which, under favourable conditions, protects grain from insect damage without the use of insecticides.

VIDEOS

WATCH: GCTV. Stored grain: Managing sealed and unsealed storage



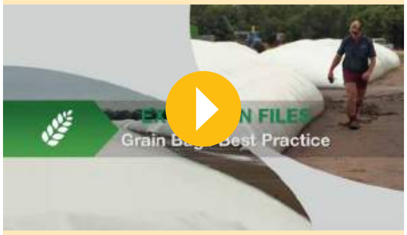
MORE INFORMATION

Fumigating with phosphine, other fumigants and controlled atmospheres

10 GRDC (2010) National standard for sealed silos. GCTV2. GRDC, http://www.youtube.com/watch?v=iS3tUbJZI6U

VIDEOS

WATCH: GCTV extension files: Grain bags—best practice



WATCH: GCTV extension files: Grain bags—a grower's perspective

MORE INFORMATION

Successful storage in grain bags

The advantages of using grain-storage bags include the low capital set-up costs, improved harvest management, less harvest stress, reduced harvest freight requirements, minimal cost to meet occupational health and safety (OH&S) needs, reduced insecticide requirements, and the opportunity to segregate and blend grain.

Disadvantages include the need to dispose of used bags, bag deterioration, and the need to ensure bag integrity. Another disadvantage of this system, compared to longer-term structures such as silos, is that once the grain has been take out of the storage there is no asset value in the storage system other than for the bagging machinery. [11]

Photo 2: *A bag 100 m long can be filled in 30 minutes if there is a constant supply of grain.*

Source: Star Tribune

13.1.3 Monitoring stored grain

Whatever method is used to store grain on the farm, monitoring grain temperature and moisture content should occur regularly:

- Pests and grain moulds thrive in warm, moist conditions. Monitor grain moisture content and temperature to prevent these becoming problems.
- Use a grain-temperature probe to check storage conditions and aeration performance (Photo 3).
- When checking grain, smell the air at the top of storages for signs of high grain moisture or mould.
- Check germination and the vigour of planting seed held in storage.
- Aeration fans can be used to cool and dry grain to reduce storage environment problems.

It is vital to monitor grain moisture content to prevent pests and grain moulds from thriving. [12]

11 J Francis (2006) An analysis of grain storage bags, sealed grain silos and warehousing for storing grain. Holmes Sackett and Associates

12 Plant Health Australia (2015) Monitoring stored grain on farm. Plant Health Australia, http://www.planthealthaustralia.com.au/wp-content/uploads/2017/05/Monitoring-stored-grain-on-farm-2017.pdf

Photo 3: *A digital probe is used to check grain temperature and aeration performance.*

Source: Plant Health Australia

13.1.4 Grain storage: getting the economics right

As growers continue to expand their on-farm grain storage, the question of economic viability gains significance. There are many examples of growers investing in on-farm grain storage and paying if off in one or two years because they struck the market at the right time, but are these examples enough to justify the expansion of on-farm grain storage for all growers?

GRDC's grain-storage extension team conducts approximately 100 grower workshops every year Australia wide, and it's evident that no two growers use on-farm storage in exactly the same way. Like many other economic comparisons in farming, the point at which storage might become viable is different for each grower. Depending on the business's operating style, the location, the resources the farm has and that are needed to install storage, and the factor that most limits profit increases, grain storage may or may not be the next best investment. For this reason, all growers need to do a simple cost–benefit analysis for their operation.

To make a sound financial decision, the grower needs to compare the expected returns from grain storage to expected returns from other farm investments, e.g. buying more land, a chaser bin, a wider boom spray, or a second truck, or paying off debt. They also need to determine if they can store grain on the farm cheaper than paying a bulk handler to store it.

Calculating the costs and benefits of on-farm storage gives the grower a return-on investment (ROI) figure, which can be compared with other investment choices, and a total cost of storage to compare to the bulk handlers.

The key to a useful cost–benefit analysis is identifying which financial benefits to plan for and costing an appropriate storage to suit that plan. People often ask: What's the cheapest form of storage? The answer is the storage that suits the planned benefits: if the farmer is seeking short-term storage for harvest logistics or freight advantages, they might choose grain bags or bunkers; if flexibility is required for longer-term storage, they might choose gas-tight, sealable silos with aeration cooling that allow quality control and insect control.

Benefits and costs

The best way to compare the benefits and costs is to work everything out on the basis of dollars per tonne (Table 2). On the benefit side, most growers will require multiple financial gains for storing grain if they are to make money out of it. These might include harvest logistics or timeliness, taking advantage of market premiums, freight savings, or cleaning, blending, or drying grain to add value.

The costs of grain storage can be broken down into fixed and variable. The fixed costs are those that don't change from year to year and have to be covered over the life of the storage. Examples are depreciation, and the opportunity or interest cost on the capital.

The variable costs are all those that vary with the amount of grain stored and the length of time it's stored for. Interestingly, the costs of good hygiene, aeration cooling and monitoring are relatively low compared to the potential gains the farmer gets back in maintaining grain quality. One of the most significant variable costs, and one that is often overlooked, is the opportunity cost of the stored grain, i.e. the cost of having grain in storage rather than having the money in the bank paying off an overdraft or a term loan.

The result

While it's difficult to put an exact dollar value on each of the potential benefits and costs, a calculated estimate will determine if on-farm storage is worth a more thorough investigation. If the farmer compares the investment in this to other investments and the result is similar, then they can revisit the numbers and work on increasing their accuracy. If the return is not even in the ball park, they've potentially avoided a costly mistake for a small investment in time. On the contrary, if, after checking the numbers, the return is favourable, they can proceed with the investment confidently.

Summary

Unlike a machinery purchase, grain storage is a long-term investment that cannot be easily changed or sold. Based on what the grain storage extension team is seeing around Australia, those growers who take a planned approach to on-farm grain storage and do it well are being rewarded for it. This is because grain buyers seek out growers who have a well-designed storage system that can deliver insect-free, quality grain without delay.

Table 2 is a tool that can be used to figure out the likely economic result of on-farm grain storage for each individual business. Each column can be used to compare various storage options including type of storage, length of time held or paying a bulk handler. [13]

Table 2: *Cost–benefit template for grain storage.*

Financial gains from storage		Example $/t
Harvest logistics/ timeliness	Grain price x reduction in value after damage % x probability of damage %	$16
Marketing	Post-harvest grain price – harvest grain price	
Freight	Peak rate $/t – post-harvest rate $/t	$20
Cleaning to improve grade	Clean grain price – original grain price – cleaning costs – shrinkage	
Blending to lift average grade	Blended price – ((low grade price x %mix) + (high grade price x %mix))	
Total benefits	Sum of benefits	$36.20

13 C Warrick (2016).Grain storage: get the economics right. GRDC Update Paper, GRDC, https://grdc.com.au/Research-and-Development/GRDC-Update-Papers/2016/09/Grain-storage-get-the-economics-right

MORE INFORMATION

Economics of on-farm grain storage: cost–benefit analysis

Economics of on-farm grain storage: a grains industry guide

Grain storage pest control options and storage systems.

VIDEOS

WATCH: Over the Fence: On-farm storage delivers harvest flexibility and profit.

WATCH: Stay safe around grain storage.

Financial gains from storage		Example $/t
Capital cost	Infrastructure cost ÷ storage capacity	$155
Fixed costs		
Annualised depreciation cost	Capital cost $/t ÷ expected life storage, e.g. 25 years	$6.20
Opportunity cost on capital	Capital cost $/t x opportunity or interest rate, e.g. 8% ÷ 2	$6.20
Total fixed costs	Sum of fixed costs	$12.40
Variable costs		
Storage hygiene	(Labour rate $/h x time to clean h ÷ storage capacity) + structural treatment	$0.23
Aeration cooling	Indicatively 23 c for the first 8 days then 18 c per month ÷ t	$0.91
Repairs and maintenance	Estimate e.g. capital cost $/t x 1%	$1.51
Inload/outload time and fuel	Labour rate $/h ÷ 60 minutes ÷ auger rate t/m x 3	$0.88
Time to monitor and manage	Labour rate $/h x total time to manage h ÷ storage capacity	$0.24
Opportunity cost of stored grain	Grain price x opportunity interest rate e.g. 8% ÷ 12 x number of months stored	$7.20
Insect treatment cost	Treatment cost $/t x number of treatments	$0.35
Cost of bags or bunker trap	Price of bag ÷ bag capacity tonne	
Total variable costs	Sum of variable costs	$11.32
Total cost of storage	Total fixed costs + total variable costs	$23.72
Profit/Loss on storage	Total benefits – total costs of storage	$12.48
Return on investment	Profit or loss ÷ capital cost x 100	8.1%

Source: GRDC

13.2 Stored-grain pests

Key points:

- Effective grain hygiene and aeration cooling can overcome 85% of pest problems.
- When fumigation is needed, it must be carried out in pressure-tested, sealed silos.
- Recirculation and ground-level applications have a role in effective, safe fumigation.
- Monitor stored grain monthly (even more regularly if possible) for moisture, temperature and pests.
- Combining good hygiene, well-managed aeration cooling and regular grain inspections provides the best foundation for successful grain storage.
- Darling Downs producers should achieve grain temperatures in storage of 20–23°C during summer storage, and less than 15°C in winter.

13.2.1 Prevention is better than cure

The combination of meticulous grain hygiene and well-managed aeration cooling generally overcomes 85% of storage-pest problems.

For grain storage, three factors provide significant gains for both pest control and grain quality: hygiene, aeration cooling and correct fumigation. [14]

13.2.2 Common species

Cereal grains include rye, wheat, barley, oats, triticale, sorghum and millet. The most common insect pests of stored cereal grains in Australia are:

- weevils *(Sitophilus spp.)—the r*ice weevil is the most common weevil in wheat in Australia
- lesser grain borer *(Rhyzopertha dominica)*
- rust-red flour beetles *(Tribolium spp.)*
- saw-toothed grain beetles *(Oryzaephilus spp.)*
- flat grain beetles *(Cryptolestes spp.)*
- Indian meal moth *(Plodia interpunctella)*
- angoumois grain moth *(Sitotroga cerealella)*

Most of them can be differentiated relatively quickly (Figure 4). [15] Another dozen or so beetles, psocids (booklice) and mites are sometimes present as pests in stored cereal grain.

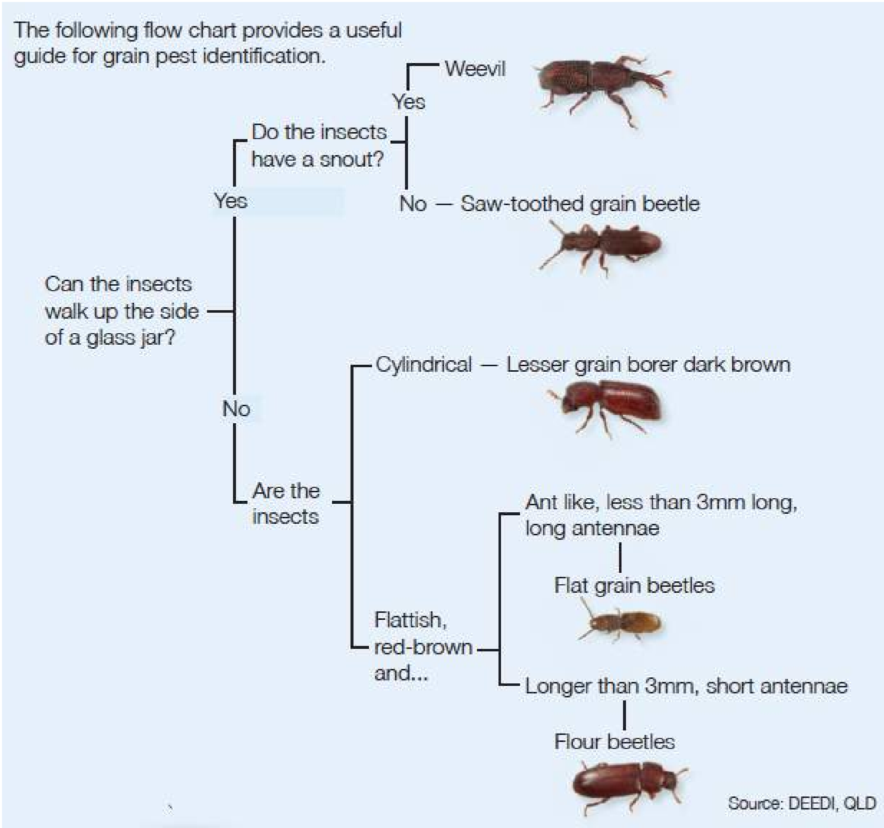


Figure 4: *Identification of common pests of stored grain.*

Source: GRDC.

MORE INFORMATION

Stored grain pests: identification—northern and southern regions

14 Stored Grain Information Hub (2016) Grain storage pest control guide: northern and southern regions. GRDC, http://storedgrain.com.au/pest-control-guide-ns/

15 Plant Health Australia (2015) Monitoring stored grain on farm. Plant Health Australia, http://www.planthealthaustralia.com.au/wp-content/uploads/2015/11/Monitoring-stored-grain-on-farm.pdf. See also GRDC (2011) Stored gain pests identification: the back-pocket guide. GRDC, http://storedgrain.com.au/wp-content/uploads/2013/05/Stored-grain-pests_NorthSouthWest_Pocketguide.pdf

VIDEOS

WATCH: GCTV2: Grain storage insect ID

MORE INFORMATION

Identification of insect pests in stored grain

Stored grain pests identification: the back-pocket guide

Monitoring stored grain on farm

Why identify stored insect grain pests?

Most insect-control methods for stored grain work against all species, so you don't need to identify the storage pests to make decisions about most control methods. But if you intend to spray grain with insecticides you may need to know which species are present if:

- A previous application has failed, and you want to know whether resistance was the reason—if more than one species survived, resistance is unlikely to be the cause.
- You intend to use a residual protectant to treat infested grain—pyrimiphos-methyl, fenitrothion and chlorpyrifos-methyl are ineffective against lesser grain borer, and pyrimiphos-methyl and fenitrothion are generally ineffective against saw-toothed grain beetles.
- You intend using dichlorvos to treat infested grain—if lesser grain borers are present you need to apply the higher dose rate, which increases the withholding period before grain can be marketed from seven days to 28 days.

13.2.3 Monitoring grain for pests

Damage by grain insect pests often goes unnoticed until the grain is removed from storage. Regular monitoring will help to ensure that grain quality is maintained.

- Sample grain in each storage at least monthly. During warmer periods of the year, fortnightly sampling is recommended.
- Take samples from the top and bottom of grain stores and sieve using 2 mm mesh onto a white tray to separate any insects (Photo 4).
- Hold the tray in sunlight for 10–20 seconds to trigger movement of any insects, making them easier to see. Use a magnifying glass to identify them.
- Grain probes or pitfall traps should also be used to check for insects. Traps are left in the grain during storage and are often able to be used to detect the start of an infestation.
- Push the probe or trap into the grain surface, pull up, and inspect for insects. Conduct inspection fortnightly or monthly at most. Place 1–2 traps in the top of a silo or several traps in a grain shed.
- Be sure to check the grain three weeks before sale to allow time for treatment if required. [16]

Photo 4: *A 2 mm mesh sieve will separate insects from grain.*

Source: Plant Health Australia.

16 Plant Health Australia (2015) Monitoring stored grain on farm. Plant Health Australia, http://www.planthealthaustralia.com.au/wp-content/uploads/2017/05/Monitoring-stored-grain-on-farm-2017.pdf

13.2.4 Hygiene

Key points:

- Effective grain hygiene requires the complete removal of all waste grain from storages and equipment.
- Be meticulous with grain hygiene: pests only need a small amount of grain for survival.

In a year, a bag of infested grain can produce more than one million insects, which can walk and fly to other grain storages, where they will start new infestations. Therefore, meticulous grain hygiene is vital. It involves removing any grain that can harbour pests and allow them to breed. It also includes regular inspection of seed and stockfeed grain so that any infestations can be controlled before the pests spread.

Where to clean

Grain pests live in dark, sheltered areas and breed best in warm conditions. They are commonly found in:

- empty silos and grain storages
- aeration ducts, augers and conveyers
- harvesters, field bins and chaser bins
- left-over bags of grain trucks
- spilt grain around grain storages
- equipment and rubbish around storages
- seed grain
- stockfeed grain [17]

Successful grain hygiene involves cleaning all areas where grain gets trapped in storages and equipment (Photo 5). Grain pests can survive in a tiny amount of grain, so any parcel of fresh grain, wherever it is, can become infested, and a source of infestation elsewhere.

Photo 5: *Grain left in trucks is an ideal place for grain pests to breed. Keep trucks, field bins and chaser bins clean.*

Source: GRDC

17 Stored Grain Information Hub (2013) Hygiene and structural treatments for grain storages. Fact sheet. GRDC, http://storedgrain.com.au/hygiene-structural-treatments/

When to clean

Straight after harvest is the best time to clean grain-handling equipment and storages, before insects have a chance to breed. In a trial carried out in Queensland, more than 1,000 lesser grain borers were counted in the first 40 litres of grain through a harvester at the start of harvest—and the harvested had been considered to be reasonably clean at the end of the previous season. Discarding the first few bags of grain at the start of the next harvest is a good idea. Further studies in Queensland revealed that insects are least mobile during the colder months of the year. Farmers can take advantage of this by cleaning around silos in July–August to reduce insect numbers before they become mobile.

How to clean

The better the cleaning job, the less chance there is of pests being harboured. The best ways to get rid of all grain residues use a combination of:

- sweeping
- vacuuming
- compressed air
- blow or vacuum guns
- pressure washers
- fire-fighting hoses

Using a broom or compressed air gets rid of most grain residues (Photo 6), and a follow-up wash-down removes grain and dust left in crevices and hard-to-reach spots. Choose a warm, dry day to wash storages and equipment so they dry out quickly (which helps to prevent rusting). When inspecting empty storages, look for ways to make the structures easier to keep clean. Seal or fill any cracks and crevices to prevent grain lodging there and becoming a harbour for insects. Bags of left-over grain lying around storages and in sheds create a perfect harbour and breeding ground for storage pests. After collecting spilt grain and residues, dispose of them well away from any grain-storage areas.

A concrete slab underneath silos makes cleaning much easier (Photo 7).

Photo 6: *Clean silos, including the silo wall, with air or water to provide a residue-free surface to apply structural treatments.*

Source: GRDC

The process of cleaning on-farm storages and handling equipment should start with the physical removal, blowing out or hosing out of all residues. Once the structure

VIDEOS

WATCH: Grain Silo Hygiene.

MORE INFORMATION

Aeration cooling for pest control

is clean and dry, consider the application of diatomaceous earth (DE) as a structural treatment. (See Section 1.2.4 Structural treatments below for more information.)

Photo 7: *A concrete slab under silo makes cleaning up spilled grain much easier.*

Source: GRDC

13.2.5 Aeration cooling for pest control

While adult insects can survive at low temperatures, most juveniles stop developing at temperatures below 18–20°C (Table 3). At temperatures below 15°C, the common rice weevil stops developing.

At low temperatures insect life cycles (i.e. egg, larvae, pupae and adult) are lengthened from the typical four weeks at warm temperatures (30–35°C) to 12–17 weeks at cooler temperatures (20–23°C). [18] (See Section 13.3.2 Aeration cooling, below, for more information.)

Table 3: *The effect of grain temperature on insects and mould.*

Grain temp (°C)	Insect and mould development	Grain moisture content (%)
40–55	Seed damage occurs, reducing viability	
30–40	Mould and insects are prolific	>18
25–30	Mould and insects are active	13–18
20–25	Mould development is limited	10–13
18–20	Young insects stop developing	9
<15	Most insects stop reproducing, mould stops developing	<8

Source: Kondinin Group

13.2.6 Structural treatments

Key points:

- Structural treatments, such as diatomaceous earth (DE), can be used on storages and equipment to protect against grain pests.
- Check delivery requirements before using chemical treatments.

18 Stored Grain Information Hub (2014) Aeration cooling for pest control. Fact sheet. GRDC, http://storedgrain.com.au/aeration-cooling/

MORE INFORMATION

Hygiene and structural treatments for grain storages

Managing maximum residue limits in export grain

To avoid the high risk of exceeding the maximum residue limits for crops, it is recommended that chemical treatments, even in structural treatments, be avoided for all grains.

A better option is to use diatomaceous earth (DE) also known as inert dust, as a structural treatment. It is important to wash and dry the storage and equipment that has come into contact with DE before using them. This will ensure the DE doesn't discolour the grain surface. Diatomaceous earth is an amorphous silica. (A commonly available commercial formulation is Dryacide®.) DE acts by absorbing the insect's cuticle, or protective waxy exterior, causing death by desiccation. If applied correctly, DE can provide up to 12 months of protection for storages and equipment.

If unsure, check with the grain buyer before using any product that will come in contact with the stored grain. [19]

Applying to silos

Inert dust requires a moving air-stream to direct it onto the surface being treated; alternatively, it can be mixed into a slurry with water and sprayed onto the surface. Read and follow the label directions. Throwing dust into silos by hand will not achieve an even coverage, so will not be effective. For very small grain silos and bins, a hand-operated duster, such as a bellows duster, is suitable. Larger silos and storages require a powered duster operated by compressed air or a fan. If compressed air is available, it is the most economical and suitable option for use on the farm; connected it to a Venturi duster (e.g. the Blovac BV-22 gun) (Photo 8).

Photo 8: *A blower and vacuum gun such as the Venturi gun is the best applicator for inert dusts. Aim for an even coat of diatomaceous earth across the roof, walls and base.*

Photo: C. Warrick, Proadvice

The application rate is calculated at 2 g/m^2 of the surface being treated (Table 4). Although the dust is inert, breathing in excessive amounts of it is not ideal, so use a disposable dust mask and goggles during application.

Apply DE in silos, starting at the top (and following OH&S procedures), and coating the inside of the roof then working your way down the silo walls, and finishing by

VIDEOS

WATCH: GCTV7: Applying diatomaceous earth demonstration

19 Stored Grain Information Hub (2014) Storing Pulses. Fact sheet. Revised. GRDC, http://storedgrain.com.au/storing-pulses/

MORE INFORMATION

Hygiene and structural treatment for grain storages.

pointing the stream at the bottom of the silo. If silos are fitted with aeration systems, distribute the inert dust into the ducting without getting it into the motor, where it could cause damage. [20]

Table 4: *Diatomaceous earth application guide.*

Storage capacity (t)	DE quantity (kg)
20	0.12
56	0.25
112	0.42
224	0.60
450	1.00
900	1.70
1800	2.60

13.2.7 Fumigation

There are a number of chemical options for the control of grain pests in stored cereals (Table 5) [21].

Table 5: *Resistance and efficacy guide for stored-grain insects.*

Treatment and example product	WHP	Lesser grain borer	Rust-red flour beetle	Rice weevil	Saw-toothed grain beetle	Flat grain beetle	Psocids (booklice)	Structural treatments
Grain disinfestants—used on infested grain to control full life cycle (adults, eggs, larvae, pupae)								
Phosphine (Fumitoxin®)[1,3] when used in gas-tight, sealable stores	2	Effective	Effective	Effective	Effective	High-level resistance	Effective	Not registered
Sulfuryl fluoride (ProFume®)[10]	1	Effective	Effective	Effective	Effective	Effective	Not registered	Not registered
Grain protectants—applied postharvest. Poor adult control if applied to infested grain								
Pirimiphos-methyl (Actellic 900®)	nil[2]	Not registered	Effective	Effective	Resistance widespread	Effective	Not registered	Resistant species likely to survive
Fenitrothion (Fenitrothion 1000®)[4, 7]	1–90	Not registered	Effective	Effective	Resistance widespread	Not registered	Not registered	Resistant species likely to survive
Chlorpyrifos-methyl (Reldan Grain Protector®)[5]	Nil[2]	Resistance widespread	Effective	Effective	Resistance widespread	Not registered	Not registered	Resistant species likely to survive
'Combined products' (Reldan Plus IGR Grain Protector)	Nil[2]	Resistance widespread	Effective	Effective	Effective	Not registered	Not registered	Resistant species likely to survive
Deltamethrin (K-Obiol®)[10]	Nil[2]	Effective	Effective	Resistance widespread	Effective	Effective	Not registered	Not registered
Spinosad and Chlorpyrifos-methyl (eg Conserve On-Form™)[9]		Effective	Effective	Effective	Effective	Effective	Not registered	Not registered
Diatomaceous earth, amorphous silica—effective internal structural treatment for storages and equipment. Specific-use grain treatments								
Diatomaceous earth, amorphous silica (Dryacide®)[8]	Nil[2]	Effective	Effective	Effective	Effective	Not registered	Not registered	Effective

Not registered for this pest
High-level resistance in flat grain beetle has been identified, send insects for testing if fumigation failures occur
Resistant species likely to survive this structural treatment for storage and equipment
Resistance widespread (unlikely to be effective)
Effective control

1 Unlikely to be effective in unsealed sites, causing resistance, see label for definitions
2 When used as directed on label
3 Total of (exposure + ventilation + withholding) = 10 to 27 days
4 Nufarm label only
5 Stored grains except malting barley and rice/ stored lupins registration for Victoria only/ not on stored maize destined for export
6 When applied as directed, do not move treated grain for 24 hours
7 Periods of 6–9 months storage including mixture in adulticide (e.g. Fenitrothion at label rate

20 Pulse Australia (2013) Northern Chickpea—Best Management Practices Training Course Manual 2013. Pulse Australia.

21 Stored Grain Information Hub (2016) Grain storage pest control guide—northern and southern regions. Fact sheet. GRDC, http://storedgrain.com.au/wp-content/uploads/2016/10/GSFS-1A_GSPestControl_NS_R3.pdf

8 Do not use on stored maize destined for export, or on grain delivered to bulk-handling authorities
9 Dichlorvos 500 g/L registration only
10 Restricted to licensed fumigators or approved users
11 Restriced to use under permit 14075 only. Unlikely to be practical for use on farm

Source: Registration information courtesy of Pestgenie, APVMA and InfoPest (DEEDI) websites

Source: GRDC

It is important to apply fumigants according to the label instructions. Before applying, also check with your grain buyers or bulk handlers for their requirements. Taking fumigation shortcuts may kill enough adult insects in grain so it passes delivery standards, but if poor fumigation techniques result in failure to kill pests at all stages of their life cycle, grain will soon be reinfested once the larvae and eggs develop.

The repercussions of such practices are detrimental to the grains industry. Grain may be rejected at receival. What's worse, every time a poor fumigation is carried out, insects with some resistance survive, making the chemical less effective in the future.

Photo 9: *Phosphine is widely accepted as having no residue problems.*

Photo: DAF Qld

Fumigation with phosphine is a common component of many integrated pest-control strategies (Figure 13).

While there is some insect resistance to phosphine, it is widely accepted because it causes no residue problems for grain or pulses. The grains industry has adopted a voluntary strategy to manage the build-up of phosphine resistance in pests. Its core recommendations are to limit the number of conventional phosphine fumigations on undisturbed grain to three per year, and to employ a break strategy. [22]

Maximum residue limits

By observing several precautions, growers can ensure that grain coming off their farm is compliant with the maximum pesticide residue limits that apply to Australian exports. Violations of maximum residue limits (MRLs) affect the marketability of Australian grain exports, and consequences may include costs being imposed on exporters and/or growers.

Measures growers need to take to avoid MRL violations are detailed in a new *Grain Marketing and Pesticide Residues* Fact Sheet, produced by the Grains Research

VIDEOS

WATCH: GCTV Stored Grain. Fumigation recirculation.

22 P Collins (2009) Strategy to manage resistance to phosphine in the Australian grain industry. Cooperative Research Centre for National Plant Biosecurity, http://www.graintrade.org.au/sites/default/files/file/NWPGP/NWPGP%202017/Chemical%20Resistence%20Management%20Strategy%20-%20June%202017.pdf

MORE INFORMATION

[Managing MRLs factsheet]

[Fumigating with phosphine, other fumigants and controlled atmospheres]

[Grain fumigation – a guide.]

[Fumigation to control insects in stored grain]

VIDEOS

WATCH: GCTV Stored Grain: Phosphine Dose Rates.

and Development Corporation (GRDC). The Fact Sheet states it is essential that both pre-harvest and post-harvest chemical applications adhere to the Australian Grain Industry Code of Practice, only registered products are used and all label recommendations, including rates and withholding periods, must be observed. Other key points include:

- Trucks or augers that have been used to transport treated seed or fertiliser can be a source of contamination – pay particular attention to storage and transport hygiene;
- Silos that have held treated fertiliser or pickled grain will have dust remnants – these silos either need to be cleaned or designated as non-food grade storage;
- Know the destination of your grain. When signing contracts, check the importing countries' MRLs to determine what pesticides are permitted on a particular crop. [23]

Phosphine application

For effective phosphine fumigation, a minimum of 300 parts per million (ppm) gas concentration for seven days or 200 ppm for 10 days is required. Fumigation trials in silos with small leaks demonstrated that phosphine levels are as low as 3 ppm close to the leaks. The rest of the silo also suffers from reduced gas levels.

Where to apply

Achieve effective fumigation by placing the correct phosphine dose (as directed on the label) onto a tray and hanging it in the headspace of a pressure-tested, sealed silo, or into a ground-level application system if the silo is fitted with recirculation.

Arrange the tablets so that as much surface area as possible is exposed to air; this helps the gas disperse freely throughout the grain stack. Spread the phosphine tablets evenly across trays. Hang bag chains in the head space or roll out flat on the top of the grain so air can freely pass around the tablets as the gas dissipates. Bottom-application facilities must have a passive or active air-circulation system to carry the phosphine gas out of the confined space as it evolves. Without air movement in a confined space, phosphine can become explosive.

Time to kill

To control pests at all life stages and prevent insect resistance, phosphine-gas concentration need to reach 300 parts per million (ppm) for seven days when grain is above 25°C, or 200 ppm for 10 days for grain at 15–25°C. In cooler temperatures, insect activity is slower, so they must be exposed to the gas for longer. [24]

After fumigation, ventilate grain for a minimum of one day with aeration fans running, or five days if no fans are fitted.

A minimum withholding period of two days is required after ventilation before grain can be used for human consumption or stockfeed.

The total time needed for fumigating is 10–17 days.

As a general rule, only keep a silo sealed while carrying out the fumigation (e.g., one to two weeks). After fumigation has been completed, return to aeration cooling to hold the stored grain at a suitable temperature.

Handle with care

Phosphine is a highly toxic gas with potentially fatal consequences if handled incorrectly. As a minimum requirement, the label directs the use of cotton overalls buttoned at the neck and wrist, eye protection, elbow-length PVC gloves, and a breathing respirator with combined dust and gas cartridge.

23 S Watt. (2014). Know your maximum residue limits. https://grdc.com.au/Media-Centre/Media-News/South/2014/07/Know-your-maximum-residue-limits

24 GRDC Stored Grain Information Hub. Grain Fumigation – A guide. http://storedgrain.com.au/fumigation-guide/

Non-chemical treatments

The two non-chemical treatments available both use controlled atmospheres to kill pests. They are:

- carbon dioxide
- nitrogen

Treatment with carbon dioxide (CO_2) involves displacing the oxygen inside a gas-tight silo with CO_2, to create a toxic atmosphere to grain pests. To achieve a complete kill of all the main grain pests at all life stages, CO_2 must be retained at a minimum concentration of 35% for 15 days.

Grain stored under nitrogen (N_2) also provides insect control while preserving grain quality without chemicals. It is safe to use and more environmentally acceptable than CO_2 because of the CO_2's contribution to greenhouse gases. The main operating cost is the capital cost of equipment and electricity. It also produces no residues, so grains can be traded at any time, in contrast to chemical fumigants, which have withholding periods. Insect control with N_2 involves a process using pressure swinging adsorption (PSA) technology, which modifies the atmosphere in the grain storage to remove everything except N_2 , thus starving the pests of oxygen. [25]

13.3 Aeration during storage

13.3.1 Dealing with high-moisture grain

Key points:

- Deal with high-moisture grain promptly.
- Monitoring grain moisture and temperature daily will enable the early detection of mould and insects.
- Aeration drying requires airflow rates in excess of 15 L/s/t.
- Dedicated-batch or continuous-flow dryers are a more reliable way to dry grain than aeration drying in less-than-ideal ambient conditions.

The Queensland Department of Employment, Economic Development and Innovation conducted a trial that revealed that high-moisture grain generates heat when put into a confined storage, such as a silo. Cereal grain with 16.5% MC and a temperature of 28°C was put into a silo with no aeration. Within hours, the grain temperature had reached 39°C, and within two days had reached 46°C, providing ideal conditions for mould growth and grain damage (Figure 5).

Grain that is over the standard safe storage moisture content of 12.5% can be dealt with by:

- Blending—mix high-moisture grain with low-moisture grain, then aerate.
- Aeration cooling—grain of moderate moisture, up to 15% MC, can be held for a short term under aeration cooling until drying equipment is available.
- Aeration drying—use large volumes of air to force a drying front through the grain in storage, to slowly remove moisture. Supplementary heating can be added.
- Continuous flow drying—grain is transferred through a dryer, which uses a high volume of heated air to pass through a continuous flow of grain.
- Batch drying—usually a transportable trailer dries 10–20 tonnes of grain at a time, using a high volume of heated air, which passes through the grain and out through perforated walls.

25 C Warrick (2011) Fumigating with phosphine, other fumigants and controlled atmospheres: Do it right—do it once. A Grains Industry Guide. GRDC, https://grdc.com.au/__data/assets/pdf_file/0025/206791/fumigating-with-phosphine.pdf.pdf

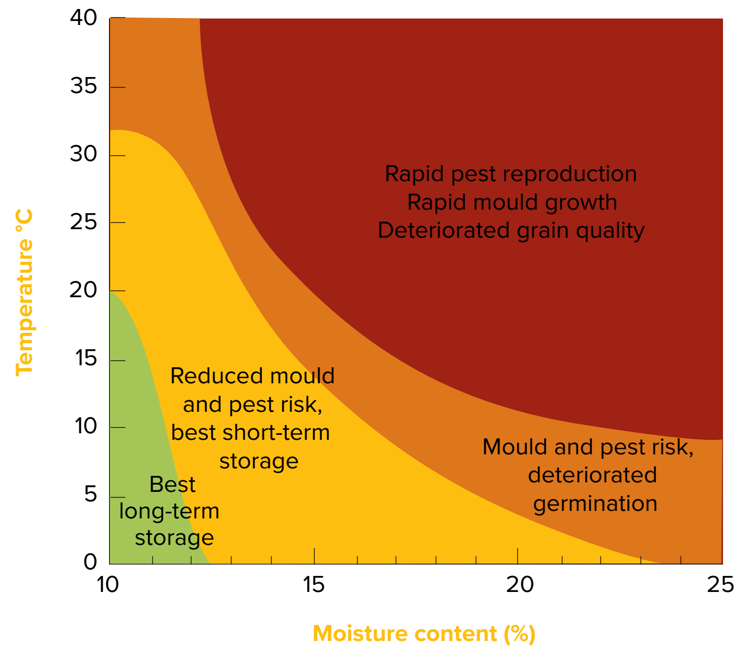


Figure 5: *Effects of temperature and moisture on stored grain.*

Source: CSIRO Ecosystems Sciences

13.3.2 Aeration cooling

Key points:

- Grain temperatures below 20°C significantly reduce mould and insect development.
- Reducing grain temperature with aeration cooling protects seed viability.
- Controlling aeration cooling is a three-stage process: continuous, rapid, and then maintenance.
- Stop aeration if ambient, relative humidity exceeds 85%.
- Automatic grain-aeration controllers that select optimum fan running times provide the most reliable results.

Aeration cooling can be used to reduce the risk of mould and insect development for a month or two until drying equipment is available to dry grain down to a safe level for long-term storage or delivery. In most circumstances, grain can be stored safely at up to 14–15% MC with aeration cooling fans running continuously, and delivering at least 2–3 L/s/t. It is important to keep fans running continuously for the entire period, only stopping them if the ambient relative humidity is above 85% for more than about 12 hours. If aeration fans run for longer than this in humid weather, they will cause the grain to become wet.

Blending

Blending is the principle of mixing slightly over-moist grain with lower-moisture grain to achieve an average moisture content below the ideal of 12.5%. It is a successful technique for grain moisture content levels up to 13.5%, and can be an inexpensive way of dealing with wet grain, providing the infrastructure is available. Aeration cooling does allow blending in layers, but if aeration cooling is not available blending must be evenly distributed (see Figure 6). [26]

26 Stored Grain Information Hub (2013) Dealing with high moisture grain. Fact sheet. GRDC, http://storedgrain.com.au/dealing-with-high-moisture-grain/

VIDEOS

WATCH: GCTV2: Grain storage cooling aeration

MORE INFORMATION

GRDC Aerating stored grain: Cooling or drying for quality control.

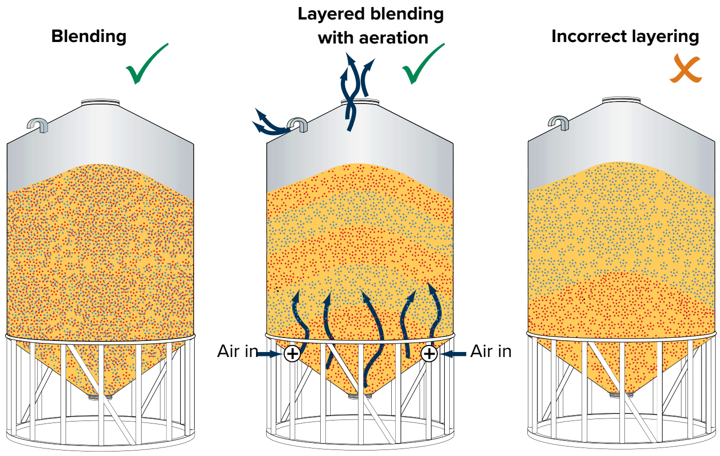


Figure 6: *Diagram demonstrating the correct practices for blending.*

Source: Kondinin Group

Seed viability

Research trials reveal that wheat at 12% MC stored for six months at 30–35°C (unaerated grain temperature) will have reduced germination percentage and seedling vigour.

13.3.3 Aeration drying

Aeration drying relies on high air volume and is usually done in a purpose-built drying silo or a partly filled silo with high-capacity aeration fans. It is a slow process and relies on having:

- high airflow rates
- well-designed ducting for even airflow through the grain
- exhaust vents in the silo roof, and
- warm, dry weather conditions.

It is important to seek reliable advice on equipment requirements and the correct management of fan running times, otherwise there is a high risk of damaging the grain, to the detriment of quality.

High airflow for drying

Unlike aeration cooling, aeration drying requires high airflow, in excess of 15 L/s/t, to move drying fronts quickly through the whole grain profile and depth to carry moisture out of the grain bulk. As air passes through the grain, it collects moisture and forms a drying front. If the airflow is too low, the drying front will take too long to reach the top of the grain stack; this is often referred to as a 'stalled drying front'. Providing the storage has sufficient aeration ducting, a drying front can pass through a shallow stack of grain much faster than a deep stack. As air will take the path of least resistance, make sure the grain is spread to an even depth.

Ducting for drying

The way to avoid hot spots is with adequate ducting to deliver an evenly distributed flow of air through the entire grain stack (Photo 10). A flat-bottomed silo with a full floor-aeration plenum is ideal providing it can deliver at least 15 L/s/t of airflow. The silo may only be able to be part filled, which in many cases is better than trying to dry grain in a cone-bottomed silo with insufficient ducting.

Photo 10: *A flat-bottomed silo designed for aeration drying.*

Source: GRDC

Venting for drying

Adequate ventilation maximises airflow and allows moisture to escape rather than forming condensation on the underside of the roof and wetting the grain on the top of the stack. The amount of moisture that has to be able to escape with the exhaust air is 10 L for every 1% MC removed per tonne of grain.

Weather conditions for drying

For moisture transfer (i.e. drying) to occur, air with a lower relative humidity than the grain's equilibrium moisture content must be used. For example, wheat at 25°C and 14% MC has an equilibrium point of the air around it at 70% relative humidity (Table 6). In order to dry this wheat from its current state, the aeration drying fans would need to be turned on when the ambient air was below 70% relative humidity.

Table 6: *Equilibrium moisture content for wheat.*

Relative humidity (%)	Temperature 15	25	35
	Grain moisture content %)		
30	9.8	9.0	8.5
40	11.0	10.3	9.7
50	12.1	11.4	10.7
60	13.4	12.8	12.0
70	15.0	14.0	13.5

Note: values may be different for rye grain.

Source: GRDC

Phase one of drying

Aeration drying fans can be turned on as soon as the aeration ducting is covered with grain. They are left running continuously until the air coming out of the top of the storage has a clean, fresh smell. The only time drying fans are to be turned off during this phase is if ambient air exceeds 85% relative humidity for more than a few hours.

Phase two of drying

By monitoring the temperature and moisture content of the grain, and referring to an equilibrium moisture table, such as Table 6, a suitable relative-humidity trigger point can be set. As the grain dries the equilibrium point will fall, so the relative-humidity trigger point will need to be reduced to dry down the grain further.

Reducing the relative-humidity trigger point slowly during phase two will help keep the difference in grain moisture from the bottom to the top of the stack to a minimum, by ensuring the fans get adequate running time to push each drying front through the entire grain stack.

Supplementary heating

Heat can be added to aeration drying in proportion to the airflow rate. Higher airflow rates allow more heat to be added as it will push each drying front through the storage fast enough to avoid overheating the grain close to the aeration ducting. As a general guide to avoid overheating this grain, inlet air shouldn't exceed 35°C.

Cooling after drying

Regardless of whether supplementary heat is added during the process, the grain should be cooled immediately after it has been dried to the desired level. [27]

13.3.4 Aeration controllers

Aeration controllers manage aeration drying, cooling and maintenance functions in up to 10 storages (Photo 11). The unit takes into account the moisture content and temperature of grain at loading and the desired grain condition after time in storage, and selects appropriate settings to achieve safe storage levels. [28]

Research carried out by the then Department of Agriculture, Fisheries and Forestry Queensland showed that, with the support of a controller, aeration can rapidly reduce stored-grain temperatures to a level that helps maintain grain quality and inhibits insect development.

During trials where grain was harvested at 30°C and 15.5% MC, grain temperatures rose to 40°C within hours of being put into storage. An aeration controller was used to rapidly cool grain to 20°C, and then hold it between 17°C and 24°C from November to March.

To replicate these results on the farm, growers need to:

- Know the capacity of their existing aeration system.
- Determine whether grain requires drying before cooling can be carried out.
- Understand the effects of relative humidity and temperature when aerating stored grain.
- Determine the target conditions for the stored grain.

VIDEOS

WATCH: GCTV5: Aeration drying—getting it right

MORE INFORMATION

Dealing with high moisture grain

27 Stored Grain Information Hub (2013) Dealing with high moisture grain. Fact sheet. GRDC, http://storedgrain.com.au/dealing-with-high-moisture-grain/

28 GRDC (2007) New generation aeration controller. Ground Cover. Issue 57. GRDC, https://grdc.com.au/Media-Centre/Ground-Cover-Supplements/Ground-Cover-Issue-57-Grain-Storage-Supplement/New-generation-aeration-controller

VIDEOS

WATCH: Grain storage with Phillip Burrill—using aeration controllers.

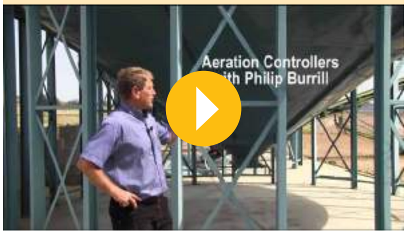


Photo 11: *Automatic aeration controllers such as this one are not only the most effective way to cool grain, one unit can manage up to 10 storages.*

Source: GRDC

13.4 Grain protectants for storage

The widespread resistance of the lesser grain borer (*Rhyzopertha dominica*) to grain protectants is being halted with the availability of deltamethrin (e.g. K-Obiol® EC Combi) and spinosad (e.g. Conserve™ On-Farm) products for use on farms.

13.4.1 K-Obiol® EC Combi

K-Obiol® EC Combi is a synergised grain protectant for use on cereal grains, malting barley and sorghum. [29] It can be used in any type of storage, sealed or unsealed. It is suitable for use by grain growers and grain accumulators. Like all protectants it is a liquid and must be evenly applied as a dilution to the grain as it is fed into the storage. It is for use on un-infested grain and is not recommended for eradicating insect pests when they have infested grain.

The active constituent is deltamethrin. [30] Piperonyl butoxide is added as a synergist; i.e. it increases the effectiveness of the deltamethrin. Because the product is based on deltamethrin, there are none of the insect-resistance problems that growers and bulk handlers have with other protectants.

Because protectants are residual, grain end-users will be concerned to ensure that the grain does not contain excessive levels of chemicals. This would normally come about from incorrect treatment or double treatment as the grain moves along the supply chain. To protect the end-user, and ultimately Australian grain growers, a product stewardship program has been developed to ensure the correct use of the product. The program also aims to ensure the product is used in the way that minimises the development of insect resistance and increases it usable life. [31]

13.4.2 Conserve™ On-farm

Conserve™ On-Farm_is a grain protectant from Dow AgroSciences that has three active ingredients to control most major insect pests of stored grain, including the resistant lesser grain borer (LGB). [32] It provides six to nine months of control and has

29 Stored Grain Information Hub (n.d.) K-Obiol Combi. GRDC, http://storedgrain.com.au/k-obiol-combi/

30 Bayer (n.d.) Welcome to K-Obiol. Bayer, http://www.k-obiol.com.au/

31 GRDC Stored Grain information hub. K-Obiol Combi. http://storedgrain.com.au/k-obiol-combi/

32 Dow AgroSciences (n.d.) Conserve™ On-Farm, Conserve™ Plus. Dow AgroSciences, http://www.conserveonfarm.com.au/en

no withholding period (WHP). Maximum residue limits (MRLs) have been established with key trading partners and there are no meat-residue bioaccumulation problems.

Conserve™ On-Farm is a combination product of two parts that are mixed before application. Using Part A and Part B together is very important to get control of the complete spectrum of insects. They comprise:

- Part A, 1 x 5 L of chlorpyrifos-methyl and S-methoprene—controls all stored grain insect pests other than the resistant lesser grain borer (*Rhyzopertha dominica*)
- Part B, 2 x 1 L of spinosad—is very effective on the lesser grain borer, including resistant strains, but has little to no activity on other key species. [33]

33 Stored Grain Information Hub (n.d.) Conserve. GRDC, http://storedgrain.com.au/conserve-farm/

Environmental issues

Key messages

- Rye can withstand sandblasting and is more tolerant of drought and frost than other cereals.
- Rye is less sensitive to frost and more sensitive to hot weather than oats and barley.
- Rye is the most productive of the cereal grain crops under conditions of low temperature, low fertility and drought.
- Rye can tolerate acid soils better than wheat, barley or canola. Cereal rye is thought to be relatively tolerant of saline soils, similar to barley, but will be affected in highly saline soils (8-16 ECe (dS/m)).

14.1 Frost issues for cereal rye

Key points:

- Although frost events can have major and sudden impacts on cereal yields (Photo 1), rye is more tolerant of frosts than other cereals.
- Frost is a relatively rare occurrence but some areas are more prone to it.
- There has been an increase in frost frequency in many areas in the last 20 years—and a decrease in other areas.
- In the event of severe frost, monitoring needs to occur up to two weeks after the event to detect all the damage. [1]
- Cereal rye is one of the least susceptible cereals to frost, and is renowned for its tolerance to cold. Crop susceptibility to frost from most to least susceptible is triticale, wheat, barley, cereal rye, and oats. [2]
- Flowering about two weeks later than SA Commercial, Bevy is less prone to frost, which often affected yields of the SA Commercial variety. [3]

1 D Grey (2014) Frost damage in crops: where to from here? GRDC Update Paper. GRDC, https://grdc.com.au/Research-and-Development/GRDC-Update-Papers/2014/03/Frost-damage-in-crops-where-to-from-here

2 GRDC (2009) Managing the risk of frost. Fact sheet. GRDC, https://grdc.com.au/__data/assets/pdf_file/0020/202826/frost-factsheet.pdf.pdf

3 Agriculture Victoria (2013) Growing cereal rye. Note AG0403. Updated. Agriculture Victoria, http://agriculture.vic.gov.au/agriculture/grains-and-other-crops/crop-production/growing-cereal-rye

Photo 1: *Cereal heads showing frost damage.*

Source: DAFWA

VIDEOS

WATCH: Plant frost mechanisms with Glenn McDonald

Rye is the most frost-tolerant cereal species. During winters it can survive intense frosts. Winter hardiness is a complex feature that involves resistance to the cold and to damping. Frost tolerance may be increased by land treatment e.g. melioration, high quality of tillage and timely sowing. Cold-resistant rye plants have some typical morphological and biological features: they have narrow and short rosette leaves with a microcellular structure, spreading bushes, a thicker outer epidermis wall, a short mesocytyl, and therefore, a deeper tillering node. Frost-resistant plants grow more slowly in autumn, and have a relatively higher concentration of dry matter in their cell sap. They expend this in their growth processes and respiration in a more economical way than other plants.

Cold temperatures induce cold-tolerance and antifreeze activity in rye. Antifreeze proteins are found in a wide range of overwintering plants; they work by inhibiting the growth and recrystillisation of ice that forms in intercellular spaces. In rye, antifreeze proteins accumulate in response to cold, short days, dehydration and ethylene. [4]

Clear, calm and dry nights following cold days are the precursor conditions for a radiation frost (or hoar frost). These conditions most often occur during winter and spring where high-pressure air masses follow a cold front, bringing cold air from the Southern Ocean and settled, cloudless weather (Figure 1). A frost occurs when daytime heat is lost from the earth during the night, and the temperature at ground level reaches 0°C. Wind and cloud reduce the likelihood of frost by decreasing the loss of heat to the atmosphere. The extent of frost damage is determined by how quickly the temperature drops to zero, the length of time its stays below zero, and the how far below zero it gets.

4 H Domanska (1960) The influence of the autumn and spring drought on the development of winter rye and barley. Rocz Nauk Rolniczych Ser. A, 229–241, http://eurekamag.com/research/014/254/014254711.php

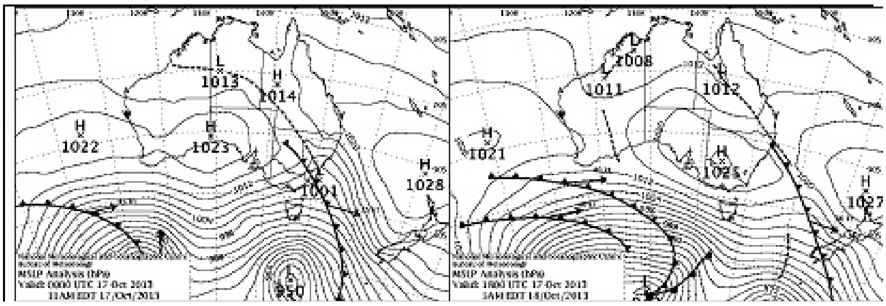


Figure 1: *A cold front passes through, injecting cold air from the Southern Ocean the day before frost (left). Overnight the high pressure system stabilises over SE Australia, bringing clear skies and no wind, and leading to a frost (right).*

Source: GRDC

Though temperatures generally (particularly those in winter and spring) are getting warmer, frost is still a major concern. The pattern of its occurrence seems to be changing. CSIRO researchers have found that, in some areas of Australia, the number of frost events are increasing (and are greatest in August). However, the crop-growing areas of central western NSW, the Eyre Peninsula, Esperance, and the northern Victorian Mallee have been less affected by frost in the period 1961–2010. This increase in frost events seen in areas of northern NSW and elsewhere (Figure 2), is thought to be caused by the latitude of the sub-tropical ridge of high pressure drifting south (causing more stable pressure systems), and the existence of more El Niño conditions during this period. [5]

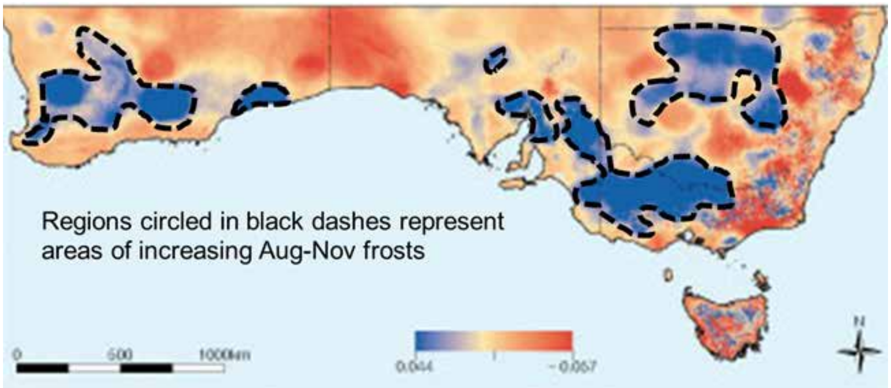


Figure 2: *Region of increasing August–November frost events.*

Source: GRDC

14.1.1 Diagnosing stem and head frost damage in cereals

In the paddock

- Symptoms may not be obvious until 5 to 7 days after the frost.
- Heads on affected areas have a dull appearance that becomes paler as frosted tissue dies.
- At crop maturity, severely frosted areas remain green for longer.
- At harvest, severely frosted crops crop have a dirty appearance due to blackened heads and stems and discoloured leaves.

In the plant

- Before flowering:

VIDEOS

WATCH: GCTV20: Frost's emotional impact—is it greater than its economic impact?

5 D Grey (2014) Frost damage in crops: where to from here? GRDC Update Paper. GRDC, https://grdc.com.au/Research-and-Development/GRDC-Update-Papers/2014/03/Frost-damage-in-crops-where-to-from-here

- Freezing of the emerging head by cold air or water is caught next to the flag leaf, or travels down the awns into the boot. Individual florets or the whole head can be bleached and shrivelled, stopping grain formation. Surviving florets will form normally.
- Stem frost by a small amount of water that has settled in the boot and frozen around the peduncle shows in paleness or discolouration and roughness at the affected point on the peduncle, and blistering or cracking of nodes and leaf sheath. Stems may be distorted.
- Flowering head:
- The ovary in frosted flowers is 'spongy' when squeezed, and turns dark. (In normal flowers the ovary is bright white and 'crisp' when squeezed.)
- Anthers are dull coloured and are often banana shaped. As the grain develops it turns green. Anthers are green to yellow before flowering, and yellow, turning white, after flowering
- Grain:
- At the milk stage, frosted grain is white, turning brown, with a crimped appearance. It is usually spongy when squeezed, and doesn't exude milk (or dough). (Healthy grain is light to dark green and plump, and exudes white milk or dough when squeezed (Photo 2). [6])
- At the dough stage, frosted grain is shrivelled and creased along the long axis, rather as if a pair of pliers has crimped the grain (Photo 3). [7]

Photo 2: *A normal cereal head (left) compared to frost-damaged cereal showing discoloured glumes and awns.*

Source: DAFWA

6 DAFWA (2015) Diagnosing stem and head frost damage in cereals. DAFWA, https://www.agric.wa.gov.au/mycrop/diagnosing-stem-and-head-frost-damage-cereals

7 J Christopher, B Zheng, S Chapman, A Borrell, T Frederiks and K Chenu (2016) An analysis of frost impact plus guidelines to reduce frost risk and assess frost damage. GRDC Update Paper. GRDC, https://grdc.com.au/Research-and-Development/GRDC-Update-Papers/2016/07/An-analysis-of-frost-impact-plus-guidelines-to-reduce-frost-risk-and-assess-frost-damage

VIDEOS

WATCH: GCTV15: Frost ratings

WATCH: GCTV15: The frost ranking challenge

WATCH: GCTV12: Frost susceptibility ranked

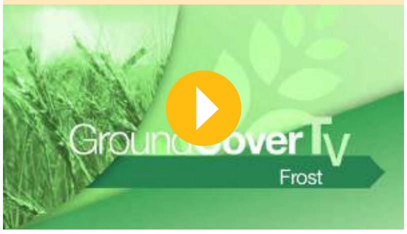


Figure 3: *The typical crimped look of frosted grain.*

Source: GRDC

IN FOCUS

New insight into managing for frost in a changing climate

- Growers need to consider carefully whether earlier sowing is justified in seasons where warmer temperatures are predicted.
- Warmer temperatures may reduce the frequency of frosts, but they also increase the rate of crop development bringing crops to the susceptible, post-heading stages earlier.
- Situation analysis of national frost impact indicates substantial losses in all regions, with an average of approximately 10%.
- In the northern region, losses were much higher, between 23% and 38%, due to late sowing.
- These results indicate that, despite increasing temperatures overall, continued research into reducing frost risk remains a high priority.
- Variety guides and decision-support software are useful for matching cultivars to sowing opportunities.
- Current variety ratings based on floret damage may not provide a useful guide to frost damage to heads and stems.
- Crops are most susceptible to frost once awns emerge.
- If crop temperature at canopy height drops below –3.5°C after the awns emerge, crops should be assessed for damage.
- To spread risk, consider multiple sowing dates and/or crops of different phenology.

The first nationwide assessment of the comparative impact of frost in different Australian cropping regions provides important insights into how to manage frost risk.

In a GRDC-funded project, climate data from 1957–2013 were used to assess the frequency and severity of frosts in each region of the Australian cropping belt. [8] Night-time minimum temperatures were observed to have increased over much of the Australian cropping region during that period. However, when the researchers analysed the data, it showed that neither the risk nor the impact of frost was reduced over the whole cropping area. It turned out that warmer temperatures accelerate plant development, causing crops to develop to the frost-susceptible, heading stages more rapidly. So, counterintuitively, planting earlier or even at the conventional date during warmer seasons may sometimes increase frost risk.

The researchers used historic climate data from a grid database at 60 locations in the four major cropping regions of Australia to determine the frequency and severity of frosts (Figure 4, top). They used the modelling program Agricultural Production Systems sIMulator (APSIM) to estimate crop yields, and expert knowledge and data from frost trials to estimate crop losses (Figure 4, bottom). The computer simulation allowed them to use this data to predict crop losses, and also potential yields. For the yields, the researchers used sowing dates optimised for yield in the hypothetical absence of frost risk, something that had not previously been achieved experimentally.

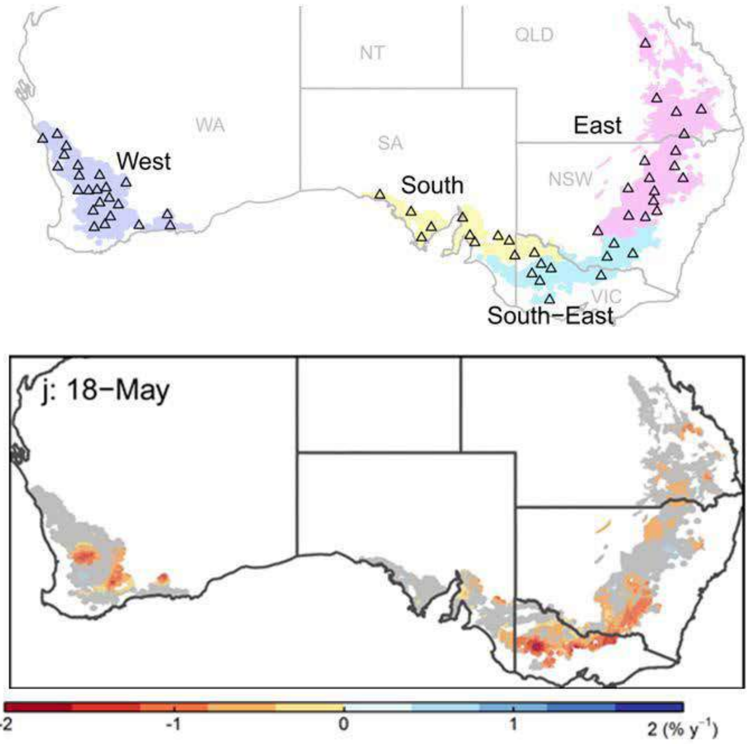


Figure 4: *Maps showing sites and regions for which climate data were analysed for the frequency and severity of frosts (top); and annual percentage change in yield loss due to frost from 1957 to 2013 (bottom). In the bottom panel ,areas coloured yellow, orange and tan are negative values that show where yield loss became worse in recent decades. Estimations in the lower panel were for the cultivar Janz, which was sown on 18 May and are based on a ~5 km x 5 km grid of climatic data. (Gridded climate data may not reflect the climatic conditions of particular paddocks within each grid, as frost is highly variable in an area.)*

Source: GRDC

8 J Christopher, B Zheng, S Chapman, A Borrell, T Frederiks and K Chenu (2016) An analysis of frost impact plus guidelines to reduce frost risk and assess frost damage. GRDC Update Paper. GRDC, https://grdc.com.au/Research-and-Development/GRDC-Update-Papers/2016/07/An-analysis-of-frost-impact-plus-guidelines-to-reduce-frost-risk-and-assess-frost-damage

The researchers estimated that yield losses due to direct frost damage averaged close to 10% nationally for all crop maturity types, when current sowing guidelines were followed (Figure 5).

In many areas, growers must sow late to minimise frost damage. The researchers estimated the loss of yield potential for late-sown crops using a theoretical optimal sowing date (as early as 1 May). When lost yield potential from delayed sowing (indirect cost of frost) is added to direct damage (current best-sowing date), estimated yield losses doubled from 10% to 20% nationally (Figure 5, 'direct + indirect' impact). In the eastern grains region (Queensland to central NSW), losses were even greater, with estimated yield losses due to direct and indirect damage of 34% for early-flowering cultivars, 38% for mid-flowering and 23% for late-flowering cultivars (Figure 5).

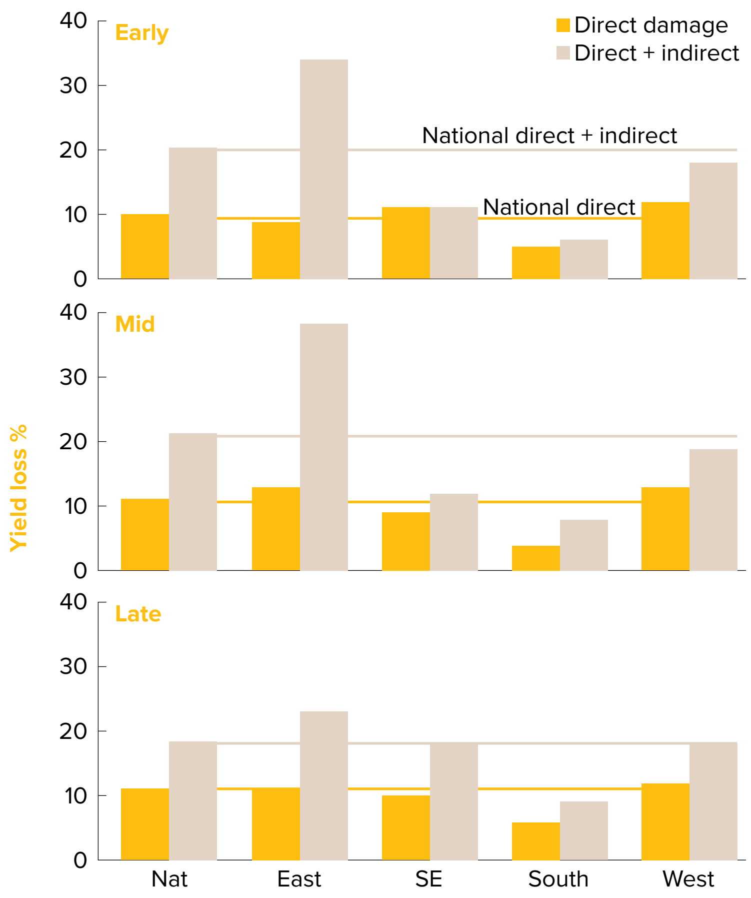


Figure 5: *Estimated wheat yield losses (%) due to frost damage for crops sown at the current best sowing date (labelled 'direct damage'); and crop losses due to both direct damage and delayed sowing currently necessitated to manage frost risks (labelled 'direct + indirect') for early, mid and late flowering crops.*

Source: GRDC

In some areas in each region, simulated frost impact has significantly increased between 1957 and 2013 (yellow, orange and tan areas, Figure 5, bottom panel). The estimated date of last frost has changed to later in some areas and earlier in others. However, even in areas where it now comes significantly earlier, higher temperatures have also increased the rate of development to the heading stage, when the crop is more susceptible to frost. The modelling suggests that crop-heading dates have been brought forward more rapidly than the date of last frost, leading to an overall increase (in the model) in frost impact in many areas. This may actually increase the risk of frost.

Counterintuitively, yield losses were greatest in the northern grains region, with the greatest yield losses actually due to delayed sowing rather than frost per se.

These trends may force growers to change planting decisions. Sowing early to increase yield potential may now not always be the best course of action in warmer seasons, even when a lower frequency of frost events is anticipated.

These results indicate that continued research to reduce frost risk remains a high priority, despite increasing temperatures due to climate change.

Guidelines to reduce frost risk

Match variety to planting opportunity

The current best strategy for maximising long-term crop yields is to aim for crop heading, flowering and grainfilling to be completed in the short window of opportunity between the end of the main frost risk and before day-time maximum temperatures become too high.Of course, planting in this window does not guarantee that crop loss due to frost will be averted; nor does it always prevent drastic yield reduction due to late-season heat and drought stress. However, planting a variety too early can leave growers with a very high probability of crop loss.

Seasonal temperature variations mean that the days to flowering for each variety will change from season to season. It is essential that varieties are sown within the correct window for the district as outlined in variety guides.

Current variety ratings based on floret damage may not be a useful guide, as floret-damage ratings are yet to be correlated with more significant head- and stem-damaging frosts.

Measure crop temperature accurately

In-crop temperature measurements are useful to determine whether a crop may have been exposed to damaging temperatures. A historic comparison of on-farm and district minimum temperatures also allows growers to fine-tune management recommendations for their district to better suit their particular property, and even individual paddocks. District recommendations are based on one, or at best a few, sites, in each district and may not reflect the conditions of individual properties; thus, in many instances, the recommendations likely err on the side of caution.

Stevenson screen temperatures measured at Bureau of Meteorology stations do not fully explain frost risk, either. In crops, the temperature can vary by several degrees from that measured in the screen. On nights when still, cold air, clear skies, and low humidity combine, temperatures can drop rapidly, resulting in radiant frost (Figure 6). The crop temperatures recorded can vary widely due to differences in topography, micro-environment and recording method.

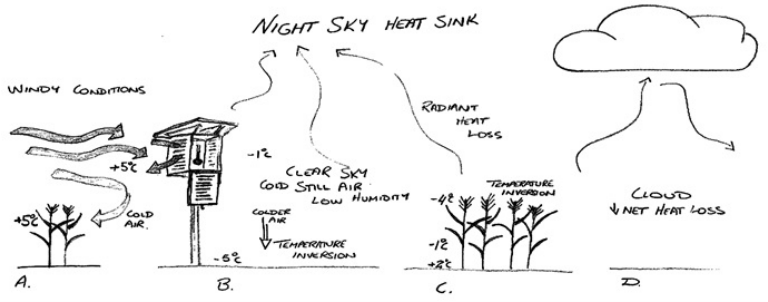


Figure 6: *If clear skies and still, cold, dry air coincide, heat can be lost rapidly to the night sky, resulting in a radiant frost. Minimum air temperatures measured at head height can be several degrees colder than those recorded in screened boxes. Some indicative temperatures are illustrated for (A) windy conditions, (B) clear, still conditions in an open area, (C) clear, still conditions in a cropping area, and (D) cloudy conditions.*

Measurements taken using exposed thermometers at canopy height (Photo 3) give a much more accurate indication of the likelihood of crop damage. [9]

Photo 3: *Canopy temperature measured using a calibrated minimum/maximum thermometer. For best results, a minimum of two or three field thermometers are required to give representative temperatures for a crop. In undulating country, more thermometers should be used to record temperatures at various heights in the landscape.*

Source: GRDC

9 J Christopher, B Zheng, S Chapman, A Borrell, T Frederiks and K Chenu (2016) An analysis of frost impact plus guidelines to reduce frost risk and assess frost damage. GRDC Update Paper. GRDC, https://grdc.com.au/Research-and-Development/GRDC-Update-Papers/2016/07/An-analysis-of-frost-impact-plus-guidelines-to-reduce-frost-risk-and-assess-frost-damage

14.1.2 Managing frost risk

Key points:

- In some areas the risk of frost has increased due to widening of the frost event window and changes in grower practices.
- The risk, incidence and severity of frost varies between and within years, as well as across landscapes, so growers need to assess their individual situation regularly.
- Frosts generally occur when nights are clear and calm, and follow cold days. These conditions occur most often during winter and spring.
- The occurrence of frost and the damage it causes to grain crops are determined by a combination of environmental and management factors including: temperature; humidity; wind; topography; soil type, texture and colour; crop species and variety; and how the crop is managed.
- The greatest losses in grain yield and quality are observed when frosts occur between the booting and grain-ripening stages of growth.
- Frost damage is not always obvious, and crops should be inspected within five to seven days after a suspected frost.
- Methods to deal with the financial and personal impact of frost need to be considered in a farm management plan.
- Careful planning and zoning, and choosing the right crops, are the best options to reduce frost risk. [10]

The variability in the incidence and severity of frost means that growers need to have on hand a number of tactics they can employ as part of their farm-management plan. These include pre-season, in-season, and post-frost actions.

There are two types of pre-season management tactics available to growers:

- at the level of the whole farm; and
- within identified frost zones on a farm.

Farm-management planning tactics

Step 1: Assess personal approach to risk

The first step is to consider your personal approach to risk in your business; every individual will have a different approach. Identify and measure the extent of the risk, evaluate risk-management options, and tailor the risk advice according to individual attitude to risk. The risk of frost can promote conservative farming practices, which should be carefully and regularly reviewed in light of the latest research.

Step 2: Assess frost risk of property

Carefully consider the risk of frost on your property due to its location. Use historical seasonal records and forecasts, and consider spatial variability (topography and soil type) across the farm landscape. Cold air will flow into lower regions. Temperature-monitoring equipment such as Tiny Tags, iButtons and weather stations can determine temperature variability across the landscape.

Step 3: Diversify the business

A range of enterprise options should be considered as part of a farm-management plan to spread financial risk in the event of frost damage. This is subject to the location of the business and skill set of the manager but the largest financial losses with frost have occurred among growers who have a limited range of enterprises or crop types. For example, intensive-cropping systems where the focus is only on canola and spring wheat are often more at the mercy of frost than a diversified business as both crops are highly susceptible to frost damage.

10 GRDC (2016) Managing frost risk: northern and southern regions. Tips and Tactics. GRDC, www.grdc.com.au/ManagingFrostRisk

Step 4: Zone the property and paddocks

Paddocks or areas in paddocks that are prone to frost can be identified through past experience, and the use of precision tools such as topographic, electromagnetic and yield maps, and temperature monitors. Knowing precisely the pattern of frost on a farm can help a grower determine the specific management practice needed to mitigate damage. Be aware that frost-prone paddocks can be high yielding areas on a farm when frosts do not occur.

Frost-zone management tactics

Step 1: Consider use within a zone

The use that frost zones are put to should be carefully considered; for example, using them for grazing, or hay or oat production, so as to avoid large-scale exposure to frost of highly susceptible crops like peas or expensive crops like canola. It may be prudent to sow annual or perennial pastures on areas that frost regularly in order to avoid the high costs of crop production.

Step 2: Review nutrient management

In high-risk paddocks, target the amount of fertiliser (nitrogen, phosphorus, potassium) used and seeding rates to achieve realistic yields that minimise financial exposure, and that simultaneously reduce frost damage, and increase the profitability of the whole paddock over time. Fertiliser not used in these paddocks could be reallocated for use on lower-risk paddocks.

While high nitrogen (N) increases yield potential, it also promotes the production of vegetative biomass and thus increases the susceptibility of the crop to frost. Using conservative N rates at seeding and avoiding late top-ups results in less crop damage.

It is best if crops are not deficient in potassium or copper, as this may increase a crop's susceptibility to frost events. Levels of these elements can be assessed from initial soil tests and with plant-tissue testing. Copper deficiency can be ameliorated with a foliar spray before flowering starts, and as late as the booting stage, to optimise yield, even in the absence of frost. Potassium plays a role in maintaining cell-water content, which may influence a plant's tolerance to frost: it has been shown that plants deficient in potassium are more susceptible to frost. Soils that are deficient in potassium could benefit from an increase in potassium levels at the start of the growing season. However, it is unlikely that there will be a benefit of extra potassium applied to plants that are not potassium-deficient.

Frost tolerance cannot be bought by applying extra potassium or copper to a crop that is not deficient. There is no evidence that applying other micronutrients has any impact to reduce frost damage.

Step 3: Modify soil heat-bank

The soil heat-bank is important element of reducing the risk and severity of frosts (Figure 7). Heat is released from the soil heat-bank more slowly to warm the crop canopy at head height in early morning when frosts are more severe. It is managed by using farming practices that manipulate the storage and release of heat from the soil heat-bank into the crop canopy at night.

VIDEOS

WATCH: Frost initiative: Do micronutrients reduce frost risk?

WATCH: MPCN: Copper and frost relationship investigated

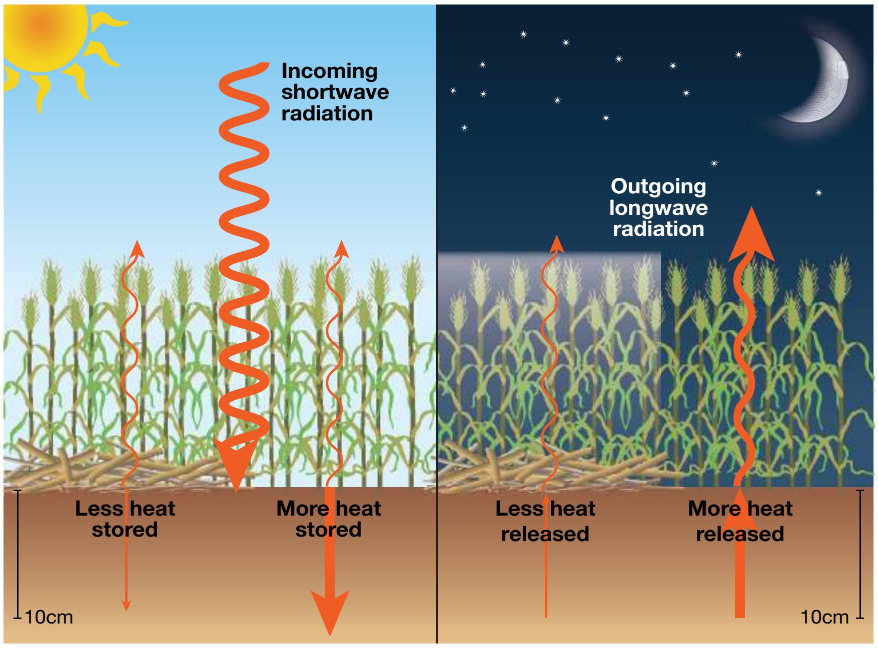


Figure 7: *The role of the soil heat-bank: soil captures heat during the day and radiates it back into the crop canopy overnight. to warm flowering heads and minimise frost damage. A range of farming practices can be utilised to increase the capacity of the soil heat-bank.*

Source: GRDC

Agronomic practices that may assist with storing heat in the soil heat-bank include:

- Practices that alleviate non-wetting sands, such as clay delving, mouldboard ploughing or spading, have multiple effects, including increasing heat storage, nutrient availability and infiltration rate.
- Rolling sandy soil and loamy clay soil after seeding, which also prepares the surface for hay cutting should it be necessary.
- Reducing the amount of stubble—stubble loads above 1.5 t/ha in low-production environments (2–3 t/ha) and 3 t/ha in high-production environments (3–5 t/ha) generally increase the severity and duration of frost events.
- Halving the normal seeding rates, which can reduce frost severity and damage by creating a thinner canopy and more tillers, which results in a spread of flowering time. However, weed competitiveness can be a problem.
- Cross-sowing—crops sown twice with half the seed sown in each direction have a more even plant density. This practice increases sowing costs.

Step 4: Select appropriate crops

Crop selection is an important factor to consider for frost-prone paddocks. There are numerous options available to farmers. For example, crops grown for hay are harvested for biomass, and so avoid the problem of grain loss from frost. Pasture rotations are a lower-risk proposition. Oats are the most frost-tolerant crop during the reproductive stage; barley is more tolerant than wheat at flowering, but it is not known if barley and wheat have different frost tolerance during grainfill. Canola is an expensive crop to risk on frost-prone paddocks, due to the high input costs.

Step 5: Manipulate flowering times

To minimise frost risk there needs to be a mix of sowing dates, crop types and maturity types to be able to incorporate frost avoidance strategies into the cropping system. In years of severe frost, regardless of which strategy is adopted it may be difficult to prevent damage.

When wheat is sown in frost-risk areas, a good tactic is to ensure the flowering window of the cropping program is spread widely. This can be done by using more than one variety and choosing sowing dates and varieties with different phenology drivers so crops flower over a wide window throughout the season. It should be noted that flowering later than the frost may result in lower yields in seasons with hot, dry finishes due to heat and moisture stress.

Staging sowing dates over a 3–6 week period is recommended. If sowing just one variety, this would provide a wide flowering window. If sowing more than one variety: sow winter cereal first, then a long-season spring cereal or a day-length-sensitive cereal, and lastly an early-maturing cereal. This sets the program up for flowering to occur over a two-week period, potentially exposing the crop to more frost risk but maximising the yield potential in the absence of frost. It is possible for crops to be frosted more than once but, flowering over a wide window will probably mean that some crop will be frosted but that losses are reduced.

Sowing time remains a major driver of yield in all crops, with the primary objective being to achieve a balance between crops flowering after the risk of frost has passed and before the onset of heat stress. Farmers who sow at the start of a variety's preferred window will achieve higher yields at the same cost as sowing late. The loss of yield from sowing late to avoid frost risk is often outweighed by the gains from sowing on time to reduce heat and moisture stress in spring.

MORE INFORMATION

Yield Prophet

Flower Power

In some trials, researchers have found that blending a short-season variety with a long-season variety is an effective strategy. However, the same effect can be achieved by sowing one paddock with one variety and a second with another variety to spread risks.

Yield Prophet is a useful tool to match the flowering time of varieties to your own farm conditions.

Step 6: Fine-tune cultivar selection

Cereal rye has relatively good tolerance to frost. When planting other, more susceptible cereals, consider using varieties that have lower susceptibility to frost during flowering to manage frost risk of the cropping program while maximising yield potential. There is no point selecting less-susceptible varieties for the whole cropping program if frost is unlikely, because then there is an opportunity cost of achieving lower yields.

Preliminary information that ranks some of the current cereal varieties for susceptibility to reproductive frost is available from the National Variety Trials website. A new variety should be managed based on how known varieties of similar ranking are managed.

Post-frost management tactics

Once a frost event (especially at or after flowering) has occurred, the first step is to inspect the crop and collect a random sample of heads to estimate the yield loss incurred. In the event of severe frost (Photo 4), monitoring needs to occur for up to two weeks after the event to detect all the damage. After the level of frost damage is estimated the next step is to consider options for the frost damaged crop.

Photo 4: *Severely frosted areas mature later and are often stained or discoloured.*

Source: DAFWA

Option 1: Take through to harvest

If the frost occurs before or around growth stages GS31 and GS32, most cereals can produce new tillers to compensate for damaged plants, provided spring rainfall is adequate. Tillers already formed but lower in the canopy may become important and new tillers can grow after frost damage, depending on the location and severity of the damage. Compensatory tillers will mature later, but where reserves of soil moisture are high, or it is early in the season, they may be able to contribute to grain yield.

A later frost is more concerning, especially for crops such as wheat and barley, as there is less time for compensatory growth. The required grain yield to recover the costs of harvesting should be determined using gross margins.

Option 2: Cut and bale

Cutting and baling is an option when late frosts occur during flowering and through grainfill. Assess crops for hay quality within a few days of a frost event, and be prepared to cut a larger area than had been intended in pre-season planning. Producing hay can also be a good management strategy to reduce stubble, weed seedbank and disease loads for the coming season. This may allow more rotational options in the following season to recover financially from frost, for example to go back with cereal-on-cereal in paddocks cut early for hay. Hay making can be an expensive exercise. Growers should have a clear path to market or a use for the hay on the farm before committing.

MORE INFORMATION

For more information on varietal susceptibility to frost, see the GRDC Update Paper; Ranking cereals for frost susceptibility using frost values: northern.

Managing frost risk: northern, southern and western regions

VIDEOS

WATCH: GCTV3: Frost R&D

WATCH: GCTV16: National Frost Initiative

Option 3: Grazing, manuring and crop-topping

Grazing is an option after a late frost, when there is little or no chance of plants recovering, or when hay is not an option. Spray-topping for weed-seed control may also be incorporated, especially if the paddock will be sown to crop the next year. Ploughing in the green crop returns organic matter and nutrients to the soil, manages crop residues and weeds, and improves soil fertility and structure. The economics need to be considered carefully. [11]

Useful tools

There are numerous useful tools that can help growers decisions about aspects of cropping to maximise yields in frost-prone areas. Among them are:

- Bureau of Meteorology's BOM Weather app
- Plant development and yield apps—MyCrop and Flower Power (both from DAFWA), Yield Prophet (although it does not cover cereal rye)
- Temperature monitors such as Tinytag

National Frost Initiative

Frost has been estimated to cost Australian growers around $360 million in direct and indirect yield losses every year. To help the grains industry minimise the damage frost causes, the GRDC has invested about $13.5 million in more than 60 frost-related projects since 1999. In 2014, it began the National Frost Initiative, to provide the Australian grains industry with targeted research, development and extension solutions to manage the impact of frost and maximise seasonal profit. [12]

The initiative is addressing frost management through multidisciplinary research projects in the following programs:

1. Genetics—developing more frost-tolerant wheat and barley germplasm and ranking current wheat and barley varieties for susceptibility to frost.
2. Management—developing best-practise strategies for crop canopy, stubble, nutrition and agronomic management so growers can minimise the effects of frost; and searching for innovative products that may minimise the impact of frost.
3. Environment—predicting the occurrence, severity and impact of frost events on crop yields and mapping frost events at the farm scale to enable better risk management. [13]

14.2 Waterlogging and flooding issues for cereal rye

Key points:

- Waterlogging occurs when roots cannot respire due to excess water in the soil profile.
- Though cereals can be prone to waterlogging, rye can withstand some degree of waterlogging. [14]
- Water does not have to appear on the surface for waterlogging to be a problem.
- Improving drainage from inundated paddocks can lessen the time that crop roots are subjected to anaerobic conditions.
- While raised beds are the most intensive management strategy, they are also the most effective at improving drainage.
- Waterlogged soils release increased amounts of nitrous oxide (N_2O), a particularly damaging greenhouse gas.

11 GRDC (2016) Managing frost risk: northern, southern and western regions. Tips and Tactics. GRDC, www.grdc.com.au/ManagingFrostRisk

12 T March, S Knights, B Biddulph, F Ogbonnaya, R Maccallum and R Belford (2015) The GRDC National Frost Initiative. GRDC Update Paper. GRDC, https://grdc.com.au/Research-and-Development/GRDC-Update-Papers/2015/02/The-GRDC-National-Frost-Initiative

13 GRDC (2016) Managing frost risk: northern, southern and western regions. Tips and Tactics. GRDC, www.grdc.com.au/ManagingFrostRisk

14 Agriculture Victoria (2013) Growing cereal rye. Note AG0403. Updated. Agriculture Victoria, http://agriculture.vic.gov.au/agriculture/grains-and-other-crops/crop-production/growing-cereal-rye

Waterlogging occurs whenever the soil is so wet that there is insufficient oxygen in the pore spaces between soil particles for plant roots to be able to adequately respire. It commonly happens as a result of floods and periods of unusually high rainfall (Photo 5) or in areas with poorly draining soils. Other gases detrimental to root growth, such as carbon dioxide and ethylene, also accumulate in the root zone and harm plants. As plants differ in their demand for oxygen, there is no one universal level of soil oxygen that can be used to identify when a soil is waterlogged. In addition, a plant's demand for oxygen in the root zone will vary with the stage of growth. [15]

Photo 5: *The 2016 July wet caused waterlogging in crops, like this one at Murrumburrah.*

Source: Harden Murrumburrah Express

14.2.1 Occurrence of waterlogging

Cereals can be sensitive to soil waterlogging, however, many rye cultivars show good tolerance to waterlogged conditions. Rye will grow in heavy clays and poorly drained soils, and many cultivars tolerate waterlogging. [16]

IN FOCUS

Waterlogging and drought tolerances of winter cereals compared

Researchers wanted to quantitatively evaluate the tolerance to waterlogging and drought of the winter cereals hulled barley, naked barley, wheat, rye and oats. They grew these plants under waterlogged (W) and drought (D) conditions from seven weeks after sowing up to maturity. During this time, they measured the growth, dry-matter production and transpiration coefficients, and compared them with those of the same plants grown under moderate soil-moisture (M) conditions.

Plant growth was relatively depressed under both W and D conditions compared with that under M conditions. Naked barley, wheat, rye and oats produced more dry matter of the whole plant under D conditions than under W, while hulled barley produced more dry matter under W conditions than under D. They considered that a crop was stable to W or D conditions when the ratio of its transpiration coefficient under W and D conditions to

15 Soilquality (2016) Waterlogging. Fact sheet. Soilquality, http://soilquality.org.au/factsheets/waterlogging

16 A Clark (ed.) 2007 Rye. In Managing Cover Crops Profitably. 3rd edn. Sustainable Agriculture Network, https://www.sare.org/Learning-Center/Books/Managing-Cover-Crops-Profitably-3rd-Edition

that under M conditions was close to or below 1.0, and was susceptible when the ratio was above 1.0. Therefore, naked barley, wheat, rye and oats were considered to have relatively large drought tolerance capacities (RLDTC), and that hulled barley had relatively large waterlogging tolerance capacities (RLWTC). Among the crops with RLDTC, rye and oats were very susceptible, and naked barley and wheat were relatively susceptible. Hulled barley, which had RLWTC, was stable to W conditions. All of the crops were stable to D conditions. [17]

Where does waterlogging occur?

Waterlogging occurs:

- Where water accumulates in poorly drained areas such as valleys, at the change of slope or below rocks.
- In duplex soils, particularly sandy duplexes with less than 30 cm sand over clay.
- In deeper-sown crops.
- in crops with low levels of nitrogen.
- In very warm conditions when oxygen is more rapidly depleted in the soil. [18]

As well, waterlogging greatly increases crop damage from salinity. Germination and early growth can be much worse on marginally saline areas after waterlogging events.

Identifying problem areas

The best way to identify problem areas is to dig holes about 40 cm deep in winter, and see if water seeps or flows into them (Photo 6). If it does, the soil is waterlogged. Some farmers put slotted PVC pipe into augered holes. They can then monitor the water levels in their paddocks. Digging holes for fence posts often reveals waterlogging.

Symptoms in the crop of waterlogging include:

- Yellowing of crops and pastures.
- The presence of weeds such as toad rush, cotula, dock and Yorkshire fog grass. [19]

17 山内章, 河野恭広, 巽二郎, & 稲垣憲孝 (Yamaneuchi, Kawano Komuro, Tatsurojiro, & Inayaki Hideo.) (1988) Comparison of the capacities of waterlogging and drought tolerances among winter cereals. Japanese Journal of Crop Science. 57 (1), 163–173.

18 DAFWA (2015) Diagnosing waterlogging in cereals. DAFWA, https://www.agric.wa.gov.au/mycrop/diagnosing-waterlogging-cereals

19 Soilquality (2016) Waterlogging. Fact sheet. Soilquality, http://soilquality.org.au/factsheets/waterlogging

Photo 6: *Water fills a hole that has been dug in waterlogged soil.*

Source: Soilquality

14.2.2 Symptoms and causes

Waterlogging occurs when the soil profile or the root zone of a plant becomes saturated. In rain-fed situations, this happens when more rain falls than the soil can absorb or the atmosphere can evaporate.

Lack of oxygen in the root zone of a plant results in anaerobic conditions that cause its root tissues to decompose. Usually this occurs from the tips of roots, and this causes roots to appear as if they have been pruned. The consequence is that the plant's growth and development is stalled. If the anaerobic circumstances continue for long enough the plant will die.

Most often, waterlogging does not last long enough for the plant to die, and once the water drains, the plants recommence respiring. As long as the soil is moist, the older roots close to the surface allow the plant to survive. However, further waterlogging-induced root pruning or dry conditions may weaken the plant to the extent that it will do very poorly and may eventually die.

Many farmers do not realise that a site is waterlogged until water appears on the soil surface. However, by this stage, plant roots may already be damaged and yield potential severely affected.

What to look for in the paddock

- Poor germination or pale plants in water-collecting areas, particularly on shallow duplex soils (Photo 7).
- The presence of wet soil and/or water-loving weeds.
- Early plant senescence in waterlogging-prone areas.

Photo 7: *Pale plants in waterlogged areas.*

Source: DAFWA

What to look for in the plant

- Plants are particularly vulnerable from seeding to tillering, with the seminal roots being more affected than the later-forming nodal roots.
- Waterlogged seed will be swollen and may have burst.
- Seedlings may die before emergence, or be pale and weak.
- Waterlogged plants appear to be nitrogen-deficient with pale plants, poor tillering, and death of the older leaves.
- If waterlogging persists, roots (particularly root tips) cease growing, become brown and then die (Photo 8).
- Seminal roots are important for accessing deep, subsoil moisture. If damaged by waterlogging the plants may be more sensitive to spring drought.

Photo 8: *Waterlogged roots (particularly seminal roots and tips) become brown and then die.*

Source: DAFWA

How can waterlogging be monitored?

- Water levels can be monitored with bores or observation pits, but water tables can vary greatly over short distances so siting needs to be done care.
- Plants can be waterlogged if there is a water table within 30 cm of the surface. There may be no indication at the surface that water is lying in the root zone. Observe plant symptoms and paddock clues, and verify by digging a hole to test for water seepage. [20]

Other impacts of waterlogging and floods

Heat from stagnant water

Stagnant water, particularly if it is shallow, can heat up in hot, sunny weather and may kill plants in a few hours. Remove excess water as soon as possible after flooding to give plants the best chance of survival.

Chemical and biological contaminants

Floodwater may carry contaminants, particularly from off-farm run-off. You should discard all produce, particularly leafy crops, that have been exposed to run-off from beyond the farm.

Make sure you take food-safety precautions, and test soils before replanting, even if crops look healthy. Contaminants will reduce over time with follow-up rainfall and sunny weather.

20 DAFWA (2015) Diagnosing waterlogging in cereals. DAFWA, https://www.agric.wa.gov.au/mycrop/diagnosing-waterlogging-cereals

VIDEOS

WATCH: GCTV3: Big wet—managing strategies after flooding

Iron chlorosis or nitrogen deficiency

Floods and high rainfall can leach essential nutrients from the soil, which can affect plant health. Nutrients such as iron and nitrogen can be replaced by fertilising.

Soils with high clay content

Soils with a high clay content can become compacted and form a crust after heavy rain and flooding. Floodwater also deposits a fine clay layer or crust on top of the soil, and this can prevent oxygen penetrating into the soil (aeration). Clay layers should be broken up and incorporated into the soil profile as soon as possible.

Pests and diseases

Many diseases are more active in wet, humid conditions, and pests can also cause problems. Remove dying or dead plants that may become an entry point for disease organisms or insect pests. Apply suitable disease-control measures as soon as possible, and monitor for pests. [21]

14.2.3 Managing waterlogging

- Sow waterlogging-tolerant crops such as oats and faba beans.
- Sow as early as possible with a higher cereal seeding rate.
- It may be appropriate to build drainage on sandy duplex soils on sloping sites.
- Raised beds are more effective on relatively flat areas and on heavier-textured soils, but areas need to be large enough to justify the machinery costs. [22]
- Reduce the impact of waterlogging through the choice of crop, seeding, fertiliser and weed control.

Drainage is usually the best way of reducing waterlogging. Drain waterlogged soils as quickly as possible, and cultivate between rows to aerate the soil.

Good drainage is essential for maintaining crop health. Wet weather provides a good opportunity to improve the drainage of your crop land, as it allows you to identify and address problem areas.

There are several things you can do to improve crop drainage, immediately and in the longer term.

Drainage problems after flooding

After significant rain or flooding, inspect the crops when it is safe to do so and mark areas (e.g. with coloured pegs) that are affected by poor drainage. If possible, take immediate steps (e.g. by digging drains) to improve the drainage of these areas so that the water can get away.

Irrigation after waterlogging

To avoid recurrence of waterlogging, time irrigation by applying small amounts often until the crop's root system has recovered.

Ways to improve drainage

In the longer term, look for ways to improve the drainage of the affected areas. Options include:

- reshaping the layout of the field
- improving surface drainage
- installing subsurface drainage

21 Queensland Government Business and Industry Portal (2016). Managing risks to waterlogged crops. Queensland Government, https://www.business.qld.gov.au/industry/agriculture/crop-growing/disaster-recovery-for-crop-farming/saving-crops-floods/managing-risks-waterlogged-crops

22 DAFWA (2015) Diagnosing waterlogging in cereals. DAFWA, https://www.agric.wa.gov.au/mycrop/diagnosing-waterlogging-cereals

MORE INFORMATION

Cropping on raised beds in southern NSW

If the drainage can't be improved, consider using the area for some other purpose (e.g. as a silt trap). [23]

Choice of crop species

Some species of grains crop are more tolerant to waterlogging and being flooded than others. Grain legumes and canola are generally more susceptible to waterlogging than cereals and faba beans.

Seeding crops early and using long-season varieties help to avoid crop damage from waterlogging. Damage will be particularly severe if plants are waterlogged between germination and emergence. Plant first those paddocks that are susceptible to waterlogging. However, if waterlogging delays emergence and reduces cereal-plant density to fewer than 50 plants/m^2, resow the crop.

Seeding rates

Increase sowing rates in areas susceptible to waterlogging to give some insurance against uneven germination, and to reduce the dependence on cereal crops on tillering to produce grain. Waterlogging depresses tillering. High sowing rates will also increase the competitiveness of the crop against weeds, which take advantage of stressed crops.

Nitrogen fertiliser

Crops tolerate waterlogging better if they previously had a good nitrogen level. Applying nitrogen at the end of a waterlogging period can be an advantage if nitrogen was applied at or shortly after seeding because it avoids loss by leaching or denitrification. However, as nitrogen cannot usually be applied from vehicles when soils are wet, consider aerial applications.

If waterlogging has been moderate (7–30 days waterlogging of the soil), nitrogen application after waterlogging, when the crop is actively growing again, is recommended where basal nitrogen applications were 0–50 kg of N/ha. However, if waterlogging has been severe (greater than 30 days to the soil surface), the benefits of nitrogen application after waterlogging are questionable. However, this recommendation requires verification in the field at a range of basal nitrogen applications using a selection of varieties.

Weed density affects the ability of a crop to recover from waterlogging. Weeds compete for water and the small amount of remaining nitrogen, hence the waterlogged parts of a paddock are often weedy and require special attention if the yield potential is to be reached. [24]

14.3 Other environmental issues for cereal rye

14.3.1 Drought

Drought is one of the major environmental factors reducing grain production in rain-fed and semi-arid regions. Plants cope with drought stress by manipulating key physiological processes such as photosynthesis, respiration, water relations, antioxidant and hormonal metabolism.

As the most drought resistant of cereals, rye has an extensive root system and adjusts the time it takes to mature to the amount of moisture available (Photo 9). It uses 20–30% less water per unit of dry matter than wheat. Tetraploid varieties are more sensitive to drought than diploids. In Australia's extensive arid regions, rye withstands adverse conditions better than other cereals. Its drought resistance and ability to withstand sand blasts enable it to produce soil-binding cover on land where

23 Queensland Government Business and Industry Portal (2016) Improving drainage of crop land. Queensland Government, https://www.business.qld.gov.au/industry/agriculture/crop-growing/disaster-recovery-for-crop-farming/saving-crops-floods/improving-drainage-crop-land

24 DAFWA (2015) Management to reduce the impact of waterlogging in crops. DAFWA, https://www.agric.wa.gov.au/waterlogging/management-reduce-impact-waterlogging-crops

other cereals will not grow. [25] Under conditions where wheat, oats or barley will grow only a few centimetres high, or may even be blown away, rye often grows vigorously and reaches a height of a metre or more. [26]

Photo 9: *Cereal rye during a drought year: it develops a large root system and less above-ground growth.*

Source: Kauffman Seed

VIDEOS

WATCH: MEF research breaking ground in drought tolerance

Dr Pattison drills into drought tolerance

IN FOCUS

The influence of the autumn and spring drought on the development of winter rye and barley

Researchers reported on their experiments on how autumn soil dryness influenced the development of winter rye and barley. The experiments were carried out in different years. Some plants were grown in the autumn in dry soil (about 25% of water capacity), and were compared with others grown in wetter soil (60% or 70% of the soil water capacity). The first group showed greater resistance against the winter period. The plants dried up in the autumn, but in the spring they grew rapidly and produced higher stems and bigger yields of straw and grain than the plants that had been grown in wetter soil.

They concluded that when drought occurs during gametogenesis (the formation of gametes in the anther and ovule), the sensitivity of plants is not affected by autumn drought. In fact, autumn dryness allows the plants to recover quickly once spring arrives and growth accelerates. In natural conditions, soil dryness is linked with atmospheric dryness, which may cause damage if it is prolonged. However, under normal conditions dry soil stimulates rye and barley to a quicker growth in the depth of the root system, which may make the plants less sensitive to spring-time drought. [27]

25 L Martin (2015) Growing cereal rye to increase carbon and prevent wind erosion. Liebe Group, http://www.liebegroup.org.au/wp-content/uploads/2015/03/Case-Study-Jeff-Pearse-March-2015.pdf

26 RHJ Schlegel (2013) Rye: genetics, breeding, and cultivation. CRC Press, Boca Raton, Florida.

27 H Domanska (1960) The influence of the autumn and spring drought on the development of winter rye and barley. Rocz Nauk Rolniczych. Ser A, 229–241.

Managing drought

Because drought events can be unpredictable and can last for extended periods of unknown length, it is difficult to prepare for them.

In drought, it is important to not ignore the signs and to have a plan, act early, review and then plan again, and revise the plan with each action as you play out your strategy.

Step One: Check the most limiting farm resources:

- mental and physical energy to do the continuous tasks required;
- funds available;
- stock and domestic water available;
- surface/subsoil moisture for crop leaf and root growth;
- need to service machinery – breakdowns cost time, money and frustration.

Audit sheets are provided on the following pages to assist in guiding you through the resource audit.

Step Two: Set action strategies, considering:

- breakeven position of each strategy chosen;
- windows of opportunity to adopt management practices that will be profitable during drought;
- available resources and the implications for ground cover, chemical residues, etc., of carrying out each strategy;
- when situations are changing, conditional and timely fall-back options.

Step Three: Monitor and review performance, position and outlook by:

- using your established network to stay informed about key factors that affect your drought strategies;
- being proactive about the decisions made;
- being prepared for change;
- remembering that the impact falls very heavily not only on the decision makers but on the whole farm family. [28]

MORE INFORMATION

Drought planning

Soil management following drought

Herbicide residues after drought

Winter cropping following drought

DPI NSW Drought Hub

Soil management following drought

The principal aim after rain should be to establish either pasture or crop as a groundcover on your bare paddocks as quickly as possible. This is especially important on the red soils, but is also important for the clays. After drought, many soils will be in a different condition to what is considered to be their 'normal' condition. Some will be bare and powdery on the surface, some will be further eroded by wind or water, and some will have higher levels of nitrogen (N) and phosphorus (P) than expected. Loss of effective ground cover (due to grazing or cultivation) leaves the soil highly prone to erosion by wind and water. Research by the former Department of Land and Water Conservation's Soil Services showed that erosion due to droughtbreaking rain can make up 90% of the total soil loss in a 20–30 year cycle. Following a drought, available N and P levels in the soil are generally higher than in a normal season. However, most of the N and P is in the topsoil, so if erosion strips the topsoil much of this benefit is lost. [29]

28 Meaker G, McCormick L, Blackwood I. (2007). Primefacts: Drought planning. NSW DPI. http://www.dpi.nsw.gov.au/__data/assets/pdf_file/0008/96236/drought-planning.pdf

29 Jenkins A. (2007). Primefacts: Soil management following drought. NSW DPI. http://www.dpi.nsw.gov.au/__data/assets/pdf_file/0012/104007/soil-management-following-drought.pdf

14.3.2 Heat stress

Key points:

- Heat stress is a key yield limiting factor in crop production.
- Heat stress has been shown to adversely affect yield as early as growth stage 45.
- Delayed sowing increases the chance of the crop being exposed to heat stress, particularly at the vulnerable pre-flowering growth stages.

Heat is a key abiotic stress. The effects of heat on grain yield can be as damaging as drought and frost. Varieties that are better adapted to drought also generally perform better in heat-stress conditions.

Rye is more sensitive to hot weather than oats and barley. [30]

Heat-stress affects crop and cereal production in most cropping regions in Australia. It can have significant effects on grain yield and productivity, with potential losses equal to, and potentially greater than, other abiotic stress such as drought and frost. Controlled-environment studies have established that a 3–5% reduction in grain yield of wheat can occur for every 1°C increase in average temperature above 15°C. Field data suggest that yield losses can be in the order of 190 kg/ha for every 1°C rise in average temperature, in some situations having a more severe effect on yield loss than water availability does.

The reproductive stages of growth are more sensitive to elevated temperatures, with physiological responses including premature leaf senescence, reduced photosynthetic rate, reduced seedset, reduced duration of grainfill, and reduced grain size, all ultimately leading to reduced grain yield. Such elevated temperatures are a normal, largely unavoidable occurrence during the reproductive phase of Australian crops in September and October. [31]

In some cereals heat stress can be identified by the withering and splitting of leaf tips (Photo 10). The tips of the leaves may also turn brown to grey in colour. Some or all grains fail to develop in the panicle. [32]

Photo 10: *Withered and split leaf tips in heat-stressed cereal.*

Source: DAFWA

30 A Clark (ed.) 2007 Rye. In Managing Cover Crops Profitably. 3rd edn. Sustainable Agriculture Network, https://www.sare.org/Learning-Center/Books/Managing-Cover-Crops-Profitably-3rd-Edition

31 P Telfer, J Edwards, H Kuchel, J Reinheimer and D Bennett (2013) Heat stress tolerance of wheat. GRDC Update Paper. GRDC, http://www.grdc.com.au/Research-and-Development/GRDC-Update-Papers/2013/02/Heat-stress-tolerance-of-wheat

32 DAFWA (2016) Diagnosing heat stress in oats. DAFWA, https://www.agric.wa.gov.au/mycrop/diagnosing-heat-stress-oats

MORE INFORMATION

Managing heat stress in wheat

Managing heat stress

Key points:

- Choose varieties more tolerant to heat stress
- Sowing crops early may reduce the exposure to very hot conditions and heat stress.

Trials were conducted in South Australia in 2013 to test whether strategic sowing time and variety selection can reduce yield loss due to heat stress in wheat. The research suggests that variety selection and early sowing remain the most effective means to reduce the risk of a crop being damaged by excessive heat. A later sown crop will have an increased likelihood of being exposed to the heat stress at more sensitive growth stages, particularly pre-flowering, and will have greater consequences to the potential grain yield. [33]

14.3.3 Salinity

Water moves into plant roots by a process known as osmosis, which is controlled by the level of salts in the soil water and in the water contained in the plant. If the level of salts in the soil water is too high, water may flow from the plant roots back into the soil. This results in dehydration of the plant, which causes yield decline or even the death of the plant.

As a result of rising water tables in irrigated as well as non-irrigated cropping lands, or because of the use of saline water supplies, salinity has become a major form of land degradation in Australia.

Crop yield losses may occur even though the effects of salinity may not be obvious. The salt tolerance of a specific crop depends on its ability to extract water from soils that are have become saline.

As well as affecting osmosis, salinity affects production in crops, pastures and trees by interfering with nitrogen uptake, reducing growth and stopping plant reproduction.

Some ions (particularly chloride) are toxic to plants, and as the concentration of these ions increases, the plant becomes poisoned and dies. [34]

Cereal rye is thought to be relatively tolerant to saline soils, similar to barley, but will be affected in highly saline soils of 8–16 ECe (dS/m). [35] Rye can tolerate acid soils better than wheat, barley or canola. [36]

CASE STUDY

How salinity affects the emergence, growth, yield and quality of rye

Researchers wanted to know how rye would respond to saline conditions. To find out, they conducted a two-year field study in the arid south-west of the USA, where some soils have become highly saline. They gave six salinity treatments to rye grown on a Holtville silty clay by irrigating with Colorado River water made artificially saline with sodium chloride (NaCl) and calcium chloride ($CaCl_2$) (1:1 by weight). The electrical conductivity of the irrigation waters were 1.1, 4.0, 8.0, 12.1, 16.0, and 20.1 dS/m–1 in the first year, and 1.1, 3.9, 7.5, 11.6, 15.6, and 19.8 dS/m–1 in the second year. The researchers measured vegetative growth and grain yield. Relative grain

33 Telfer P, Edwards J, Bennett D, Kuchel H. (2014). Managing heat stress in wheat. Australian Grain Technologies. http://www.msfp.org.au/wp-content/uploads/Managing-heat-stress-in-wheat.pdf

34 Queensland Government (2015) Impacts of salinity. Queensland Government, https://www.qld.gov.au/environment/land/soil/salinity/impacts/

35 C Henschke and T Herrmann (2007) Testing for soil and water salinity. Fact sheet. No. 66/00. Agdex 533. PIRSA

36 Alberta Agriculture and Forestry (2016) Fall rye production. Revised. AgDex 117/20-1. Alberta Agriculture and Forestry, http://www1.agric.gov.ab.ca/$department/deptdocs.nsf/all/agdex1269/$file/117_20-1.pdf

yield of two cultivars, Maton and Bonel, was unaffected up to a soil salinity of 11.4 dS/m–1 (electrical conductivity of the saturation extractKe). Each unit increase in salinity above 11.4 dS/m–1 reduced yield by 10.8%.

These results place rye in the salt-tolerant category.

The researchers found that both cultivars were slightly less salt tolerant during plant emergence than during subsequent stages of growth. (Seeds were planted in greenhouse sand cultures.) They found that straw yield was more sensitive to salinity than was grain yield. They attributed the reduction in yield primarily to reduced spike weight and individual seed weight, rather than to the number of spikes. They also found that bread quality decreased slightly with increasing levels of salinity. [37]

Symptoms

What to look for in the paddock

- Moist bare patches where seed has failed to germinate or seedlings have died (Photo 11).
- Patches of stunted and apparently water stressed or prematurely dead plants in areas subject to salinity.
- Most crop weeds, with the exception of salt-tolerant species, will also be affected.
- Salt crystals may occur on the dry soil surface.

Photo 11: *Bare saline area with surviving plants dying prematurely.*

Source: DAFWA

37 LE Francois, TJ Donovan, K Lorenz and EV Maas (1989) Salinity effects on rye grain yield, quality, vegetative growth, and emergence. Agronomy Journal. 81 (5), 707–712.

What to look for in the plant

- Plants have a harsh, droughty appearance, and may be smaller with smaller dull leaves (Photo 12).
- Old leaves develop dull yellow tips and die back from the tips and edge.
- Heads are smaller with small grain.
- Plants die prematurely.
- Root growth is reduced, and may be brown and poorly branched. Poor root development may mean that the plant dies if it is also waterlogged.

Photo 12: *Surviving plants are limp and look water stressed.*

Source: DAFWA

Management

The amount of crop yield reduction depends on such factors as crop growth, the salt content of the soil, climatic conditions, etc. In extreme cases where the concentration of salts in the root zone is very high, crop growth may be entirely prevented. To improve crop growth in such soils the excess salts must be removed from the root zone. The term reclamation of saline soils refers to the methods used to remove soluble salts from the root zone. Methods commonly adopted or proposed to accomplish this include the following:

Scraping:

Removing the salts that have accumulated on the soil surface by mechanical means has had only a limited success although many farmers have resorted to this procedure. Although this method might temporarily improve crop growth, the ultimate disposal of salts still poses a major problem.

MORE INFORMATION

Preventing and managing salinity

Managing saline soils

Flushing:

Washing away the surface accumulated salts by flushing water over the surface is sometimes used to desalinize soils having surface salt crusts. Because the amount of salts that can be flushed from a soil is rather small, this method does not have much practical significance.

Leaching:

This is by far the most effective procedure for removing salts from the root zone of soils. Leaching is most often accomplished by ponding fresh water on the soil surface and allowing it to infiltrate. Leaching is effective when the salty drainage water is discharged through subsurface drains that carry the leached salts out of the area under reclamation. Leaching may reduce salinity levels in the absence of artificial drains when there is sufficient natural drainage, i.e. the ponded water drains without raising the water table. Leaching should preferably be done when the soil moisture content is low and the groundwater table is deep. Leaching during the summer months is, as a rule, less effective because large quantities of water are lost by evaporation. The actual choice will however depend on the availability of water and other considerations. In some parts of India for example, leaching is best accomplished during the summer months because this is the time when the water table is deepest and the soil is dry. This is also the only time when large quantities of fresh water can be diverted for reclamation purposes. [38]

38 FAO. Saline soils and their management. http://www.fao.org/docrep/x5871e/x5871e04.htm

Marketing

Key messages

- Utilise the knowledge and resources provided by local grower groups.
- Know and understand key marketing principles:
- Expand the sales window
- You can't sell what you don't have
- Don't lock in a loss
- Don't be a forced seller
- If increasing production risk, take price risk off the table
- Separate the pricing decision from the delivery decision
- Sell valued commodities; not undervalued commodities
- Don't leave money on the table
- Read market signals
- Sell when there is buyer appetite
- Separate the delivery decision from the pricing decision

The final step in generating farm income is converting the tonnes of grain produced per hectare into dollars at the farm gate. This section provides best in-class marketing guidelines for managing price variability to protect income and cash flow.

MORE INFORMATION

Grain Marketing - 2016

Grain marketing lingo – what does it all mean?

The psychology of grain marketing

15.1 Links to industry boards

The Cereal Rye Growers' Association industry body operated in the early 2000s. It was the industry's only representative body and in its time managed to achieve significant benefits for millers processors and growers. Due to lack of growers and funding, it has since closed. [1]

However, rye growers can look to their local cereal grower groups for information and resources.

15.1.1 Northern grower alliance

Northern Grower Alliance (NGA) is an Incorporated Association that was established in 2005 to provide a regional capacity for industry-driven, applied agronomic research into the challenges of grain production. NGA is currently working on a five year project, fully funded by GRDC, focusing on the validation and adoption of new agronomic practices in northern NSW and southern QLD.

15.1.2 Central west farming systems

Central West Farming Systems (CWFS) is an independent, not-for-profit, farmer driven organisation. We operate in an area covering 14 million hectares in the lower rainfall, mixed farming region of Central West NSW (350–500 mm rainfall). Formed in 1998, the group now boasts over 300 members made up primarily of farmers but also private and public sector advisers, researchers and stakeholders.

15.1.3 Conservation Farmers Inc.

Conservation Farmers Inc. is a not-for-profit grower member Association established almost 40 years ago. It has approximately 250 active members, 85% of whom are farmers, based in northern NSW and southern Qld. Conservations Farmers supports our member base by facilitating the extension of research through network groups and field days and the distribution of information in the quarterly newsletter.

1 http://www.abc.net.au/site-archive/rural/sa/stories/s776029.htm 2003

Conservation Farmers Inc. is a farmer's network and our focus is on telling the farmers stories and getting producers together to learn from each other.

15.1.4 FarmLink

FarmLink is made up of growers, advisers and researchers in southern NSW. FarmLink gives growers the power to influence research priorities and be actively involved in the research process.

15.1.5 Grain Orana Alliance

Grain Orana Alliance. Improving the profitability and sustainability of grain growers through remedying key production constraints highlighted by the industry. GOA strives to improve the profitability and sustainability of grain growers through effective research and extension activities on the most important production constraints as identified by the local industry. Responsive and localised efforts ensure adaptability of results but coupled with input from industry leading experts ensures effective solutions.

15.1.6 Conservation Agriculture Australia

Conservation Agriculture Australia is an incorporated not-for-profit association dedicated to the advancement and dissemination of information, products and services relating to all aspects of conservation agriculture, regional sustainability and carbon farming. CANFA is a member of CAA. CANFA is now run by a volunteer committee of farmers and conservation agriculture advocates keen to learn from each other through farm visits and organised trips to conservation farming events.

15.2 Selling principles

The aim of a selling program is to achieve a profitable average price (the target price) across the entire business. This requires managing several factors that are difficult to quantify to establish the target price and then working towards achieving that target price.

These factors include the amount of grain available to sell (production variability), the final cost of that production, and the future prices that may result. Australian farm-gate prices are subject to volatility caused by a range of global factors that are beyond our control and difficult to predict.

The skills that growers have developed to manage variability and costs can be used to manage and overcome price uncertainty.

15.2.1 Be prepared

Being prepared and having a selling plan are essential for managing uncertainty. The steps involved are forming a selling strategy, and having a plan for effective execution of sales. A selling strategy consists of when and how to sell.

Expand the sales window

Expand the selling window by expanding the period in which growers can make grain sales, growers are able to capture price opportunities in volatility observed year to year and achieve higher overall returns.

When to sell

This requires an understanding of the farm's internal business factors including:

- production risk
- a target price based on cost of production and a desired profit margin
- business cash-flow requirements

How to sell?

This depends more on external market factors including:

- time of year, which determines the pricing method
- market access, which determines where to sell
- relative value, which determines what to sell

The key selling principles when considering sales during the growing season are described in Figure 1.

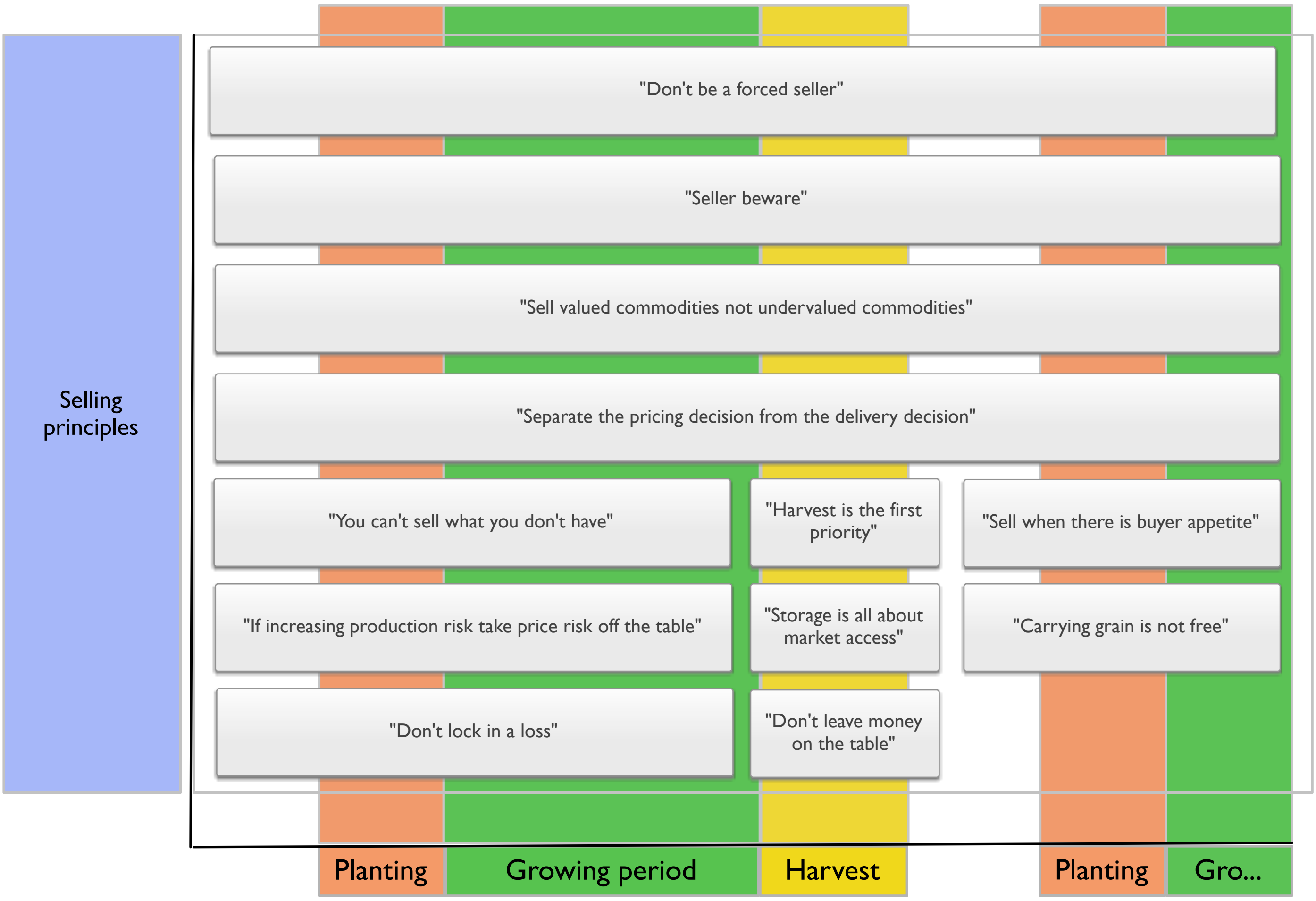


Figure 1: *Grower commodity selling-principles timeline. The illustration demonstrates the key selling principles throughout the production cycle of the crop.*

Source: Profarmer Australia.

15.2.2 Establishing the business risk profile – when to sell

Establishing your business risk profile allows the development of target price ranges for each commodity and provides confidence to sell when the opportunity arises. Typical business circumstances of a cropping enterprise, and how the risks may be quantified during the production cycle, are described in Figure 2.

When does a growers sell their grain? This decision is dependent on:

- Does the production risk allow sales? And what proportion of production?
- Is the price profitable?

- Are business cash requirements being met?

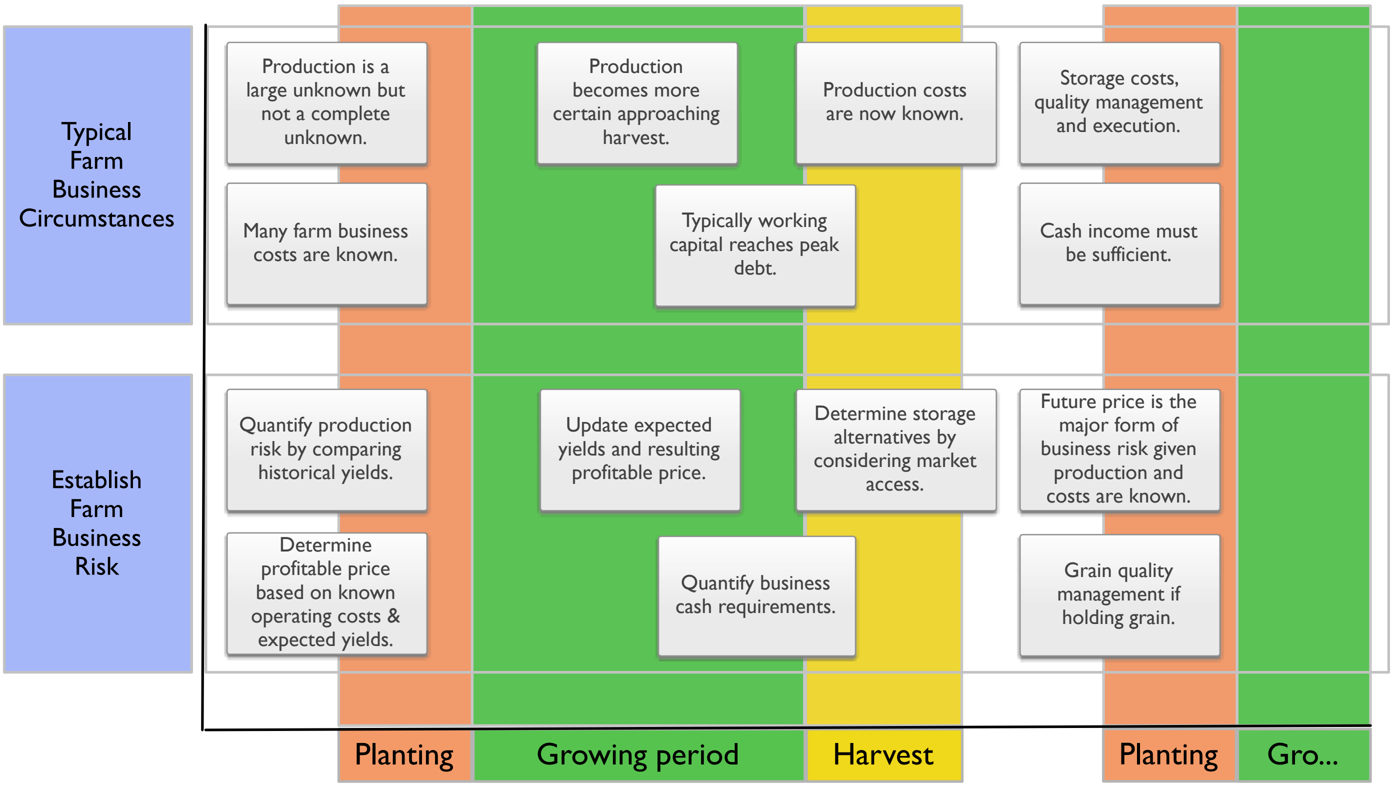


Figure 2: *Typical farm business circumstances and risk.*

Source: Profarmer Australia.

15.2.3 Production risk profile of the farm

Production risk is the level of certainty around producing a crop and is influenced by location (climate and soil type), crop type, crop management, and time of the year.

You can't sell what you don't have

Do not increase business risk by overcommitting production.

Establish a production risk profile (Figure 3) by:

- collating historical average yields for each crop type and a below-average and above-average range
- assessing the likelihood of achieving average based on recent seasonal conditions and seasonal outlook
- revising production outlooks as the season progresses

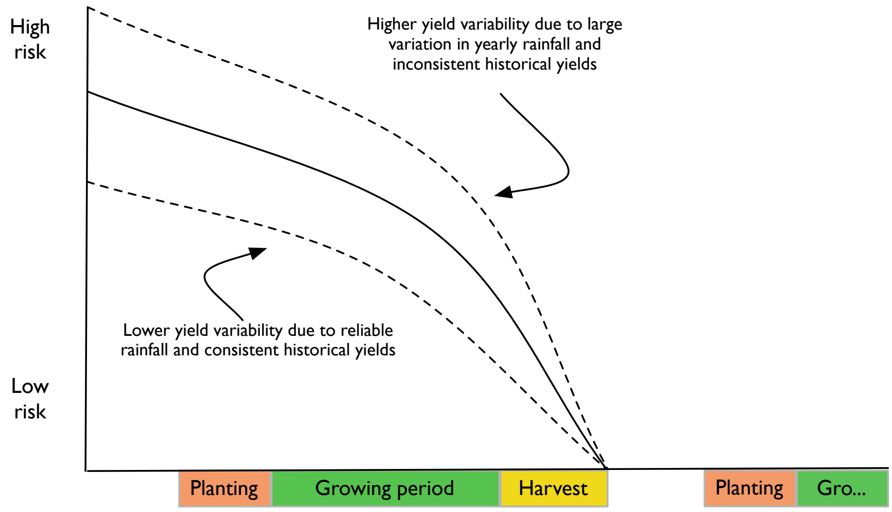


Figure 3: *Typical production risk profile of a farm operation.*

Source: Profarmer Australia.

The quantity of crop grown is a large unknown early in the year however not a complete unknown. 'You can't sell what you don't have' but it is important to compare historical yields to get a true indication of production risk. This risk reduces as the season progresses and yield becomes more certain. Businesses will face varying production risk levels at any given point in time with consideration to rainfall, yield potential, soil type, commodity etc.

15.2.4 Farm costs in their entirety, variable and fixed costs (establishing a target price)

A profitable commodity target price is the cost of production per tonne plus a desired profit margin. It is essential to know the cost of production per tonne for the farm business.

Don't lock in a loss

If committing production ahead of harvest, ensure that the price is profitable.

Steps to calculate an estimated profitable price based on total cost of production and a range of yield scenarios are provided in Figure 4.

Estimating cost of production - Wheat	
Planted Area	1,200 ha
Estimate Yield	2.85 t/ha
Estimated Production	3,420 t
Fixed costs	
Insurance and General Expenses	$100,000
Finance	$80,000
Depreciation/Capital Replacement	$70,000
Drawings	$60,000
Other	$30,000
Variable costs	
Seed and sowing	$48,000
Fertiliser and application	$156,000
Herbicide and application	$78,000
Insect/fungicide and application	$36,000
Harvest costs	$48,000
Crop insurance	$18,000
Total fixed and variable costs	$724,000
Per Tonne Equivalent (Total costs + Estimated production)	$212 /t
Per tonne costs	
Levies	$3 /t
Cartage	$12 /t
Freight to Port	$22 /t
Total per tonne costs	$37 /t
Cost of production Port track equiv	$248.70
Target profit (ie 20%)	$50.00
Target price (port equiv)	**$298.70**

Step 1: Estimate your production potential. The more uncertain your production is, the more conservative the yield estimate should be. As yield falls, your cost of production per tonne will rise.

Step 2: Attribute your fixed farm business costs. In this instance if 1,200 ha reflects 1/3 of the farm enterprise, we have attributed 1/3 fixed costs. There are a number of methods for doing this (see M Krause "Farming your Business") but the most important thing is that in the end all costs are accounted for.

Step 3: Calculate all the variable costs attributed to producing that crop. This can also be expressed as $ per ha x planted area.

Step 4: Add together fixed and variable costs and divide by estimated production

Step 5: Add on the "per tonne" costs like levies and freight.

Step 6: Add the "per tonne" costs to the fixed and variable per tonne costs calculated at step 4.

Step 7: Add a desired profit margin to arrive at the port equivalent target profitable price.

Figure 4: *Steps to calculate an estimated profitable price for grain.*

Source: Profarmer Australia.

The GRDC Farming the Business manual also provides a cost-of production template and tips on skills required for grain selling, as opposed to grain marketing. [2]

15.2.5 Income requirements

Understanding farm business cash-flow requirements and peak cash debt enables grain sales to be timed so that cash is available when required. This prevents having to sell grain below the target price to satisfy a need for cash.

Don't be a forced seller

Be ahead of cash requirements to avoid selling in unfavourable markets. Price variability also means growers who are not organised with their cash flow may risk becoming a forced seller in unfavourable markets.

VIDEOS

WATCH: 'Farming the Business' eBook resources.

2 M Krause (2014) Farming the business. Sowing for your future. GRDC, http://www.grdc.com.au/FarmingTheBusiness

As the market falls, growers need to sell greater volumes of grain in order to achieve the same cash flow outcome. This reduces their ability to capture any favourable price moves that may eventuate later in the season.

A typical cash flow to grow a crop is illustrated in Figure 5. Costs are incurred upfront and during the growing season, with peak working capital debt incurred at or before harvest. This will vary depending on circumstance and enterprise mix. Figure 6 demonstrates how managing sales can change the farm's cash balance.

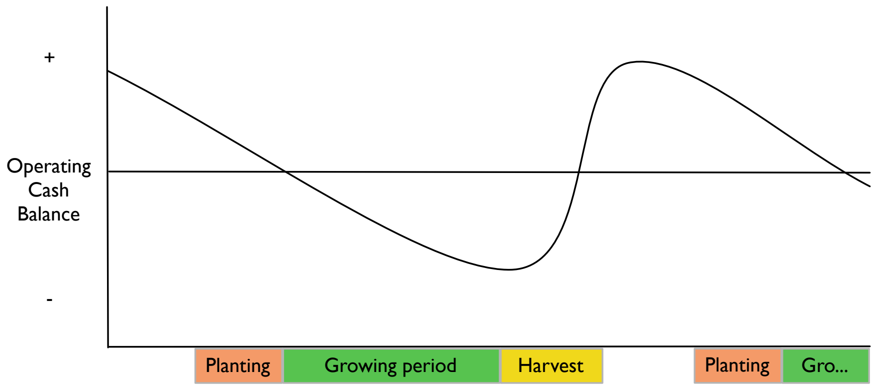


Figure 5: *Typical farm operating cash balance, assuming harvest cash sales. In this scenario, peak cash surplus starts higher and peak cash debt is lower.*

Source: Profarmer Australia.

The chart above illustrates the operating cash flow of a typical farm assuming a heavy reliance on cash sales at harvest. Costs are incurred during the season to grow the crop, resulting in peak operating debt levels at or near harvest. Hence at harvest there is often a cash injection required for the business. An effective marketing plan will ensure a grower is 'not a forced seller' in order to generate cash flow.

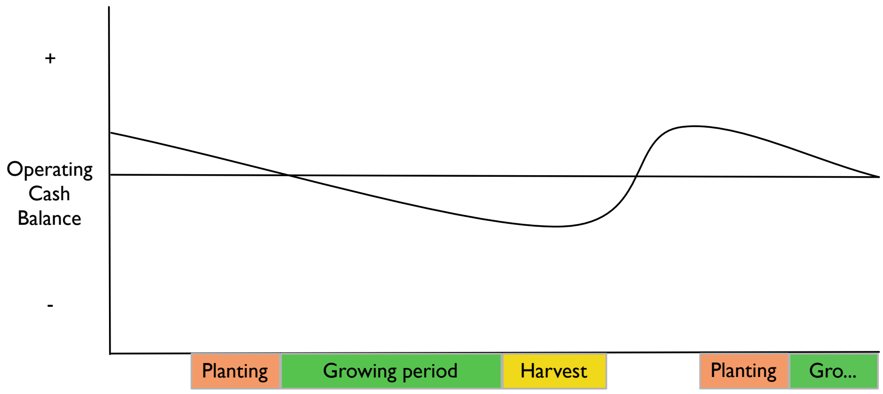


Figure 6: *Typical farm operating cash balance, with cash sales spread throughout the year. In this scenario, peak cash surplus starts lower and peak cash debt is higher.*

Source: Profarmer Australia.

By spreading sales throughout the year a grower may not be as reliant on executing sales at harvest time in order to generate required cash flow for the business. This provides a greater ability to capture pricing opportunities in contrast to executing sales in order to fulfil cash requirements.

Summary

The when-to-sell steps above result in an estimated production tonnage and the risk associated with that tonnage, a target price range for each commodity, and the time of year when cash is most needed.

15.2.6 Managing your price – how to sell

This is the second part of the selling strategy.

Methods of price management

The pricing methods for products provide varying levels of price-risk coverage.

Figure 7 provides a summary of when different methods of price management are suited for the majority of farm businesses.

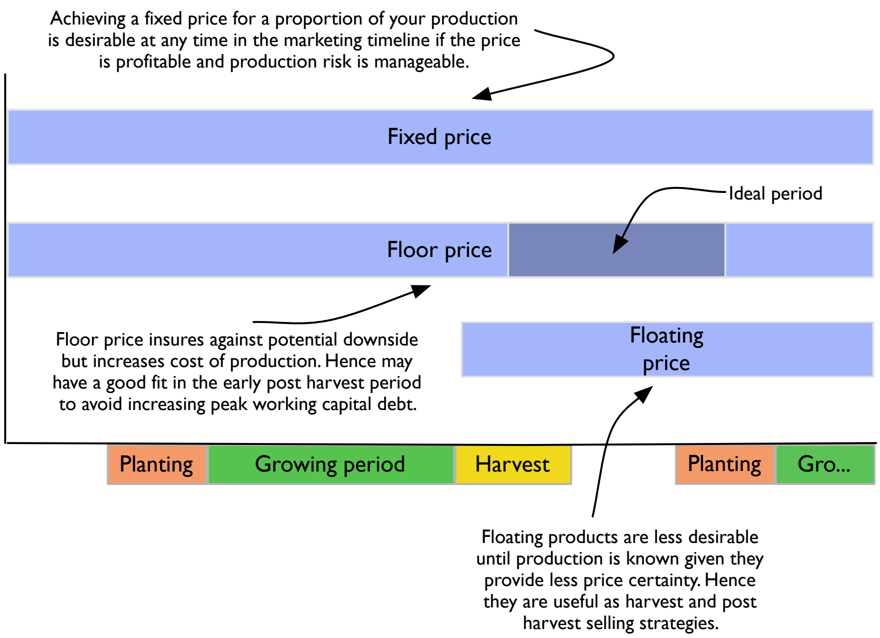


Figure 7: *Price strategy timeline through the growing season.*

Source: Profarmer Australia.

Different price strategies are more applicable through varying periods of the growing season. If selling in the forward market growers are selling something not yet grown hence the inherent production risk of the business increases. This means growers should achieve price certainty if committing tonnage ahead of harvest. Hence fixed or floor products are favourable. Comparatively a floating price strategy may be effective in the harvest and post-harvest period.

If increasing production risk, take price risk off the table.

When committing unknown production, price certainty should be achieved to avoid increasing overall business risk.

Separate the pricing decision from the delivery decision.

Most commodities can be sold at any time with delivery timeframes negotiable; hence, price management is not determined by delivery.

Fixed price

A fixed price is achieved via cash sales and/or selling a futures position (swaps) (Figure 8). It provides some certainty around expected revenue from a sale because the price is largely a known, except when there is a floating component in the price, for example, a multi-grade cash contract with floating spreads or a floating basis component on futures positions.

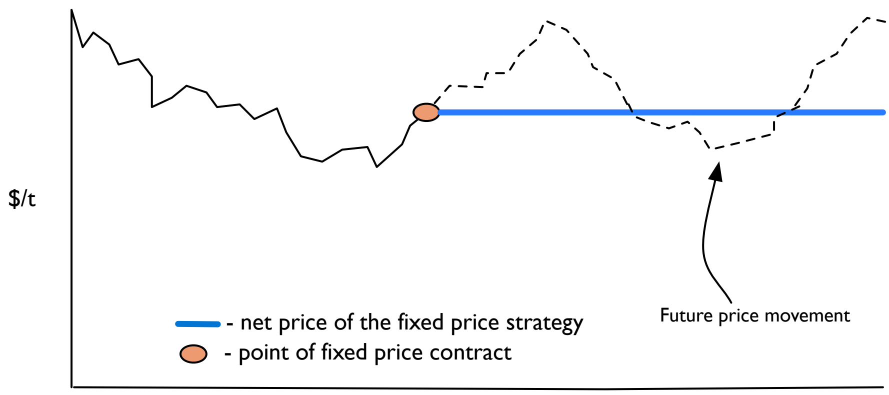


Figure 8: *Fixed price strategy.*

Source: Profarmer Australia.

Fixed price product locks in price and provides certainty over what revenue will be generated regardless of future price movement.

Floor price

Floor-price strategies can be achieved by utilising ‘options’ on a relevant futures exchange (if one exists), or via a managed sales program product by a third party (i.e. a pool with a defined floor-price strategy). This pricing method protects against potential future downside while capturing any upside (Figure 9). The disadvantage is that the price ‘insurance’ has a cost, which adds to the farm business cost of production.

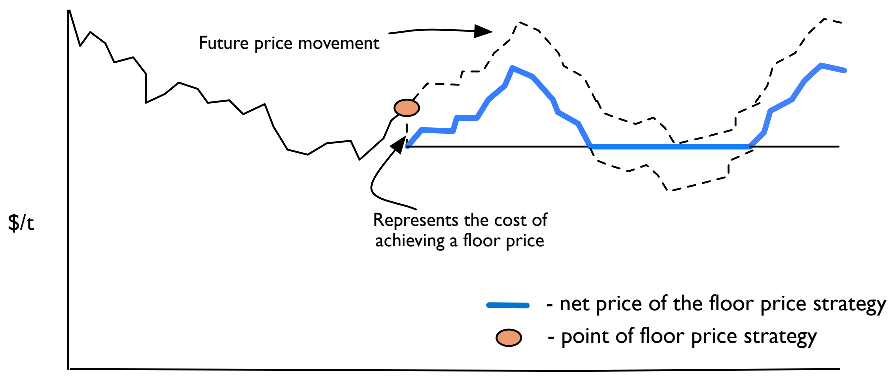


Figure 9: *Floor price strategy.*

Source: Profarmer Australia.

A floor price strategy insures against potential future downside in price while allowing price gains in the event of future price rallies.

Floating price

Many of the pools or managed sales programs are a floating price where the net price received will move both up and down with the future movement in price (Figure 10). Floating-price products provide the least price certainty and are best suited for use at or after harvest rather than pre-harvest.

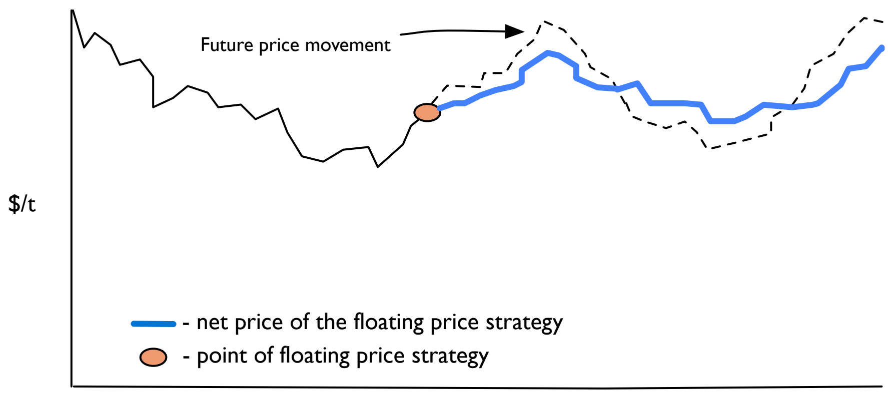


Figure 10: *Floating price strategy.*

Source: Profarmer Australia.

A floating price will move to some extent with future price movements.

Summary

Fixed-price strategies include physical cash sales or futures products and provide the most price certainty; however, production risk must be considered.

Floor-price strategies include options or floor-price pools. They provide a minimum price with upside potential and rely less on production certainty; however, they cost more.

Floating-price strategies provide minimal price certainty and they are best used after harvest.

15.2.7 Ensuring access to markets

Once the selling strategy is organised, the storage and delivery of commodities must be planned to ensure timely access to markets and execution of sales. At some point, growers need to deliver the commodity to market; hence, planning on where to store the commodity is important in ensuring access to the market that is likely to yield the highest return (Figure 11).

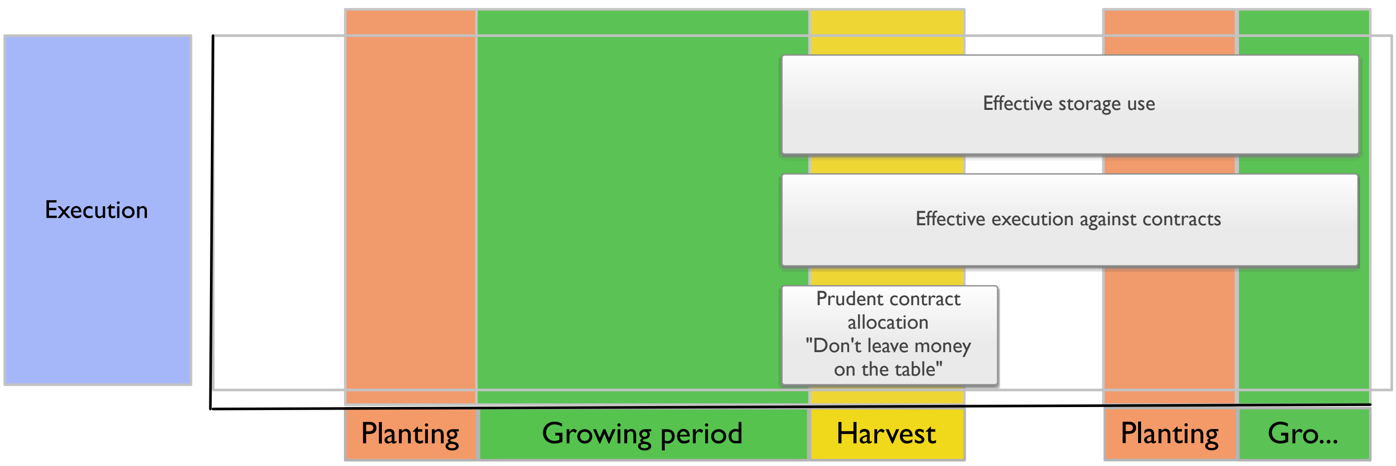


Figure 11: *Effective storage decisions.*

Source: Profarmer Australia.

Once a grower has made the decision to sell the question becomes how they achieve this? The decision on how to sell is dependent on:

- Time of the year determines the pricing method
- Market Access determines where to sell.
- Relative value determines what to sell.

Storage and logistics

Return on investment from grain handling and storage expenses is optimised when storage is considered in light of market access to maximise returns as well as harvest logistics.

Storage alternatives include variations around the bulk handling system, private off-farm storage, and on-farm storage. Delivery and quality management are key considerations in deciding where to store your commodity (Figure 12).

Harvest is the first priority

Getting the crop into the bin is most critical to business success during harvest; hence, selling should be planned to allow focus on harvest.

Bulk export commodities requiring significant quality management are best suited to the bulk-handling system. Commodities destined for the domestic end-user market (e.g. feedlot, processor, or container packer) may be more suited to on-farm or private storage to increase delivery flexibility.

Storing commodities on-farm requires prudent quality management to ensure delivery at agreed specifications and can expose the business to high risk if this aspect is not well planned. Penalties for out-of-specification grain on arrival at a buyer's weighbridge can be expensive. The buyer has no obligation to accept delivery of an out-of-specification load. This means that the grower may have to suffer the cost of taking the load elsewhere, while also potentially finding a new buyer. Hence, there is potential for a distressed sale, which can be costly.

On-farm storage also requires prudent delivery management to ensure that commodities are received by the buyer on time with appropriate weighbridge and sampling tickets.

Storage is all about market access

Storage decisions depend on quality management and expected markets.

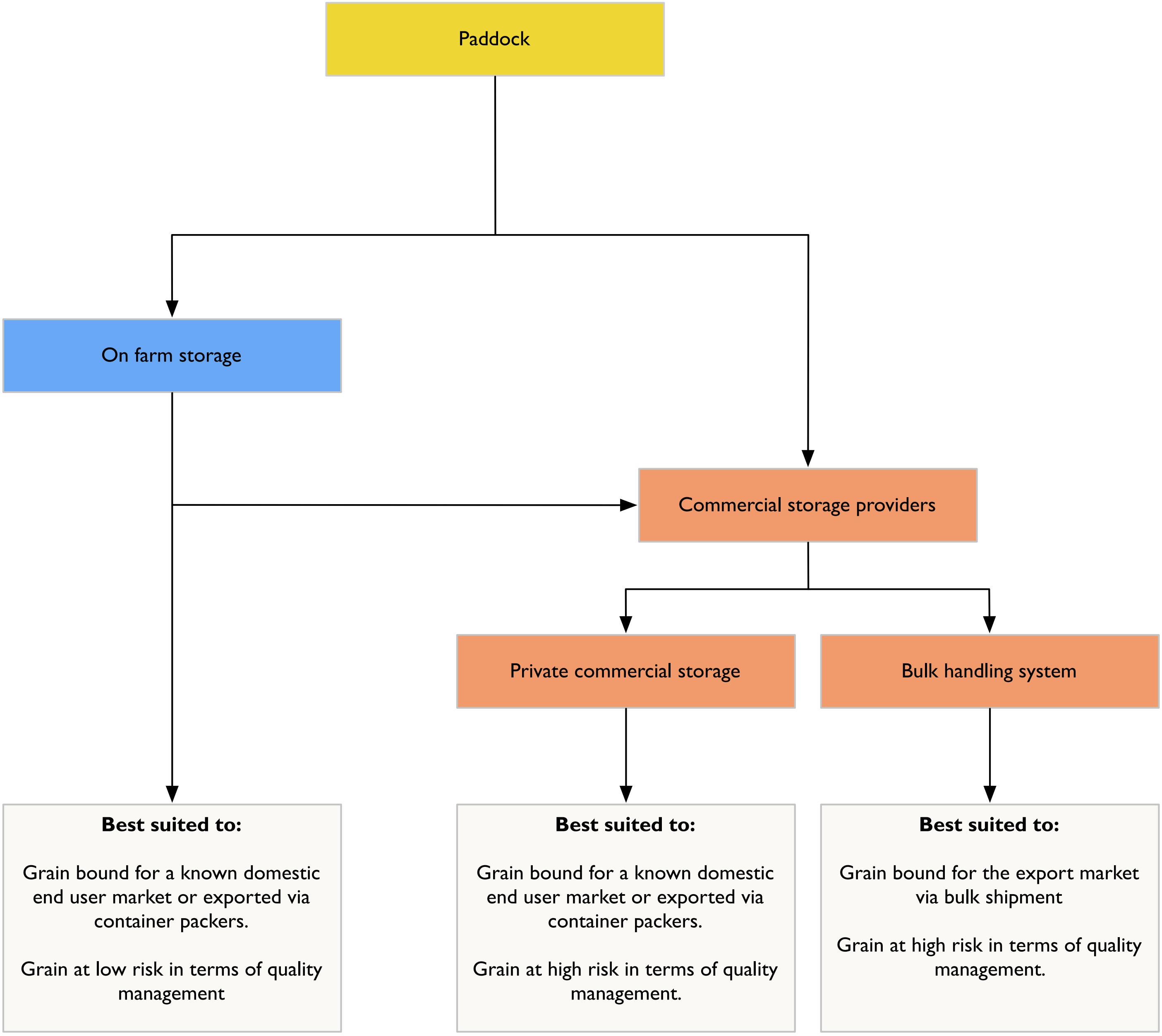


Figure 12: *Grain storage decision making.*

Source: Profarmer Australia

Decisions around storage alternatives of harvested commodities depend on market access and quality management requirements.

For more information about on-farm storage alternatives and economics, see Section 13: Storage.

Cost of carrying grain

Storing grain to access sales opportunities post-harvest invokes a cost to 'carry' grain. Price targets for carried grain need to account for the cost of carry. Carry costs per month are typically $3–4/t, consisting of:

- monthly storage fee charged by a commercial provider (typically ~$1.50–2.00/t); and

- monthly interest associated with having wealth tied up in grain rather than cash or against debt (~$1.50–2.00/t, depending on the price of the commodity and interest rates).

The price of carried grain therefore needs to be $3–4/t per month higher than was offered at harvest. The cost of carry applies to storing grain on-farm because there is a cost of capital invested in the farm storage plus the interest component. A reasonable assumption is $3–4/t per month for on-farm storage.

Carrying grain is not free

The cost of carrying grain needs to be accounted for if holding grain and selling it after harvest is part of the selling strategy. If selling a cash contract with deferred delivery, a carry charge can be negotiated into the contract.

Summary

Optimising farm-gate returns involves planning the appropriate storage strategy for each commodity to improve market access and cover carry costs in pricing decisions.

15.2.8 Executing tonnes into cash

Below are guidelines for converting the selling and storage strategy into cash by effective execution of sales.

Set up the tool box

Selling opportunities can be captured when they arise by assembling the necessary tools in advance. The toolbox includes:

1. Timely information. This is critical for awareness of selling opportunities and includes: market information provided by independent parties; effective price discovery including indicative bids, firm bids, and trade prices; and other market information pertinent to the particular commodity.
2. Professional services. Grain-selling professional service offerings and cost structures vary considerably. An effective grain-selling professional will put their clients' best interests first by not having conflicts of interest and by investing time in the relationship. Return on investment for the farm business through improved farm-gate prices is obtained by accessing timely information, greater market knowledge and greater market access from the professional service.
3. Futures account and bank swap facility. These accounts provide access to global futures markets. Hedging futures markets is not for everyone; however, strategies that utilise exchanges such as CBOT (Chicago Board of Trade) can add significant value.

MORE INFORMATION

Current financial members of Grain Trade Australia, including buyers, independent information providers, brokers, agents, and banks providing over-the-counter grain derivative products

Commodity futures brokers

How to sell for cash

Like any market transaction, a cash grain transaction occurs when a bid by the buyer is matched by an offer from the seller. Cash contracts are made up of the following components, with each component requiring a level of risk management (Figure 13):

- Price. Future price is largely unpredictable; hence, devising a selling plan to put current prices into the context of the farm business is critical to manage price risk.
- Quantity and quality. When entering a cash contract, you are committing to delivery of the nominated amount of grain at the quality specified. Therefore, production and quality risk must be managed.
- Delivery terms. Timing of title transfer from the grower to the buyer is agreed at time of contracting. If this requires delivery direct to end users, it relies on prudent execution management to ensure delivery within the contracted period.
- Payment terms. In Australia, the traditional method of contracting requires title of grain to be transferred ahead of payment; hence, counterparty risk must be managed.

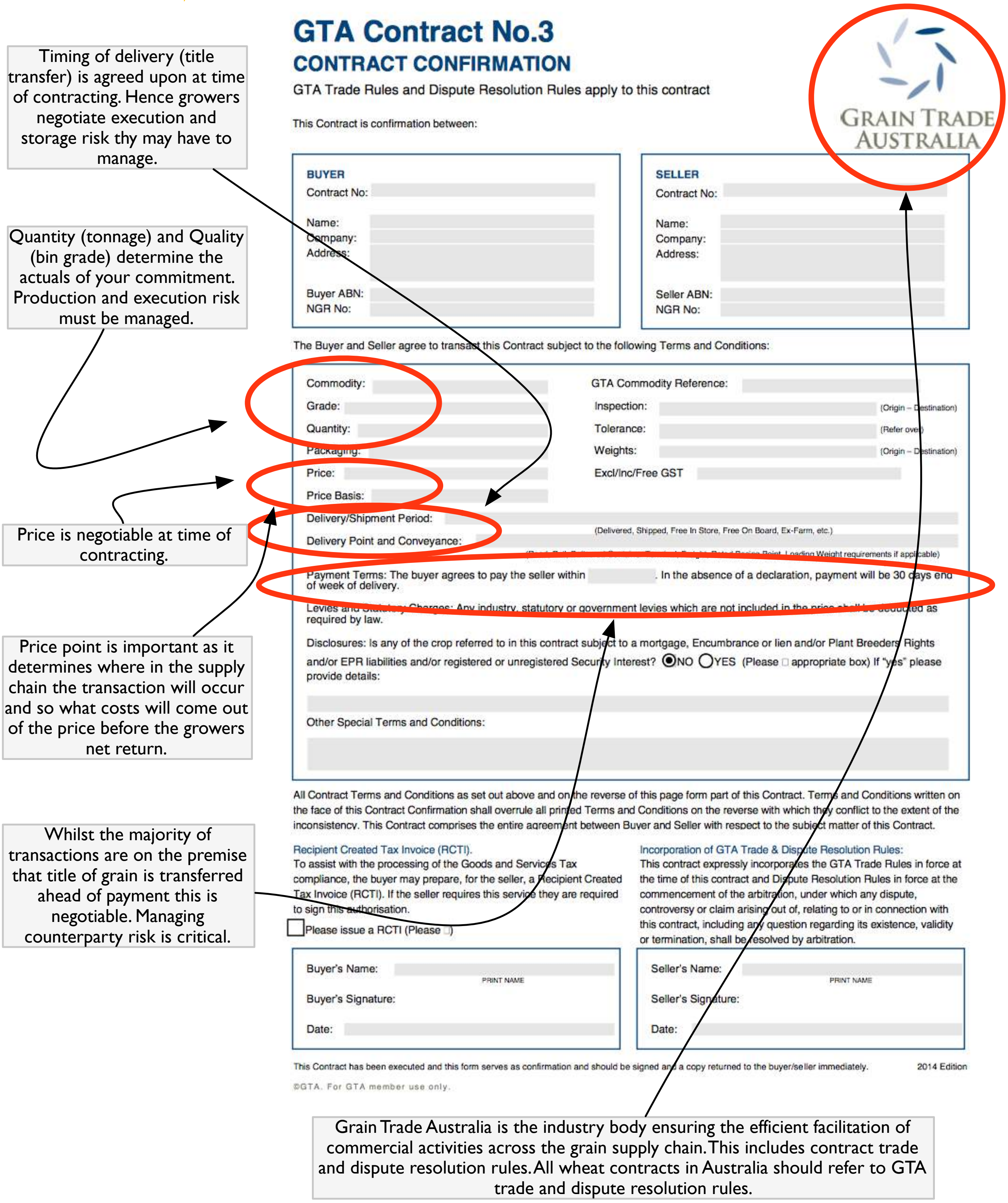


Figure 13: *Typical cash contracting as per Grain Trade Australia standards.*

The price point within a cash contract will depend on where the transfer of grain title will occur along the supply chain. Figure 14 shows the terminology used to describe pricing points along the grain supply chain and the associated costs to come out of each price before growers receive their net farm-gate return.

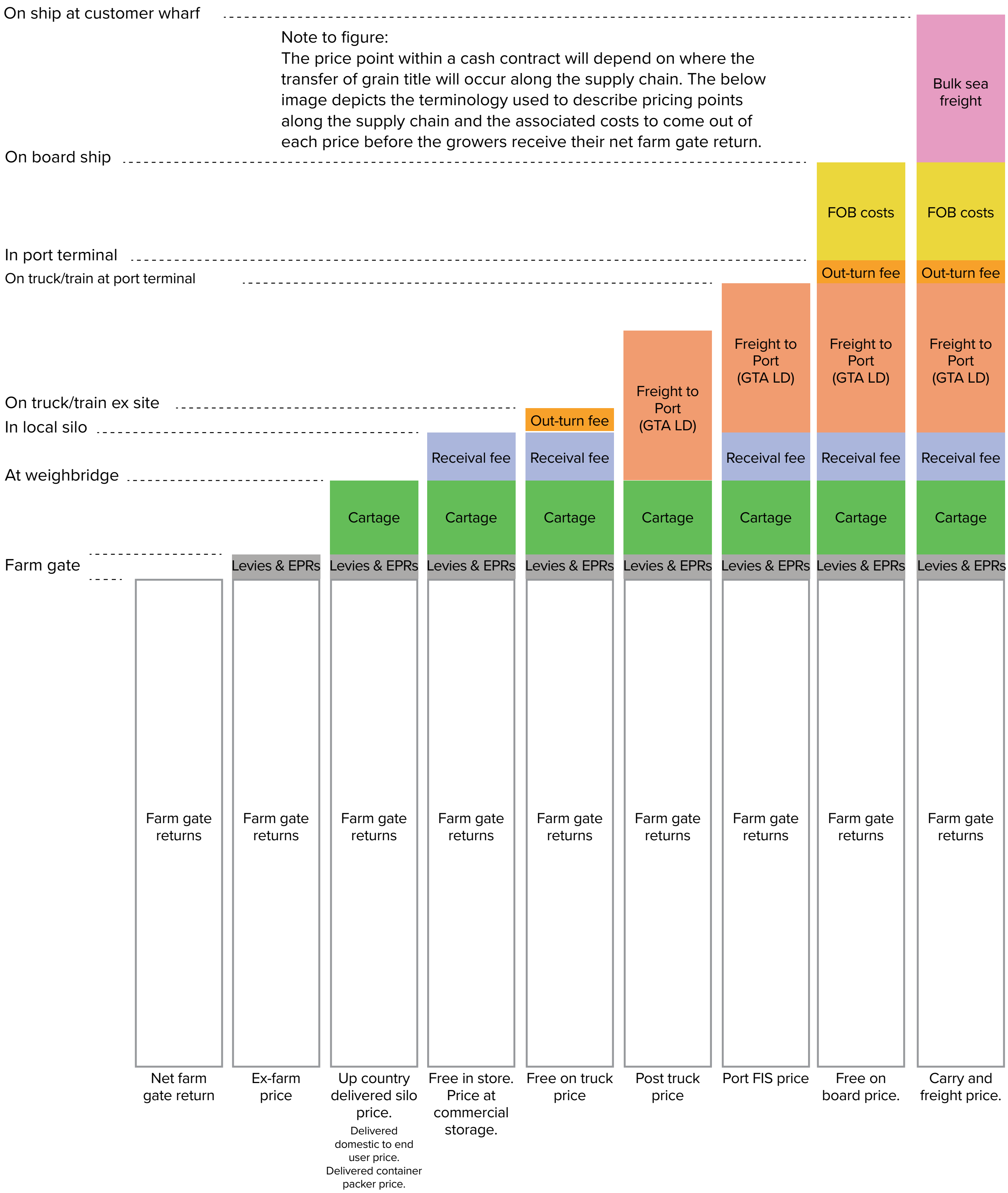


Figure 14: *Costs and pricing points throughout the supply chain.*

Cash sales generally occur through three methods:

1. Negotiation via personal contact. Traditionally, prices are posted as a 'public indicative bid'. The bid is then accepted or negotiated by a grower with the merchant or via an intermediary. This method is the most common and is available for all commodities.
2. Accepting a 'public firm bid'. Cash prices in the form of public firm bids are posted during harvest and for warehoused grain by merchants on a site basis. Growers can sell their parcel of grain immediately, by accepting the price on offer via an online facility and then transferring the grain online to the buyer. The availability of this depends on location and commodity.
3. Placing an 'anonymous firm offer'. Growers can place a firm offer price on a parcel of grain anonymously and expose it to the entire market of buyers, who then bid on it anonymously using the Clear Grain Exchange, which is an independent online exchange. If the firm offer and firm bid match, the parcel transacts via a secure settlement facility where title of grain does not transfer from the grower until funds are received from the buyer. The availability of this depends on location and commodity. Anonymous firm offers can also be placed to buyers by an intermediary acting on behalf of the grower. If the grain sells, the buyer and seller are disclosed to each counterparty.

Counterparty risk

Most sales involve transferring title of grain prior to being paid. The risk of a counterparty defaulting when selling grain is very real and must be managed.

Conducting business in a commercial and professional manner minimises this risk.

Seller beware

Selling for an extra $5/t is not a good deal if you do not get payment. Counterparty risk management includes the following principles:

- Deal only with known and trusted counterparties.
- Conduct a credit check (banks will do this) before dealing with a buyer you are unsure of.
- Sell only a small amount of grain to unknown counterparties.
- Consider credit insurance or letter of credit from the buyer.
- Never deliver a second load of grain if payment has not been received for the first.
- Do not part with title of grain before payment, or request a cash deposit of part of the value ahead of delivery. Payment terms are negotiable at time of contracting; alternatively, the Clear Grain Exchange provides secure settlement whereby the grower maintains title of grain until payment is received from the buyer, and then title and payment are settled simultaneously.

Above all, act commercially to ensure that the time invested in a selling strategy is not wasted by poor counterparty risk management. Achieving $5/t more and not receiving payment is a disastrous outcome.

Relative values

Grain sales revenue is optimised when selling decisions are made in the context of the whole farming business. The aim is to sell each commodity when it is priced well and hold commodities that are not well priced at any given time; that is, give preference to the commodities of the highest relative value. This achieves price protection for the overall farm business revenue and enables more flexibility to a grower's selling program while achieving the business goals of reducing overall risk.

Sell valued commodities; not undervalued commodities.

If one commodity is priced strongly relative to another, focus sales there. Do not sell the cheaper commodity for a discount.

Contract allocation

Contract allocation means choosing which contracts to allocate your grain against at delivery time. Different contracts will have different characteristics (price, premiums–discounts, oil bonuses, etc.), and optimising your allocation reflects immediately on your bottom line.

Don't leave money on the table.

Contract allocation decisions do not take long, and can be worth thousands of dollars to your bottom line.

To achieve the best average wheat price, growers should allocate:

- lower grades of wheat to contracts with the lowest discounts; and
- higher grades of wheat to contracts with the highest premiums.

Read market signals

The appetite of buyers to purchase a particular commodity will differ over time depending on market circumstances. Ideally, growers should aim to sell their commodity when buyer appetite is strong and should stand aside from the market when buyers are not as interested in buying the commodity.

Sell when there is buyer appetite

When buyers are chasing grain, growers have more market power to demand a price when selling. When buyer appetite is strong the seller has more ability to negotiate a better price.

Buyer appetite can be monitored by:

1. The number of buyers at or near the best bid in a public bid line-up. If there are many buyers, it could indicate buyer appetite is strong. However, if there is one buyer at $5/t above the next best bid, it may mean cash prices are susceptible to falling $5/t if that buyer satisfies their buying appetite.
2. Monitoring actual trades against public indicative bids. When trades are occurring above indicative public bids, it may indicate strong appetite from merchants and the ability for growers to offer their grain at price premiums to public bids.

Summary

The selling strategy is converted to maximum business revenue by:

- ensuring timely access to information, advice and trading facilities
- using different cash market mechanisms when appropriate
- minimising counterparty risk by effective due diligence
- understanding relative value and selling commodities when they are priced well
- thoughtful contract allocation
- reading market signals to extract value from the market or to prevent selling at a discount

Separate the delivery decision from the pricing decision

Storage is all about market access – Storage decisions depend on quality management and expected markets. Storage decisions are dependent on quality management and least cost pathways to expected markets. Alternatives include variations around the bulk handling system, private off farm storage, and on-farm storage. [3]

3 Cattle N, Janson H. Putting a dollar value on best practice grain selling. Profarm.

15.3 Other relevant marketing issues

15.3.1 Improving structures around grain marketing decision making

Take home messages

- Good grain marketing can only occur if other aspects of the business are being managed appropriately to ensure there is choice in products and timing of sales.
- Understanding the different stages of the grain marketing process and optimising the length of the sales window are two key underlying frameworks for improving decision making.
- An overall decision making framework is introduced that outlines the need for the foundation of a good internal structure and an understanding of those factors that can be controlled within a business and then overlaying good plans and strategies to deal with external factors that are outside of your control.

Grain marketing can be viewed in a simplified way as a series of decisions that start with thinking about the market right through to ensuring sales are finalised, delivered on and paid. The result is cashflow; grain has been turned into cash which can then be used for a number of things. Hence a simplified definition of grain marketing is as follows:

'a series of decisions and subsequent actions that turn grain into cashflow'

The ultimate aim is to maximise this cashflow by maximising yield and price given the constraints of any one season (both production and market constraints at the time). In terms of price, the single most important requirement is to have choice on when grain is sold. The idea behind price risk management is to create more pricing opportunities and manage them in a way that reduces overall risk, and doesn't just transfer one risk to another that can still impact the business. For example, reducing price risk if not done correctly can impact production risk.

There are three key concepts about grain marketing decision making focussing on ways of building more structure around these decisions.

1. The grain marketing process,
2. the grain marketing window, and;
3. the grain marketing pyramid.

These three concepts give a theoretical context to some of the more specific actions that can be undertaken to improve grain marketing outcomes.

Several grain marketing concepts have been introduced as ways to help build structure around the grain marketing decision making process. The theory behind the pyramid is that by building the foundation of a good internal structure then overlaying this with a strategy and a plan, and capping this off by good execution, an overall strong grain marketing process will result.

Rather than outlining specifics actions, tools and resources, a general theory is outlined to help growers design their own 'pyramid' that suits their business. [4]

MORE INFORMATION

Improving structures around grain marketing decision making

Grain marketing - The process, decisions and how to build a successful structure

Grain market update and underlying fundamentals - Does grain marketing really matter?

4 Knight B. (2014). GRDC Update Papers: Improving structures around grain marketing decision making. https://grdc.com.au/Research-and-Development/GRDC-Update-Papers/2014/09/Improving-structures-around-grain-marketing-decision-making

Current and past research

Project Summaries www.grdc.com.au/ProjectSummaries

As part of a continuous investment cycle each year the Grains Research and Development Corporation (GRDC) invests in several hundred research, development and extension and capacity building projects. To raise awareness of these investments the GRDC has made available summaries of these projects.

These project summaries have been compiled by GRDC's research partners with the aim of raising awareness of the research activities each project investment.

The GRDC's project summaries portfolio is dynamic: presenting information on current projects, projects that have concluded and new projects which have commenced. It is updated on a regular basis.

The search function allows project summaries to be searched by keywords, project title, project number, theme or by GRDC region (i.e. Northern, Southern or Western Region).

Where a project has been completed and a final report has been submitted and approved a link to a summary of the project's final report appears at the top of the page.

The link to Project Summaries is www.grdc.com.au/ProjectSummaries

Final Report Summaries http://finalreports.grdc.com.au/final_reports

In the interests of raising awareness of GRDC's investments among growers, advisers and other stakeholders, the GRDC has available final reports summaries of projects.

These reports are written by GRDC research partners and are intended to communicate a useful summary as well as present findings of the research activities from each project investment.

The GRDC's project portfolio is dynamic with projects concluding on a regular basis.

In the final report summaries there is a search function that allows the summaries to be searched by keywords, project title, project number, theme or GRDC Regions. The advanced options also enables a report to be searched by recently added, most popular, map or just browse by agro-ecological zones.

The link to the Final Report Summaries is http://finalreports.grdc.com.au/final_reports

Online Farm Trials http://www.farmtrials.com.au/

The Online Farm Trials project brings national grains research data and information directly to the grower, agronomist, researcher and grain industry community through innovative online technology. Online Farm Trials is designed to provide growers with the information they need to improve the productivity and sustainability of their farming enterprises.

Using specifically developed research applications, users are able to search the Online Farm Trials database to find a wide range of individual trial reports, project summary reports and other relevant trial research documents produced and supplied by Online Farm Trials contributors.

The Online Farm Trials website collaborates closely with grower groups, regional farming networks, research organisations and industry to bring a wide range of crop research datasets and literature into a fully accessible and open online digital repository.

Individual trial reports can also be accessed in the trial project information via the Trial Explorer.

The link to the Online Farm Trials is http://www.farmtrials.com.au/

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