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GROWNOTES™

DURUM

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Start here for answers to your immediate durum crop management issues

What variety of durum should I grow?

What fertilisers do I require?

Are the diseases of durum manageable?

Are there specific weed control issues?

How do I manage pests and insects?

How do I market my durum grain?

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MORE INFORMATION

GRDC 'Fact Sheet — Durum Quality and Agronomy': www.grdc.com.au/GRDC-FS-Durum

DPIRD 'Development of the Durum Industry in the Western Region': http://www.agrifood.info/review/2007/Nguyen_Llewellyn_Miyan.pdf

NSW Department of Primary Industries 'Durum Wheat Production': www.dpi.nsw.gov.au

Introduction

A.1 Overview

Durum wheat (*Triticum turgidum*) is closely related to bread wheat (*T. aestivum*), but is grown for pasta production.

The highest grade of Australian durum wheat — ADR1 — is known for its extreme hardness, high protein, intense yellow colour and milling qualities that make it suitable for producing semolina. This is the finely ground grain that is used to make pasta.

The market for durum wheat in Western Australia is small and niche. Growers considering producing this crop are advised to contact WA-based grain container packers to determine the marketability of the product before they consider entering the industry. See Chapter 10 for more information about durum wheat marketing.

WA's five-year average durum wheat production was only 5419 tonnes during the period 1994-95 to 2006-07 due to some poor seasons and the challenge of meeting durum grain protein requirements.[1]

In this period, production reached a high of about 7000 t in 2004-05 and there were several years of zero production including in recent years.[2]

Across Australia, durum wheat is typically grown on highly fertile soils that produce high-protein grain, as protein levels of higher than 13 percent are required to meet premium grades. Grain with protein levels of less than 10 percent is marketed as feed. Specifications for durum wheat are outlined in Table 1.

Poor soil fertility in many parts of WA make it challenging to consistently produce durum wheat at a protein level that qualifies for a premium price and is competitive with returns for other crop options, such as bread wheat.

Trials have shown there is potential to improve the grain protein of durum by including it in a legume rotation, using high rates of nitrogen (N) fertilisers and/or adopting a fallow in the rotation.

It is estimated WA is capable of producing at least 500,000 t of durum wheat annually on a potentially suitable area of three million hectares (most likely in eastern and northern grainbelt areas).[3]

The production of durum wheat in WA would add security of supply that is essential to maintaining Australia's domestic and export markets for semolina.

Benefits would flow back to growers through increased gross margins for durum wheat when grown in the appropriate conditions.

1 DAW703 (2004) Development of the Durum Industry in the Western Region, http://www.agrifood.info/review/2007/Nguyen_Llewellyn_Miyan.pdf

2 DAW703 (2004) Development of the Durum Industry in the Western Region, http://www.agrifood.info/review/2007/Nguyen_Llewellyn_Miyan.pdf

3 N Mohammed S. Miyan1, Alfredo Impiglia2, Wal K. Anderson3, Agronomic practices for durum wheat in an area new to the crop, http://agrobiol.sggw.waw.pl/~cbcs/articles/CBCS_6_2_2.pdf

Table 1: Preferred durum specifications for semolina.[4]

PASTA MANUFACTURERS	GRAIN TRADE AUSTRALIA WHEAT STANDARDS	REASON BEHIND THE SPECIFICATION
Preferred durum wheat specifications for the best quality semolina	**Industry specifications that will meet ADR1 standard and make a good quality semolina**	
At least 13 percent protein	At least 13 percent protein	Required for optimum pasta production. It produces semolina that has a uniform particle size and allows for the pasta to be physically strong and elastic.
Maximum 12 percent moisture	Maximum 12.5 percent moisture	An important parameter, particularly for processing industries and trading and will reflect grain storability.
Maximum 2 percent screenings (through 2.0 mm screen)	Maximum 5 percent screenings (through 2.0 mm screen)	Screenings are undersized grain (which can contain small foreign seeds) and is unsuitable to economically make semolina.
No material above screen chaff	0.6 percent above screen chaff	Material above the screen chaff is inconvenient for grain handlers and the processing industries and requires more extensive cleaning.
More than 90 percent hard vitreous kernels (HVK)	More than 80 percent hard vitreous kernels (HVK)	Low HVK, such as below 80 percent, can cause starchy flour production instead of semolina.
No stained grains, black point or black crease	No stained grains, black point or black crease	Fungal staining and black point creates dark flecks in the pasta sheets which are unattractive to consumers.
Test weight higher than 80 kilograms per hectolitre	Test weight above 76 kilograms per hectolitre	Poor test weight can lower the semolina yield obtained.
Falling number (FN) greater than 450 seconds	Falling number (FN) greater than 300 seconds	Weather damaged grains (FN<200) can severely affect pasta properties.
No contamination by foreign grains	Ideally, no contamination by foreign grains	Contamination of durum grain with bread wheat can increase the flour content of semolina, which affects dough performance.
No chemical contamination	No chemical contamination	Growers must follow all chemical label guidelines and monitor maximum residue limits. Pasta manufacturers have a nil tolerance.

Before broad extension and promotion of durum wheat can be successful in this State, the industry needs to overcome the perception held by many growers that durum varieties are unsuited to WA conditions and more susceptible to some diseases than bread wheats.[5] The long term success of the crop will also depend on reducing the yield gap between bread wheat and durum wheat and on the continued quality and price advantage for durum wheat.[6]

Limited trials of one of the leading Australian durum wheat varieties, DBA-Aurora⸰, have been conducted in WA by the Department of Primary Industries and Regional Development (DPIRD) – formerly Department of Agriculture and Food Western Australia (DAFWA) – alongside bread wheats to assess tolerance to abiotic stresses associated with sodic, magnesic and dispersive soils. More information is available from DPIRD researcher Dr Darshan Sharma at: darshan.sharma@agric.wa.gov.au. Adelaide University Agricultural Science department head Dr Jason Able is also interested in trials of newer durum wheat varieties in WA and can be contacted at: jason.able@adelaide.edu.au

4 Grain Trade Australia Wheat Standards (2016-17), Grain Trade Australia, http://www.graintrade.org.au

5 Nguyen, V.H, Llewellen, R.S, Miyan, M.S (2007) Explaining Adoption of Durum Wheat in Western Australia, Australasian Agribusiness Review (Vol.15 – 2007), http://www.agrifood.info/review/2007/Nguyen_Llewellyn_Miyan.pdf

6 N Mohammed S. Miyan1, Alfredo Impiglia2, Wal K. Anderson3, Agronomic practices for durum wheat in an area new to the crop, http://agrobiol.sggw.waw.pl/~cbcs/articles/CBCS_6_2_2.pdf

More than 25 field trials were carried out in this State from 2001 to 2004 at locations in low, medium and high rainfall zones and on a range of soil types to determine the most appropriate management for the production of durum wheat. The trials investigated factors such as variety, seeding rate, N rate and time of sowing.

Durum wheat and bread wheat control varieties were used in these trials and soil test data, crop emergence counts, dry matter production, grain yield and grain quality were collected each year.

This project found that successful production of durum wheat in WA depended on:

- Selection of appropriate soil types
- Crop rotation with legumes — the alternative being largely uneconomic applications of fertiliser N
- Elimination of root diseases by controlling grass weeds, due to susceptibility to crown rot (CR) (*Fusarium pseudograminearum*).[7]

These trials showed no significant yield response to N application following pasture or good pulse rotation.

Researchers suggested the release of a new variety, specifically selected and produced for conditions in the western region, could assist adoption of durum wheat.

Results from all trial sites confirmed early sowing did not reduce grain quality where the combination of soil type and legume rotation were appropriate.[8]

A.2 Durum wheat economics and grain quality

The 2001-2004 WA trials showed if durum wheat was grown on neutral to alkaline clay loam soils following good quality legume pastures or crops, profitability potential was equal to — or higher than — that of bread wheat in some parts of the State.[9,10]

When grown in medium to low rainfall areas on clay loam soils, the best durum wheats yielded only 5-10 percent less than the best performing bread wheats.

Durum wheats are more susceptible than bread wheats to crown rot, but all durum wheat varieties are triple rust resistant and resistant to moderately resistant (R-MR) to *Septoria nodorum* blotch (SNB).

As shown in Table 2, the highest grade of durum (ADR1) must have a minimum protein level of 13 percent and the protein requirement for the ADR2 grade is higher than 11.5 percent. Careful management of soil N is essential to achieve this.

Table 2: Major durum wheat quality classes*[11]

	Protein	Vitreous kernels	Falling number	Screenings	Stained grains*
ADR1	13.0%	>80%	>300	<5%	<3%
ADR2	11.5–12.9%	>70%	>300	<5%	<5%
ADR3	10.0–11.4%		>250	<10%	<20%
Feed	<10.0%				

* Includes black point.

7 Nguyen, V.H, Llewellen, R.S, Miyan, M.S (2007) Explaining Adoption of Durum Wheat in Western Australia, http://www.agrifood.info/review/2007/Nguyen_Llewellyn_Miyan.pdf

8 Anderson, W.K (2004) Development of the Durum Industry in the Western Region, http://finalreports.grdc.com.au/DAW703

9 Nguyen, V.H, Llewellen, R.S, Miyan, M.S (2007) Explaining Adoption of Durum Wheat in Western Australia, Australasian Agribusiness Review (Vol.15 – 2007), http://www.agrifood.info/review/2007/Nguyen_Llewellyn_Miyan.pdf

10 Anderson, W.K (2004) Development of the Durum Industry in the Western Region, http://finalreports.grdc.com.au/DAW703

11 Anderson, W.K (2004) Development of the Durum Industry in the Western Region, http://finalreports.grdc.com.au/DAW703

A.3 Agronomic factors

Paddock and soil type selection are essential to achieve high-yielding, high-protein durum wheat crops.

This crop performs well on deep, friable and well-drained red clay loam soils with a pH of 5.5 or above and does not tolerate acid soils.

A good legume rotation, with excellent grass weed control, is essential to ensure grain protein standards are met. At a minimum, the crop grown immediately before durum wheat in the rotation should be a pulse or a legume-based pasture.

Early sowing is beneficial for high grain yield and protein. It is recommended that growers sow newer durum wheat varieties, as these are better adapted to current growing conditions and are higher-yielding. It is advisable to use a 10 percent higher seeding rate for durum wheat than bread wheats when sowing early in WA.

Target plant density is 100-150 plants per square metre in low and medium rainfall areas. This typically requires a seeding rate of 65-75 kilograms/ha.[12]

It is advised to select planting seed from paddocks with good fertility history and test for germination, vigour and purity. Seeds should also be free from contamination with bread wheat and other cereals.

Soil testing prior to sowing is recommended to help develop a N budget for the crop.

Planning the time of sowing and early N applications are critical. Applications of N at sowing, or up to the start of stem elongation, contribute more to crop biomass and grain yield response compared to later applications, which facilitate greater protein responses. Too much applied N can result in durum wheat crops setting an unattainable yield potential.

The target depth for sowing is 25-35 millimetres, due to the short to medium coleoptile length of durum wheat varieties.[13]

Correct header settings and harvest management can reduce chaff, which causes problems for millers when cleaning the grain. Growers are advised to consider wind and quantity of grain and straw going through the machine to reduce chaff loads.

Similar to bread wheats, grain moisture at harvest for durum wheat should be no higher than 12.5 percent. Pasta produced from weather-damaged grain will not hold its shape when cooked.

12 Anderson, W.K (2004) Development of the Durum Industry in the Western Region, http://finalreports.grdc.com.au/DAW703

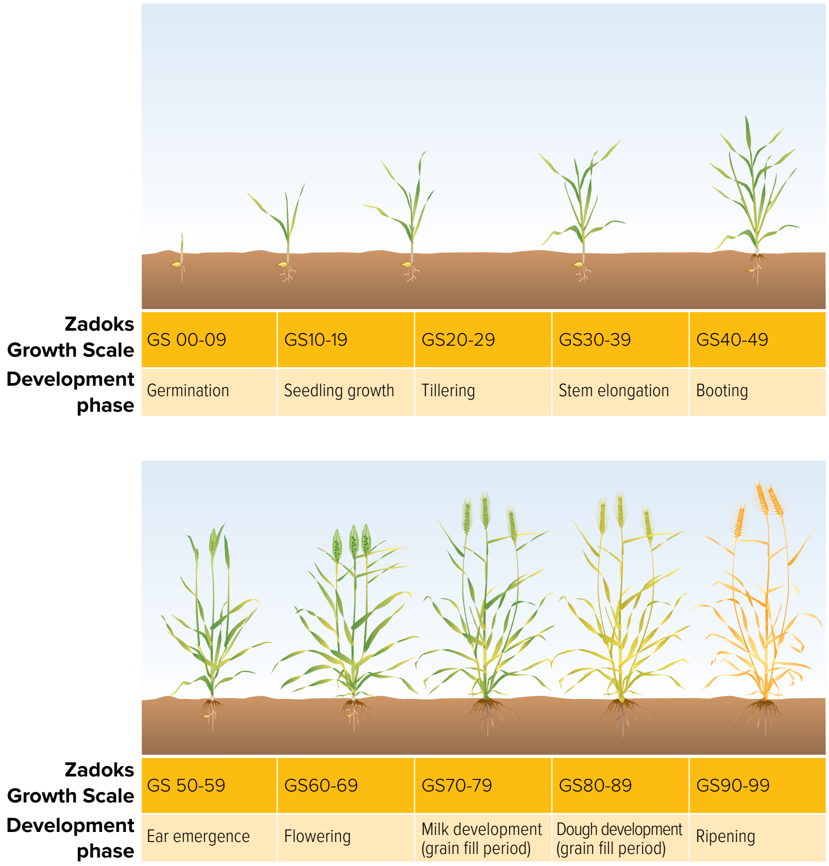
13 Anderson, W.K (2004) Development of the Durum Industry in the Western Region, http://finalreports.grdc.com.au/DAW703

A.4 Plant development and growth stages

Successful durum wheat crop management requires an ability to identify wheat growth stages and understand how these are influenced by nutrition, disease, application of herbicides and fungicides and environmental stressors.

The developmental stages of a wheat plant and the phases during which potential and actual yield are set are outlined in Figure 1.

Figure 1: *Zadoks Growth Scale for wheat*[14]
Developmental phases of a wheat plant from germination through to maturity and the Zadoks Growth Scale associated with each phase.



The Zadoks Growth Scale outlines the 10 distinct development phases of cereal crops and covers 100 individual growth stages.[15] See Chapter 3 for more information.

14 Anderson, W.K. The Wheat book: principles and practice, 2000, http://researchlibrary.agric.wa.gov.au/cgi/viewcontent.cgi?article=1005&context=bulletins

15 Anderson, W.K. The Wheat book: principles and practice, 2000, http://researchlibrary.agric.wa.gov.au/cgi/viewcontent.cgi?article=1005&context=bulletins

A.5 Estimating grain yield

There are four components to wheat grain yield:

- Number of ears (heads)/m^2
- Number of spikelets per ear
- Number of grains per spikelet
- Weight per grain.

Ear and spikelet numbers are set well before flowering, grain numbers are set around flowering and grain weight is set between flowering and maturity.

Grain weight is the least variable of the yield components because it is largely determined by the genetic potential of the variety.

Grain yield is, therefore, most closely related to the number of grains produced by the crop.

Wheat yield can respond to seasonal conditions almost to maturity, due to the capacity of the wheat plant to increase or decrease some or all of its yield components.

The yield of a wheat crop can be estimated by:

- Grain yield (kg/ha) — this is equal to: ears/m^2 x grains/spikelet x weight/grain (g) x 10
- Ears/m^2 — count the ears in 1 m^2 of crop or count the number of ears in a 1 m row length and multiply by 5.6 (there are 5.62 m of row in one square metre for a 7-inch or 17.8 cm row spacing). For 12-inch, or 30 cm, row spacing, multiply by 3.3
- Spikelets per ear — count the number of spikelets on an average ear. For most crops it will be between 16-20
- Grains per spikelet — count the grains in spikelets at the top, middle and bottom of the ear. More and heavier grains are usually set in the central spikelets. The number should be between two and four
- Grain weight — grain weight depends on growing conditions and variety, but will usually be between 0.0025 and 0.045 g/grain (2.5-4.5 mg). To determine grain weight, count and weigh 1000 grains and divide by 1000 to get weight/grain. If it is not possible to weigh grain, a good average figure to use is 0.0356 g/grain (3.56 mg/grain), which is equivalent to 28 grains/g
- Grain yield — using the components above, the grain yield can be calculated as: Yield = 100 (ears/m^2) x (18 spikelets x 2 grains/spikelet x 0.03 g/grain) = 100 x 1.08 = 108 g/m^2 or 1.08 t/ha
- This leads to the very simple rule of thumb that 100 ears/m^2 will generate about 1 t/ha of grain.

MORE INFORMATION

University of Adelaide: School of Agriculture, Food and Wine 'Durum Breeding Program': http://www.agwine.adelaide.edu.au/research/plant-genetics-breeding//

Hart Field Trial results , 2015, 'Durum Comparison, Hart Field-Site Group': http://www.hartfieldsite.org.au/media/2015%20Trial%20Results/2015_Hart_Trial_Results.pdf

GRDC National Variety Trials DBA-Aurora$^{\phi}$: http://www.nvtonline.com.au/wp-content/uploads/2014/09/DBA-Aurora-Southern-Fact-Sheet.pdf

Planning and paddock preparation

1.1 Variety development

The release of durum wheat varieties specifically selected and produced for conditions in Western Australia will assist the uptake of this crop in the western region, as most progress is made when improved management and improved varieties are adopted together.

Development of new varieties is being undertaken nationally and the promising line DBA-Aurora$^{\phi}$, bred by Durum Breeding Australia (DBA), has undergone limited assessment in some field trials in WA in recent years.

In 2016, researchers at the Department of Primary Industries and Regional Development (DPIRD) included it in an agronomy project investigating a range of germplasm on sodic, magnesic and dispersive soils.

Preliminary findings were that compared to grain yields for Mace$^{\phi}$, DBA-Aurora$^{\phi}$ achieved:

- 75 per cent (of Mace$^{\phi}$ yield) on a sodic dispersive soil at Merredin
- 54 per cent on a sodic dispersive soil at Katanning
- 32 per cent on a sandy soil at Merredin
- 100 per cent (the same as Mace$^{\phi}$) on a saline soil at Nangeenan.

(SOURCE: Dr Darshan Sharma, DPIRD, 2017 – unpublished)

For more information about this trial, contact DPIRD Genetic Improvement project manager Dr Darshan Sharma.

DBA is a national initiative between GRDC, the University of Adelaide (UA) and NSW Department of Primary Industries (NSWDPI). It was formerly the Australian Durum Wheat Improvement Program (ADWIP), which was set up in 2007.

Funded by GRDC and pasta maker San Remo Macaroni Pty Ltd, ADWIP had southern and northern research nodes to breed varieties suited to local conditions.[1]

Since 2010, Dr Jason Able has run the southern node breeding program of DBA at UA and the northern node breeding operation is led by Dr Gururaj Kadkol, at NSWDPI.

DBA-Aurora$^{\phi}$ can be considered a 'step-change' variety release from DBA and breeders are continuing to develop durum wheat lines that will provide a significant boost to national industry expansion.

A major consideration about whether to grow durum wheat each season has been the fear of crop losses from crown rot (caused by the fungus *Fusarium pseudograminearum*).

The susceptibility of durum wheat to crown rot is exacerbated by stubble retention, high levels of cereal cropping in rotations and zinc (Zn) deficiency in some soils.

Varietal reactions are confounded by the timing of water stress, presence of another closely related pathogen (*F. culmorum*) that causes Fusarium head blight (FHB), soil type and complexity of the genetics for resistance.

Some advanced breeding lines are showing reduced susceptibility to crown rot and additional improvements are expected to be made in coming years through fast-tracked pre-breeding research.

1 The University of Adelaide (2016) School of Agriculture, Food and Wine — Durum Breeding Program, http://www.agwine.adelaide.edu.au/

Diversity in parental genetics and short generation intervals are integral to the breeding program. DBA imports material from across the world to incorporate diversity into Australian breeding material.

Materials have come from as far afield as the International Maize and Wheat Improvement Center (CIMMYT) in Mexico, International Centre for Agricultural Research in the Dry Areas (ICARDA) in Syria and Società Produttori Sementi in Italy. More recently, DBA's southern node has started investigating germplasm from Canada and the USA.[2]

Worldwide, molecular markers play an important role in today's breeding programs. DBA is no exception and is collaborating with fellow researchers to develop and implement marker-assisted selection (MAS) at UA.

1.2 Choosing a suitable variety

From 2007 to 2015, several new durum wheat varieties were released in Australia. These included DBA-Aurora⫯, Hyperno⫯, Saintly⫯, Tjilkuri⫯, Yawa⫯ and WID802⫯ in the southern region and Caparoi⫯, EGA Bellaroi⫯, Jandaroi⫯, Yallaroi⫯ and Wollaroi in the northern region. Past trials in WA have found the mid-season varieties Yallaroi⫯, Kalka, EGA Bellaroi⫯ and Arrivato may be suitable for local conditions and may be best sown first in a wheat program – but not before May. These trials also indicated the short season variety Wollaroi should be sown later, but not after mid-June.[3] The commonly-grown southern region varieties Hyperno⫯ and Saintly⫯ may also have good adaptation in areas suitable for growing durum in WA.

Key characteristics of some of these older varieties – and some more recent lines – that may have potential to be grown in WA are outlined below.

DBA-Aurora⫯

Figure 1: *DBA-Aurora⫯ was released in 2014 and has good grain size and improved disease resistance.*

(SOURCE: University of Adelaide)

- Released 2014 in the southern region by DBA
- Significant improvements in grain size, screenings and disease resistance
- Very high yielding

2 The University of Adelaide (2016) School of Agriculture, Food and Wine — Durum Breeding Program, http://www.agwine.adelaide.edu.au/

3 Anderson, W.K (2004) Development of the Durum Industry in the Western Region, http://finalreports.grdc.com.au/DAW703

MORE INFORMATION

National Variety Trials 'Durum wheat trials, WA' 2009 and 2010: https://www.nvtonline.com.au/nvt-results-reports/?nocollapseomatic=1#lat=-30.77&lng=121.50&zoom=5

Queensland Department of Agriculture and Fisheries 'Durum Wheat in Queensland': https://www.daf.qld.gov.au/plants/field-crops-and-pastures/broadacre-field-crops/wheat/durum-wheat

New South Wales Department of Primary Industries 'Primefacts': http://www.dpi.nsw.gov.au/__data/assets/pdf_file/0007/63646/Agronomy-of-the-durum-wheats---Primefact-140-final.pdf

NSWDPI 'Durum Wheat Production': http://www.nvtonline.com.au/wp-content/uploads/2013/03/Crop-Guide-NSW-Durum-Wheat-Production.pdf

Wheat Quality Australia (for classification): http://wheatquality.com.au/classification/how-it-works/classes/

GRDC-DPIRD Wheat Variety Sowing Guides for Western Australia: https://www.agric.wa.gov.au/grains-research-development/2018-wheat-variety-sowing-guide-western-australia

- Limited trials undertaken in WA in 2016 as part of an agronomy project investigating a range of germplasm on sodic, magnesic and dispersive soils
- Preliminary findings were that compared to grain yields for Mace⁽ᵈ⁾, DBA-Aurora⁽ᵈ⁾ achieved:
  - » 75 per cent (of Mace⁽ᵈ⁾ yield) on a sodic dispersive soil at Merredin
  - » 54 per cent on a sodic dispersive soil at Katanning
  - » 32 per cent on a sandy soil at Merredin
  - » 100 per cent (the same as Mace⁽ᵈ⁾) on a saline soil at Nangeenan.

(SOURCE: Dr Darshan Sharma, DPIRD, 2017 - unpublished)

For more information about this trial, contact Dr Darshan Sharma at DPIRD.

Yawa⁽ᵈ⁾

Figure 2: *Yawa⁽ᵈ⁾ is a very high yielding durum wheat variety and was released in 2012.*

(SOURCE: Jason Able, University of Adelaide)

- Released 2012
- Very high yielding
- Good grain quality characteristics
- May be suited to parts of WA but check its classification through Wheat Quality Australia at http://wheatquality.com.au/classification/how-it-works/classes/.

WID802⁽ᴾ⁾

Figure 3: *The high yielding variety WID802⁽ᴾ⁾ has good grain quality traits.*

(SOURCE: Jason Able, University of Adelaide)

- Released 2012
- Very high yielding
- Good grain quality characteristics
- May be suited to parts of WA but check its classification through Wheat Quality Australia at http://wheatquality.com.au/classification/how-it-works/classes/.

Tjilkuri⁽ᴾ⁾

Figure 4: *Released in 2010, the durum wheat Tjilkuri⁽ᴾ⁾ had improved semolina quality traits compared to older varieties.*

(SOURCE: GRDC)

- Released 2010
- A slightly later maturing variety
- Consistently higher yield and quality characteristics — including semolina colour — than older varieties
- Compact stature — less likely to lodge than Hyperno⁽ᴾ⁾
- May have suitability for parts of WA but check its classification through Wheat Quality Australia at http://wheatquality.com.au/classification/how-it-works/classes/.

Hyperno⁽ᴰ⁾

Figure 5: *Hyperno⁽ᴰ⁾ has demonstrated high and stable grain yields across SA and NSW durum growing regions and performs particularly well in higher yielding environments. It may be suited to durum growing areas in WA.*

(SOURCE: AGT)

- Released 2008
- Mid-season maturing variety
- Consistently high and stable grain yields in SA and NSW
- Very good semolina and pasta making quality
- ADR classification
- Excellent stem, stripe and leaf rust resistance
- Very susceptible to crown rot
- May suit potential durum production areas of WA.

(SOURCE: AGT)

Saintly⁽ᴰ⁾

Figure 6: *Saintly⁽ᴰ⁾ is an early maturing durum that is well suited to southern production zones that risk having a sharp finish to the growing season. It may be suited to durum growing areas in WA.*

(SOURCE: AGT)

- Released 2008
- Early maturing variety
- High relative yields in tough finishes to the season
- Tip-awned, allowing for hay production
- Very good semolina and pasta making quality
- ADR quality classification in SA and VIC
- Very susceptible to crown rot.

(SOURCE: AGT)

Caparoi⌽

- Released 2010, primarily for northern Australia
- But may be suitable for central and southern parts of WA on neutral and alkaline soils (not saline or acidic)
- High-yielding, mid-season, semi-dwarf variety
- High yield performance noted in southern Queensland
- Improved dough strength relative to EGA Bellaroi⌽
- High level of resistance to stem rust, stripe rust and yellow leaf spot
- Moderately resistant-moderately susceptible to leaf rust
- Moderately tolerant to root lesion nematodes (RLN)
- Very susceptible to crown rot
- Good resistance to lodging and shattering.

Jandaroi⌽

- Released 2009
- Bred for NSW and Queensland but may be suited to parts of WA where durum can be grown, typically on neutral to alkaline soils (not saline or acidic)
- Superior semolina and pasta quality
- A bright, clean, yellow appearance and no discoloration
- High level of resistance to stem rust, leaf rust
- Very susceptible to crown rot.

EGA Bellaroi⌽

- Released 2003
- The current major variety grown in Australia
- Has been trialled in WA eastern grainbelt, where it showed some suitability
- Grain yield similar to, or better than, Yallaroi⌽ and Wollaroi⌽ in northern NSW
- Grain protein consistently higher than other current commercial varieties
- Exceptional pasta-making quality
- Resistant-moderately resistant to stem and leaf rust
- Resistant to yellow leaf spot and common root rot
- Moderately tolerant to RLN
- Very susceptible to crown rot
- Good black point and lodging resistance.

1.2.1 Future breeding directions

DBA aims to continue developing and commercially releasing export quality durum wheat varieties with traits including:

- Higher grain yield
- Improved adult plant resistance for the three major cereal crop rusts and yellow leaf spot
- Complete resistance to flag smut and common bunt (also known as stinking smut)
- Grain size higher than 45 grams
- Resistance to pre-harvest sprouting and enhanced quality characteristics.

The resistance of durum wheat varieties grown in Australia to major diseases and other conditions affecting these crops is outlined in further detail in Table 1.

Table 1: Levels of resistance to diseases and other conditions (durum varieties compared to a bread wheat variety).

	Durum wheats				Bread wheat
	Jandaroi⟨PBR⟩	**Caparoi**⟨PBR⟩	**Hyperno**⟨PBR⟩	**EGA Bellaroi**⟨PBR⟩	**Kennedy**⟨PBR⟩
Disease					
Yellow spot	MR-MS	MR	MS	MR	MR
Crown rot	VS	VS	VS	Vs	MS-S
Common root rot	MR	R-MR	R-MR	MR	MS
RLN tolerance[A]	MI	MT-MI	MT-MI	MI	MI
RLN resistance[A]	MS-S	MS	MR	MR-MS	S-VS
Stem rust	R	R-MR	R	R-MR	MS
Leaf rust	MR	MR-MS	R-MR	MR-MS	MS
Stripe rust	MR	MR	MR	MR	MS
Agronomy					
Resistance to black point[B]	MR-R	MR-MS	MR-MS	R-MR	R
Resistance to lodging	MR	MR	MR-MS	R	MR
Resistance to shattering	MR	R-MR	R-MR	R	R-MR
Resistance to sprouting	R-MR	MR-MS	MR-MS	MS	S

R = Resistant MR = Moderately resistant MS = Moderately susceptible S = Susceptible VS = Very susceptible T = Tolerant MT = Moderately tolerant I = Intolerant VI = Very intolerant.

[A]Root lesion nematode (RLN) tolerance applies to *Pratylenchus thornei* and not *P. neglectus*; tolerant varieties yield well in the presence of RLN; resistant varieties prevent RLN reproduction.

[B]Back point will not cause a reduction in yield but may result in grain receiving a lower quality classification.

1.2.2 Variety comparison trial

A major comparison trial of existing and new durum wheat varieties was set up in 2015 at the Hart Field Trial site, in SA, to assess performance against industry standards.

This provides recent data for some of the lines that show potential for WA conditions and it found average grain yield for all durum varieties was 3.07 tonnes per hectare, with a range of 2.88 t/ha to 3.22 t/ha. There was a variation of only 0.34 t/ha between yields of all seven varieties trialled, as shown in Table 2.[4]

4 Hart Field Trial results (2015) Durum Comparison, Hart Field-Site Group (2015), http://www.hartfieldsite.org.au/media/2015%20Trial%20Results/2015_Hart_Trial_Results.pdf

Table 2: Grain yields and quality results from the Hart Field Trial Site in South Australia in 2015.[5]

Variety	Grain yield t/ha	% of site average	Protein %	% of site average	Test Weight kg/hL	% of site average	Screenings %	% of site average
Caparoi$^{\phi}$	3.03	99	12.2	103	79.7	102	1.8	46
Tamaroi	2.88	94	11.8	100	78.9	101	2.1	55
Saintly$^{\phi}$	2.98	97	11.9	101	77.9	100	2.3	58
Hyperno$^{\phi}$	3.01	98	11.8	100	76.9	98	7.5	195
DBA-Aurora$^{\phi}$	3.22	105	11.4	97	77.4	99	2.7	69
Tjilkuri$^{\phi}$	3.11	102	12.2	103	77.9	100	3.9	101
Yawa$^{\phi}$	3.22	105	11.5	97	77.9	100	6.8	176
Site Average	**3.07**	**100**	**11.8**	**100**	**78.1**	**100**	**3.9**	**100**
LSD (P≤0.05)	0.21		0.4		1.2		1.2	

Test weight values of varieties trialled were high and only two varieties (Hyperno$^{\phi}$ and Yawa$^{\phi}$) exceeded a minimum 5 percent screenings. All varieties were above the minimum test weight value of 76 kg/hL. Similar to trials in 2014, Caparoi$^{\phi}$ had the highest test weight followed by Tamaroi.

Seeding date was May 6 and fungicides and herbicides were applied as necessary to keep the crop canopy free of disease and weeds.

All plots were assessed for grain yield, protein, test weight and screenings with a 2.0 millimetre screen.

The highest yielding varieties were DBA-Aurora$^{\phi}$, Yawa$^{\phi}$, Tjilkuri$^{\phi}$ and Caparoi$^{\phi}$. Achieving target protein is key to growing durum wheat and the trial showed varieties ranged from 11.4 to 12.2 percent, averaging 11.8 percent. Tjikuri$^{\phi}$ and Caparoi$^{\phi}$ had the highest protein levels at 12.2 percent.

Screening levels across the trial were generally low, with the exception of Hyperno$^{\phi}$ and Yawa$^{\phi}$.[6]

1.3 Durum wheat as a rotation crop

Durum wheat varieties are relatively resistant to the Root Lesion Nematode (RLN) *Pratylenchus thornei*, compared to other winter cereal crops.[7]

This increases their value in rotations to reduce nematode numbers in the soil.

However, durum wheat crops will tend to more rapidly build up crown rot inoculum, which can negatively affect subsequent winter cereal crops.

A robust crop rotation should be planned across several seasons if successful crops of durum wheat are to be produced.

It is advisable to sow durum wheat as the first cereal crop after a non-cereal species and to avoid growing successive durum crops.

Rotations of durum wheat with non-cereal species, including pulses, canola and pasture legumes, can provide benefits of:

- Controlling root disease, especially crown rot
- Providing for the biological fixation of nitrogen (N) by legumes
- Controlling weeds and contaminant crop species
- Aiding in herbicide group rotations.

5 Hart Field Trial results (2015) Durum Comparison, Hart Field-Site Group (2015), http://www.hartfieldsite.org.au/media/2015%20Trial%20Results/2015_Hart_Trial_Results.pdf

6 Hart Field Trial results (2015) Durum Comparison, Hart Field-Site Group (2015), http://www.hartfieldsite.org.au/media/2015%20Trial%20Results/2015_Hart_Trial_Results.pdf

7 Kneipp, J (2008) Durum Wheat Production, NSW Department of Primary Industries, http://www.nvtonline.com.au/wp-content/uploads/2013/03/Crop-Guide-NSW-Durum-Wheat-Production.pdf

1.4 Paddock selection and weed control

Durum wheat is best grown where a reliable harvest of high protein (more than 13 percent), plump hard vitreous grain can be achieved.

It is recommended to select paddocks that are fertile, store good levels of water, and receive reliable in-crop rainfall.

Durum wheat should not be sown into paddocks that are known to carry high levels of crown rot inoculum. A suitable rotation should be practiced to reduce crown rot inoculum levels.

Ground preparation is the same as for bread wheat.

Adequate weed control is vital and ideally should eliminate all weeds and volunteer plants of bread wheat, barley and/or other crop species.

This can be achieved by controlling weeds in preceding crops and during fallow periods, rotating crops, growing competitive durum wheat crops and targeted use of registered herbicides at full label rates.

1.5 Seedbed requirements

Quality seed for planting is essential. It is advised to use seed that has a high germination percentage, is large and plump, is genetically pure and free of all contaminants, such as weed seeds and impurities of other winter cereals (particularly bread wheat and barley).

Seed is best treated with an appropriate fungicide to avoid head disease (such as smuts and bunts) and leaf diseases (such as stripe rust).

Registered fungicide actives for wheat/durum wheat in WA include:

- Tebuconazole
- Propiconazole
- Flutriafol
- Metalaxyl-M
- Fluxapyroxad
- Sedaxane
- Ipconazole
- Fluquinconazole
- Prothioconazole
- Penflufen
- Triticonazole
- Triadimenol
- Difenoconazole
- Thiram
- Carboxin.

It is recommended to plant seed into a cultivated or chemically prepared seedbed at a depth of about 25-35mm as durum wheat has a short to medium coleoptile length and preferably to use minimum disturbance equipment with a press wheel adjusted to soil and moisture conditions.

Seeding rates and sowing times will vary from region to region and it is best to check with local advisers and seek local information.

MORE INFORMATION

GRDC 'Ground Cover Water Use Efficiency': http://www.grdc.com.au/Media-Centre/Ground-Cover/Ground-Cover-Issue-54/Tracking-wateruse-efficiency

1.6 Water use efficiency and salt tolerance

Plant breeders in the DBA project, a collaboration between NSWDPI, The University of Adelaide (UA) and researchers at CSIRO Plant Industry (in Canberra and WA), are developing water use efficient and salt tolerant durum wheat lines to increase yields in current production areas, as well as in new environments.[8]

Researchers are improving water use efficiency by trying to combine several traits: high transpiration efficiency, long coleoptiles and early vigour.

Using 50 years of climate data and computer simulation, they have found combining high transpiration efficiency and early vigour is likely to make durum wheat much more suitable for growing in all cropping areas of Australia.

Elite durum varieties have low transpiration efficiency, but the research team has found a highly transpiration-efficient durum line to cross with these. This will give the plants a water use efficiency trait similar to that of new bread wheat varieties.

The team is also introducing alternative dwarfing genes from European durum wheats into commercial varieties. These genes restrict plant height, but allow the expression of long coleoptiles.

Longer coleoptiles provide some insurance that the shoot reaches the soil surface, even when deep sowing is required because of receding topsoil moisture, or when there is uneven sowing depth.

CSIRO and NSWDPI are also developing salt tolerant durum wheat lines, to allow durum to be grown in areas affected by subsoil salinity. This follows a search of the Australian Winter Cereal Collection (AWCC) in Tamworth that revealed ancient Persian durum wheats with the ability to exclude salt from their roots.

Durum wheat has traditionally been more susceptible to moderately saline soils than bread wheat.

The team has identified two major genes that confer the salt tolerance and a molecular marker has been found for one of these genes. There is ongoing research to find a marker for the other, with the aim of breeding a commercial variety of durum wheat that is tolerant of saline soils.

1.7 Grain quality

Grain quality is key to obtaining premium prices for durum wheat.

Downgrading at receival points might occur if grain contains mottling, black point or weather damage.

The most frequent causes of downgrades in newer durum wheat varieties include grain with:

- » Higher than 5 percent grain screenings
- » Protein below 13 percent
- » Hard-vitreous kernels below 80 percent – resulting in mottled kernels.[9]

In environments where there is an increased risk of quality downgrading from grain screenings, it is advisable to use larger grained varieties, such as Tjilkuri⫯ and Caparoi⫯.

In high yielding environments, new varieties tend to be more likely to achieve a higher yield using the same N supply but have potential to produce lower grain protein than some older varieties.

This means more N may be needed, but is best applied as late as possible to minimise the potential for increasing screenings.

8 GRDC (2005) Tracking Water-Use Efficiency, GRDC Groundcover Issue 54, http://www.grdc.com.au/Media-Centre/Ground-Cover/Ground-Cover-Issue-54/Tracking-wateruse-efficiency

9 Department of Agriculture and Fisheries (2012) Durum Wheat in Queensland, Queensland Department of Agriculture, Fisheries and Forestry, http://www.daff.qld.gov.au/plants/field-crops-and-pastures/broadacre-field-crops/wheat/durum-wheat

1.8 Diseases and pests

Major diseases to affect durum wheat crops include: leaf, stem and stripe rust; crown rot; leaf spot diseases; and fusarium head blight. More information about managing diseases can be found in Chapter 5. Insects are not typically a major problem in WA winter cereals, but several pests can cause serious damage to wheat crops in some seasons.

The significance of particular pests to wheat growth and yield varies from season to season and within farming systems. More information can be found in Chapter 7.

Comprehensive guidelines about identification and management of pests in WA cropping systems are available through the GRDC-Department of Primary Industries and Regional Development (DPIRD) MyPestGuide app at https://mypestguide.agric.wa.gov.au/#/

This hub contains information about 200 crop and grain storage pests, beneficial and biological control agents and biosecurity pest threats specific to WA.

A key feature of the app is that it enables users to send pest reports and photos direct to entomologists at DPIRD for diagnosis and management advice.

MORE INFORMATION

GRDC 'Durum Quality and Agronomy Fact Sheet': www.grdc.com.au/GRDC-FS-Durum

GRDC Western 'Wheat' and Northern 'Durum' GrowNotes™: www.grdc.com.au/GrowNotes

Planting

2.1 Overview

Durum wheat seed size is, on average, 20 percent bigger than bread wheat seed size and it is advised to increase typical seeding rates used for bread wheat by this amount when planting durum wheat varieties.[1]

The target durum wheat plant density across southern Australia ranges from 120 to 200 plants per square metre, depending on rainfall zone, with about 120-150 plants/m^2 expected to be needed for optimal establishment in Western Australian conditions.[2]

A reduced germination percentage, or a late sowing, may necessitate increasing seeding rates.[3]

Ground preparation for durum wheat is similar to that for growing bread wheat.

Conventional sowing equipment can be used, but may have to be adjusted for the bigger seed size.

Adequate cultivation and/or herbicide application should eliminate volunteer plants of bread wheat, barley and other crop/weed species.

It is advised to treat durum wheat seed with an appropriately registered product just before sowing to control 'damping-off' from root diseases, smut or bunt.

But it is worth nothing that some chemical constituents can reduce viability and seedling vigour if these remain in contact with the seed for any length of time.

2.2 Seed germination and vigour

It is recommended to use sound seed that is clean and true to varietal type.

Seed should be high quality and preferably sourced from certified seed stocks, with a germination test result of more than 80 percent.

Before harvesting any on-farm seed stocks for the following season, ensure control of rogue 'off-types' and contaminant crop and weed plants/seeds.

Seed grain retained on-farm for sowing in subsequent seasons is ideally stored in clean silos with aeration capacity and ability to be sealed for insect control.

Durum wheat seed should be kept dry and as cool as possible to help maintain high viability for the following season.

2.2.1 Seed treatments

Registered seed dressing and in-furrow fungicides are particularly important for early sown and long-season wheat crops and, in some cases, can replace the need for a foliar spray before flag leaf emergence.

1 R Hare (2006) Agronomy of the Durum Wheats Kamilaroi, Yallaroi, Wollaroi and EGA Bellaroi, Primefacts 140, NSW Department of Primary Industries, http://www.dpi.nsw.gov.au/__data/assets/pdf_file/0007/63646/Agronomy-of-the-durum-wheats---Primefact-140-final.pdf

2 R Hare (2006) Agronomy of the Durum Wheats Kamilaroi, Yallaroi, Wollaroi and EGA Bellaroi, Primefacts 140, NSW Department of Primary Industries, http://www.dpi.nsw.gov.au/__data/assets/pdf_file/0007/63646/Agronomy-of-the-durum-wheats---Primefact-140-final.pdf

3 R Hare (2006) Agronomy of the Durum Wheats Kamilaroi, Yallaroi, Wollaroi and EGA Bellaroi, Primefacts 140, NSW Department of Primary Industries, http://www.dpi.nsw.gov.au/__data/assets/pdf_file/0007/63646/Agronomy-of-the-durum-wheats---Primefact-140-final.pdf

It is advisable to treat durum wheat seed with an appropriately registered disease control product just prior to sowing for control of some diseases. See Chapter 5 for more information.

Commercial durum wheat varieties are highly resistant to some loose smut, flag smut and stinking smut fungi.

Seed treatment can offer protection to establishing seedlings from damping-off diseases.

Registered seed fungicide actives for durum wheat include:

- Tebuconazole
- Propiconazole
- Flutriafol
- Metalaxyl-M
- Fluxapyroxad
- Sedaxane
- Ipconazole
- Fluquinconazole
- Prothioconazole
- Penflufen
- Triticonazole
- Triadimenol
- Difenoconazole
- Thiram
- Carboxin.

It is recommended to check label rates and application details closely, as some chemical constituents can reduce viability and seedling vigour if they remain in contact with the seed for a significant period of time.[4]

Some fungicide seed dressings also have potential to reduce coleoptile length and cause 'silly seedling syndrome' where leaves grow under the soil surface but do not emerge.

2.3 Time of sowing

Durum wheat yield potential can be influenced by sowing date.

The most recent durum varieties, including DBA-Aurora⍉, Tjilkuri⍉, WID802⍉ and Yawa⍉, have shown improved yield potential when sown early (May 1-15) compared to mid-season (May 15-June 5) sowing dates.

Varieties with higher yield potential, such as Yawa⍉, WID802⍉ and Hyperno⍉, require early sowing in most Australian grain growing areas.

This helps maximise yield and minimise the likelihood of quality downgrades.

In comparison, Caparoi⍉ and Tjilkuri⍉ tend to favour later sowing dates in many areas, as these lines are less likely to be downgraded due to small grain screenings. Varieties with smaller grain size should be avoided if sowing is delayed.

Optimum sowing date will depend on the maturity rank of the variety, latitude of the sowing site and topographic aspect (including north/south facing slope and elevation).

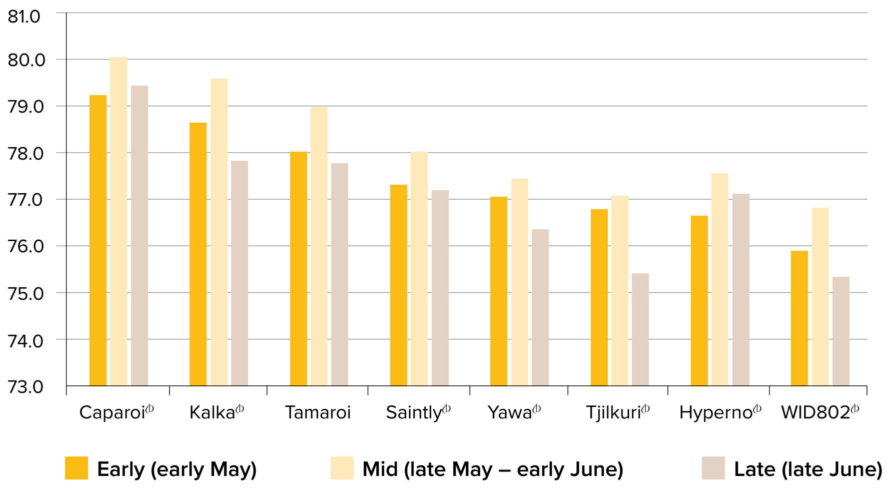
The effect of time of sowing on aspects of durum wheat grain quality (in test weights) is shown in Figure 1.

MORE INFORMATION

GRDC '2013 Update Paper: Wheat Variety Response to Dry Sowing and Seeding Depth': http://giwa.org.au

4 R Hare (2006) Agronomy of the Durum Wheats Kamilaroi, Yallaroi, Wollaroi and EGA Bellaroi, Primefacts 140, NSW Department of Primary Industries, http://www.dpi.nsw.gov.au/__data/assets/pdf_file/0007/63646/Agronomy-of-the-durum-wheats---Primefact-140-final.pdf

Figure 1: *Effect of sowing date on varietal differences in test weight.*[*5]



*Test weight averaged across three years of trials at Turretfield (2009) and Tarlee (2010/11) at early, mid, and delayed sowing dates.

The time of sowing of a particular variety is a critical factor in crop risk management. Growers in WA are advised to aim for a balance to minimise the combined risks of frost damage around flowering and grain filling, moisture stress at this time and rain or storm damage just prior to harvest.

Crops sown earlier than optimal timing can be exposed to an elevated frost risk. Those sown later than the optimal period could encounter high moisture or heat stress and/or harvest spoilage/quality issues.

These risks cannot be eliminated, but minimisation is possible using a range of management practices.

2.4 Maturity

There is a relatively small range of crop maturity in commercially available durum wheat varieties, compared with bread wheat varieties.[6]

Durum wheat lines are typically similar in maturity to the fastest-maturing bread wheats. This is an important consideration when managing frost risk, but can limit opportunities to exploit early planting opportunities.

Extended flowering could reduce the risk of pollination failure caused by frost or extended moist weather.

The time difference in reaching full maturity between the early-flowering and late-flowering tillers tend to be small. Therefore, early heads are not likely to be ripe for many days ahead of later heads.

Harvesting should not be delayed significantly.

MORE INFORMATION

GRDC 'Cereal Growth Stages Guide': www.grdc.com.au/GRDC-Guide-Cereal-Growth-Stages

5 GRDC '2013 Update Paper: Wheat Variety Response to Dry Sowing and Seeding Depth': http://giwa.org.au

6 Department of Agriculture and Fisheries (2012) Durum Wheat in Queensland, Queensland Department of Agriculture, Fisheries and Forestry, http://www.daff.qld.gov.au/plants/field-crops-and-pastures/broadacre-field-crops/wheat/durum-wheat

2.5 Sowing rates

Durum wheat seeding rates should be at least 10 percent higher than those typically used for bread wheat varieties to allow for bigger seed size.[7]

If sowing early in the season, seeding rates can be further increased — by about 10 percent — to allow for reduced tillering in durum wheat varieties and a reliance on more plants/m^2 for shoot production and, therefore, grain producing heads.[8]

Sowing rate can be considered a risk management tool.

Dense stands of plants tend to produce few tillers per plant (i.e. the primary and a few secondary tillers). Stands at a reduced density tend to have plants that produce a larger number of tillers per plant.

Such reduced-density stands typically have more flexibility in response to changing growing conditions (such as if moisture is limiting). Fewer tillers are initiated, but if seasonal conditions improve additional tillers may develop.

2.6 Sowing depth

In a well-prepared seedbed, the recommended sowing depth is between 25-35 mm.

Current durum wheat varieties are semi-dwarf lines, which means the length of the coleoptile is reduced and it cannot penetrate deeper in the soil.

Research has shown sowing large seeds (of at least 35-38 milligrams) at a depth of 25-35 mm into marginal moisture can lift plant establishment for a range of wheat varieties — even those with shorter coleoptiles.[9]

Large seed tends to produce more vigorous seedlings that can typically better tolerate early season stresses.

In a season with a dry start, deep sowing into moisture is a tool that can ensure crops are established in the optimal sowing window.

While deeper sowing can sometimes reduce crop germination percentage, the yield from the earlier sowing may offset yield losses associated with sowing later in the season.

Deep sowing into moisture may help ensure the wheat crop hits the optimum flowering window while also assisting with the logistics of a large seeding program.

Several factors influence the capacity of wheat seed to emerge from depth, including:

- Coleoptile length
- Seed size
- Soil conditions, including temperature
- Fungicide treatments
- Herbicides, such as trifluralin.

Sowing varieties with short coleoptile lengths too deep can cause poor establishment, as the shoot will emerge from the coleoptile underground and may never reach the soil surface, as illustrated in Figure 2.[10]

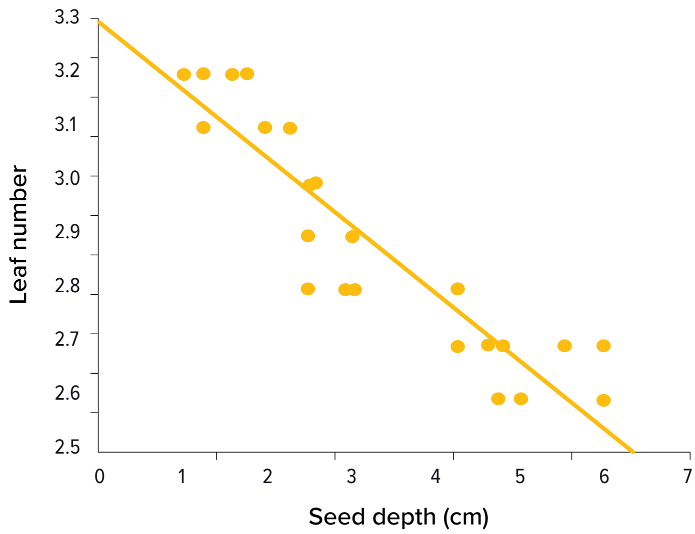
7 R Hare (2006) Agronomy of the Durum Wheats Kamilaroi, Yallaroi, Wollaroi and EGA Bellaroi, Primefacts 140, NSW Department of Primary Industries, http://www.dpi.nsw.gov.au/__data/assets/pdf_file/0007/63646/Agronomy-of-the-durum-wheats---Primefact-140-final.pdf

8 R Hare (2006) Agronomy of the Durum Wheats Kamilaroi, Yallaroi, Wollaroi and EGA Bellaroi, Primefacts 140, NSW Department of Primary Industries, http://www.dpi.nsw.gov.au/__data/assets/pdf_file/0007/63646/Agronomy-of-the-durum-wheats---Primefact-140-final.pdf

9 DAFWA (2014) Size Does Matter for Deep Sown Wheat, https://www.agric.wa.gov.au/news/media-releases/size-does-matter-deep-sown-wheat

10 Anderson, W.K. The Wheat book: principles and practice, 2000, http://researchlibrary.agric.wa.gov.au/cgi/viewcontent.cgi?article=1005&context=bulletins

Figure 2: *Impact of depth of sowing on seedling establishment.*[11]



In 1990 trials, grain yield was reduced by a minimum of 10 percent when short coleoptile wheat lines were sown deeper than 5 cm.

Coleoptile length is influenced by several factors, including variety, seed size, temperature, soil moisture and some fungicide dressings and pre-emergent herbicides.

MORE INFORMATION

GRDC '2014 Update Paper: Aim for Narrowest Possible Row Spacing': https://grdc.com.au/Research-and-Development/GRDC-Update-Papers/2014/05/Aim-for-the-narrowest-possible-row-spacing

2.7 Row spacing

Choice of wheat row spacing is a compromise between ease of stubble handling, effective use of pre-emergent herbicides, managing weed competition and crop yield.

The impact of row spacing on cereal yield varies depending on growing season rainfall, time of sowing and potential yield of the crop.

The higher the yield potential, the greater the negative impact of wider rows on wheat yield in WA, as shown in Table 1.

Table 1: Benefits and costs of a wider row spacing in wheat.[12]

Benefits	Costs
Easier stubble management at sowing and faster sowing speeds.	Lower yields.
Lower fuel and machinery costs during sowing.	Increased weed competition.
Subsequent crops can be sown on the interrow.	Slower canopy closure (more weeds and soil evaporation).
Higher rates of trifluralin can be used without crop damage.	Fertiliser toxicity if seeding pattern not altered.
Less soil disturbance and greater moisture conservation for grain filling in some seasons and lower rainfall areas.	Higher potential for lodging.

11 R Hare (2006) Agronomy of the Durum Wheats Kamilaroi, Yallaroi, Wollaroi and EGA Bellaroi, Primefacts 140, NSW Department of Primary Industries, http://www.dpi.nsw.gov.au/__data/assets/pdf_file/0007/63646/Agronomy-of-the-durum-wheats---Primefact-140-final.pdf

12 Scott, B, Martin, P, Riethmuller, G (2013) Row spacing of winter crops in broad scale agriculture in southern Australia, Graham Centre Monograph No. 3, NSW Department of Primary Industries, Orange, www.grahamcentre.net

Wider row spacing tends to reduce the impact of soil treated with pre-emergent herbicides being thrown from one row into an adjacent row — where it might reduce crop emergence.

Soil throw distance increases with the square of speed. For example, doubling the speed of planting will increase soil throw distance four times.

Research and experience has found speed can increase by about 1.4 times if row spacing is doubled, as highlighted in Table 2.

Table 2: Impact of row spacing on wheat yield in the absence of stubble in WA trials (yield from 18 cm row spacing taken as 100 percent).[13]

Number of trials	Row spacing (cm)					
	9	18	27	36	45	54
7	-	100	92	94	-	-
19	115	100	95	90	77	75
16	112	100	93	-	-	-
Average yield response (%)	+14	-	-7	-8	-23	-25
kg grain/ha per cm change in row spacing	+24	-	-11	-5	-23	-5

There is research showing wide rows can reduce grain yield, especially in higher rainfall areas.

In an Australia-wide review of row spacing trials, researchers found that at average wheat yields of 2 tonnes per hectare, widening planting rows to 36 cm reduced yields to 1.86 t/ha.[14]

At average yields below 0.7 t/ha, widening the row space beyond 18 cm increased estimated grain yield.[15]

For example, at average yields of 0.5 t/ha, doubling the row spacing to 36 cm increased yield to 0.52 t/ha — reflecting the moisture saving benefits of wider rows in drier regions.

WA wheat trials comparing row spacing from 9-54 cm found wider spacing decreased grain yield.

This research found an average 8 percent reduction in yield for each 9 cm increase in row spacing from 9-54 cm.[16]

Yield response to row spacing is also influenced by time of sowing.

These trials at Meckering examined the impact of row spacing and two sowing times (19 May and 14 June) on wheat yield, as shown in Figure 3.[17]

13 Scott, B, Martin, P, Riethmuller, G (2013) Row spacing of winter crops in broad scale agriculture in southern Australia, Graham Centre Monograph No. 3, NSW Department of Primary Industries, Orange, www.grahamcentre.net

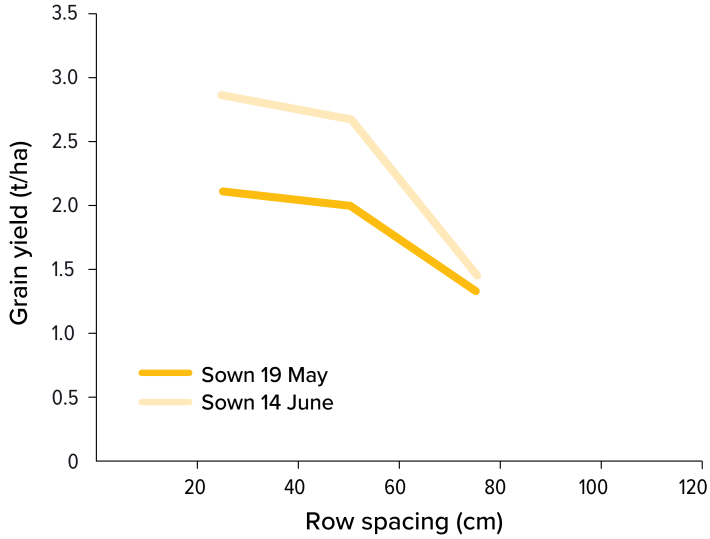
14 Scott, B, Martin, P, Riethmuller, G (2013) Row spacing of winter crops in broad scale agriculture in southern Australia, Graham Centre Monograph No. 3, NSW Department of Primary Industries, Orange, www.grahamcentre.net

15 Scott, B, Martin, P, Riethmuller, G (2013) Row spacing of winter crops in broad scale agriculture in southern Australia, Graham Centre Monograph No. 3, NSW Department of Primary Industries, Orange, www.grahamcentre.net

16 GRDC (2011) Fact Sheet A Systems Approach to Row Spacing, GRDC https://grdc.com.au/resources-and-publications/all-publications/factsheets/2011/02/crop-placement-and-row-spacing-southern-fact-sheet

17 GRDC (2011) Fact Sheet A Systems Approach to Row Spacing, GRDC https://grdc.com.au/resources-and-publications/all-publications/factsheets/2011/02/crop-placement-and-row-spacing-southern-fact-sheet

Figure 3: *Impact of row spacing and time of sowing on wheat yield at Meckering, WA.*[18]



This trial found there was a higher rate of yield reduction with wide rows in later-sown crops, which had less time for canopy development.

2.7.1 Row spacing and fertiliser

In terms of fertiliser use and row spacing, it has been found that the bulk of fertilisers used in WA can damage germinating seeds if applied in close proximity and in a concentrated band.

Figure 4: *Use of wider row spacing and no-tillage seeding systems can result in more fertiliser being placed in the seeding row, causing damage to emerging seedlings. This risk can be reduced by increasing the spread of seed and fertiliser in the row, reducing in-furrow fertiliser rates or separating seed and fertiliser bands.*

(SOURCE: GRDC)

18 Scott, B, Martin, P, Riethmuller, G (2013) Row spacing of winter crops in broad scale agriculture in southern Australia, Graham Centre Monograph No. 3, NSW Department of Primary Industries, Orange, www.grahamcentre.net

The bulk of fertilisers used in WA can damage germinating seeds if applied in close proximity and in a concentrated band.

Use of wider row spacing and no-tillage seeding systems can result in more fertiliser being placed in the seeding row, causing damage to emerging seedlings. This risk can be reduced by increasing the spread of seed and fertiliser in the row, reducing in-furrow fertiliser rates or separating seed and fertiliser bands.[19]

If row spacing is increased but the fertiliser rate per hectare remains constant, the amount of fertiliser in each row increases. The narrow seed spread typically created by disc seeders can also increase the potential for seedling damage by fertiliser.

Urea is most likely to cause damage, unless twin shoot boots are used. Diammonium phosphate (DAP) is also a potential problem when using wide row spacing on light soils.[20]

Fertilisers are essentially salts and can affect the ability of the crop seedling to absorb water by osmosis. Too much fertiliser (salt) near the seed can cause desiccation or 'burning'.

However, fertilisers vary in salt index — or burn potential — depending on composition. Most common N and K fertilisers typically have a higher salt index than P fertilisers.

Fertilisers that have the potential to release free ammonia can cause ammonia toxicity in seed and, because of this, in-furrow placement of fertilisers containing ammonium phosphate and urea is not typically advised.

A solution of urea and ammonium nitrate can be applied successfully in-furrow, but there is a risk of ammonia damage where high rates are used — especially when germinating seedlings are stressed.

Soil conditions that tend to concentrate salts or stress the germinating seed increase the potential for damage. Therefore, the safe limit for in-furrow fertilising is reduced in lighter soil texture (sands) and in drier soil conditions. It is also reduced when environmental conditions, such as cool temperatures, induce stress or slow germination — as this can prolong fertiliser-to-seed contact and increase the likelihood of damage.

Good rain immediately after sowing can reduce the potential for damage, as salts are diluted and ammonia is dissolved. This reduces the concentrations around the seed.

The toxic effects on germination can be avoided by banding fertilisers away from the seed or by topdressing.

2.8 Managing crown rot

Durum wheat remains the most susceptible of the winter cereal crops to crown rot (caused by the fungus *Fusarium pseudograminearum*).

Management strategies such as rotations, use of fallow, stubble management, inter-row sowing and planting time have been researched and benefits demonstrated.[21]

However, there is limited data about the effect of varying target plant population on the carry-over effect on soil water available for the critical crop development stages of flowering and grain fill — which dictates the extent of yield loss to crown rot.

The biggest impact on durum wheat yield from this disease is inoculum level.

Crown rot has more effect on wheat yield in environments that tend to have hotter and drier conditions during grain fill.[22]

Analysis of soil water and plant pathology data should provide additional insights into the impact of crown rot on soil water use.

19 GRDC (2011) Fact Sheet 'Crop placement and row spacing', GRDC, www.grdc.com.au/GRDC-FS-CropPlacementWest

20 GRDC (2011) Fact Sheet 'Crop placement and row spacing', GRDC, www.grdc.com.au/GRDC-FS-CropPlacementWest

21 R Hare (2006) Agronomy of the Durum Wheats Kamilaroi, Yallaroi, Wollaroi and EGA Bellaroi, Primefacts 140, NSW Department of Primary Industries, http://www.dpi.nsw.gov.au/__data/assets/pdf_file/0007/63646/Agronomy-of-the-durum-wheats---Primefact-140-final.pdf

22 Serafin, L and Simpfendorfer, S (2010) Impact of Plant Population on Crown Rot in Durum Wheat, NSWDPI, https://grdc.com.au/Research-and-Development/GRDC-Update-Papers/2010/09/IMPACT-OF-PLANT-POPULATION-ON-CROWN-ROT-IN-DURUM-WHEAT

However, under high crown rot pressure, yield losses in durum wheat cannot typically be managed by manipulating the target plant population at sowing.[23]

Given the extreme susceptibility of durum wheat to crown rot, it remains critical to target durum production only in paddocks that are known to have low levels of inoculum. See Chapter 5 for more detail.

2.9 Pre and post-emergent herbicides

When selecting a herbicide for any weed control, it is important to know the weeds present, crop growth stage, recommended growth stage for herbicide application and herbicide history of the paddock.

Research has found durum wheat varieties differ in tolerance to herbicides registered for use in durum wheat crops (see Chapter 6 for more detail).[24]

2.10 Canopy management

Canopy management refers to the practice of manipulating the green surface area of the crop canopy to optimise crop yield and inputs.

It is based on the premise that the crop's canopy size and duration determine its photosynthetic capacity and, therefore, its overall grain productivity.[25]

In eastern States grain growing regions, adopting canopy management principles and avoiding excessively vegetative crops enables durum wheat growers to ensure a better match of canopy size with yield potential as defined by the water available. WA bread wheat growers use similar strategies.

There are a range of management tactics to manipulate crop growth and development, including the rate and timing of applied fertiliser N. Some of these are outlined below:

- Select a target head density for the environment
- Adjust canopy management based on paddock nutrition, history and seeding time to achieve target head density
- Establish plant populations of 80–200 plants/m^2 (depending on location)
- Lower plant densities (80–100 plants/m^2) may suit earlier sowings/high fertility and/or low yield potential/low-rainfall environments
- Higher plant densities (150–200 plants/m^2) may suit later sowings, lower fertility situations and/or higher rainfall regions
- During stem elongation (GS30–39 on the Zadoks Growth Scale) provide the crop with necessary nutrition and fungicides to:
    - » Maximise potential grain size and grain number per head
    - » Maximise transpiration efficiency
    - » Ensure complete radiation interception from when the flag leaf has emerged (GS39)
    - » Keep the canopy green for as long as possible following anthesis.[26]

The main difference between canopy management and N topdressing is that all – or part – of the N input is tactically delayed until later in the growing season.

This tends to reduce early crop canopy size, but the canopy is maintained for longer – measured by green leaf retention – during the grain fill period.

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23 Serafin, L and Simpfendorfer, S (2010) Impact of Plant Population on Crown Rot in Durum Wheat, NSWDPI, https://grdc.com.au/Research-and-Development/GRDC-Update-Papers/2010/09/IMPACT-OF-PLANT-POPULATION-ON-CROWN-ROT-IN-DURUM-WHEAT

24 Queensland Department of Agriculture, Fisheries and Forestry (2012) Durum Wheat in Queensland, Queensland Department of Agriculture, https://www.daf.qld.gov.au/plants/field-crops-and-pastures/broadacre-field-crops/wheat/durum-wheat

25 Poole, N (2005) Cereal Growth Stages, GRDC, https://grdc.com.au/resources-and-publications/all-publications/bookshop/2010/11/disease-management-and-crop-canopies

26 GRDC (2014), Advancing the Management of Crop Canopies, GRDC, https://grdc.com.au/resources-and-publications/all-publications/publications/2014/01/gc105-canopymanagement

The timing of the applied N during the GS30-33 window can be adjusted to take into account target head numbers, earlier applications during this window (around GS30) and where tiller numbers and soil N seem deficient for the desired head number.

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 can result in less tillers surviving to produce a head.[27]

In a lower moisture profile situation, N can be applied at a rate that is less than the target yield/level requirement and topped-up before rainfall – as opportunities present. This requires careful planning and preparation to take advantage of impending rainfall, sometimes in a short time-frame.[28]

The 50–50 split application of N extends the period that N can be applied through the season without a 'cliff face' drop in yield if the N is not applied at precisely GS30–31. In practice, this improves the margin of error available to the grower if rainfall does not occur at GS30–31.

More information about nutrition and fertiliser is provided in Chapter 4.

27 GRDC (2014), Advancing the Management of Crop Canopies, GRDC, https://grdc.com.au/news-and-media/news-and-media-releases/north/2014/05/guide-details-canopy-management-principles

28 McMullen, G (2009) Canopy management in the northern grains region — the research view, Consultants Corner, Australian Grain, July 2009, http://www.nga.org.au/results-and-publications/download/31/australian-grainarticles/general-1/canopy-management-tactical-nitrogen-in-winter-cereals-july-2009-.pdf

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GRDC '2005 Growth Stages of Cereals (Illustrated)': http://www.nvtonline.com.au/resource/zadoks-growth-scale-2/

NSW Department of Primary Industries 'Durum Wheat Growth and Development': http://www.dpi.nsw.gov.au/__data/assets/pdf_file/0008/516185/Procrop-wheat-growth-and-development.pdf

Plant growth (phenology)

3.1 Wheat development stages

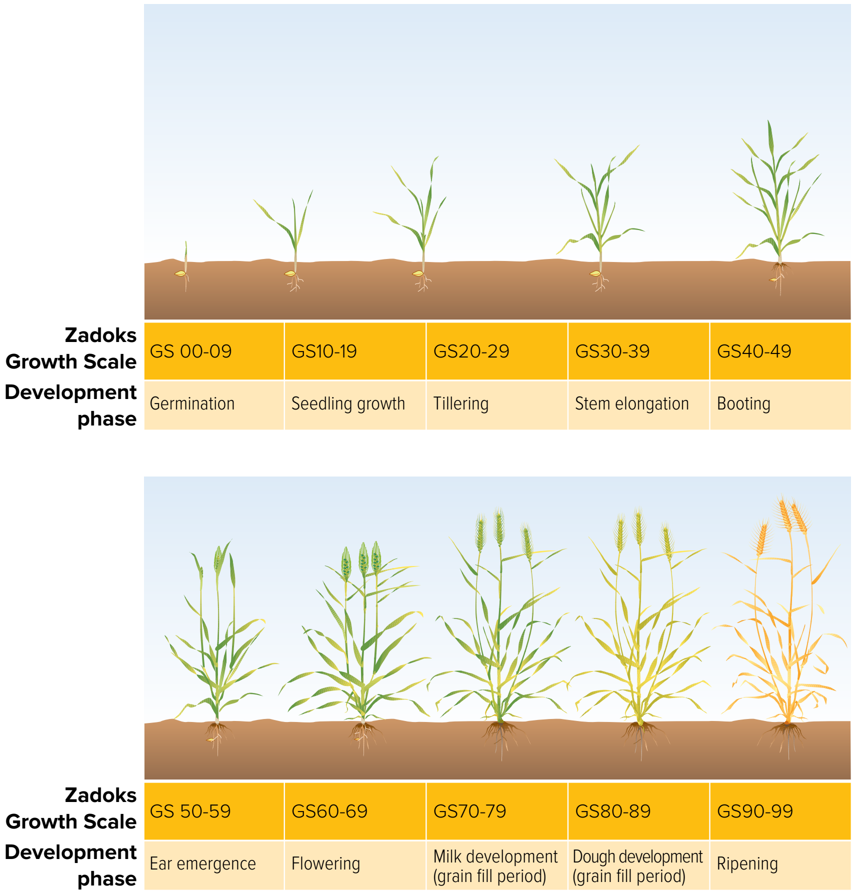
The growth and development of the wheat plant is a complex process.

During the plant's life cycle, many of the growth stages overlap and while one part of the plant may be developing another part may be dying.

Managing durum wheat crops to the correct plant developmental stage is essential to achieve optimal returns from nitrogen (N), other nutrient, fungicide and herbicide inputs.

The most commonly used wheat development scale used in Australia to identify the correct growth stage of the crop is the Zadoks Growth Scale, as shown in Figure 1 and further outlined in Table 1.

Figure 1: *Zadoks Growth Scale for wheat.*[1]
Developmental phases of a wheat plant from germination through to maturity and the Zadoks Growth Scale associated with each phase.



1 GRDC (2005) 'Growth Stages of Cereals (Illustrated)': http://www.nvtonline.com.au/resource/zadoks-growth-scale-2/

Table 1: Zadoks' decimal growth scale for cereals.[2]

Germination	**Booting**
00 Dry seed	41 Flag leaf sheath extending
01 Start of imbibition	43 Boot just visibly swollen
03 Imbibition complete	45 Boot swollen
05 Radicle emerged from seed	47 Flag leaf sheath opening
07 Coleoptile emerged	49 First awns visible
09 Leaf just at coleoptile tip	**Head Emergence**
Seedling Growth	50 1st spikelet of head just visible
10 First leaf through coleoptile	53 ¼ of head emerged
11 First leaf unfolded	55 ½ of head emerged
12 2 leaves unfolded	57 ¾ of head emerged
14 4 leaves unfolded	59 Emergence of head complete
16 6 leaves unfolded	**Anthesis (Flowering)**
18 8 leaves unfolded	61 Beginning of anthesis
Tillering	65 Anthesis 50%
20 Main shoot only	69 Anthesis compete
21 Main shoot & 1 tiller	**Milk Development**
22 Main shoot & 2 tillers	71 Seed watery ripe
24 Main shoot & 4 tillers	73 Early milk
26 Main shoot & 6 tillers	75 Medium milk
28 Main shoot & 8 tillers	77 Late milk
Stem Elongation	**Dough Development**
30 Stem starts to elongate, head at 1 cm	83 Early dough
31 1st node detectable	85 Soft dough
32 2nd node detectable	87 Hard dough
34 4th node detectable	**Ripening**
36 6th node detectable	91 Seed hard (difficult to divide by thumbnail)
37 Flag leaf just visible	92 Seed hard (can no longer be dented by thumbnail)
39 Flag leaf/collar just visible	93 Seed loosening in daytime
	94 Overripe, straw dead & collapsing
	95 Seed dormant
	96 Viable seed giving 50% germination
	97 Seed not dormant
	98 Seed dormancy induced

NOTE: Each point on the Zadoks scale has two digits, the first indicating the growth stage and the second the number of plant parts or secondary stages of development. For example, GS15 means growth stage 1 with 5 leaves on the main stem. GS24 means growth stage 2 with 4 tillers. Several of the growth stages occur together, so a plant may have more than one decimal code applied at the same time. For example, a plant may be producing leaves and tillering at the same time and so could have a code of GS15, 22, meaning it has five leaves on the main stem and two tillers.

2 GRDC (2005) 'Growth Stages of Cereals (Illustrated)': http://www.nvtonline.com.au/resource/zadoks-growth-scale-2/

The Zadoks Growth Scale is based on 10 primary plant growth stages, each divided into 10 secondary growth stages that indicate the number of plant parts on the main stem or secondary stage of development. This extends the scale from 00 to 99.

The Zadoks Growth Scale does not run chronologically from GS00 to 99.

For example, when the crop reaches three fully unfolded leaves (GS13) it begins to tiller (GS20) before it has completed four, five or six fully unfolded leaves (GS14, 15 and 16).

It is easier to assess main stem and number of tillers than it is to assess the number of leaves (due to leaf senescence) during tillering.

The plant growth stage is determined by main stem and number of tillers per plant (e.g. GS22 is main stem plus two tillers, up to GS29 – main stem plus nine or more tillers).

In Australian cereal crops, plants rarely reach GS29 before the main stem starts to elongate (GS30).

After stem elongation (GS30), the growth stage describes the stage of the main stem and is not an average of all the tillers.

This is particularly important with fungicide timing (e.g. GS39 is full flag leaf on the main stem, meaning that not all flag leaves in the crop will be fully emerged).

Successful crop management requires an ability to identify wheat growth stages and how these are impacted by nutrition, disease, application of herbicides and fungicides and environmental stressors.[3]

The principal growth stages used in relation to disease control and N/nutrient management are those from the start of stem elongation through to early flowering (GS30-GS61).

3.2 Key growth stages of wheat

3.2.1 Germination (GS00-09)

During germination and establishment, the crop is most vulnerable to pests and management practices connected to depth of sowing, fertiliser toxicity and poor soil-seed contact.

The goal is to achieve a vigorous, highly competitive crop through uniform germination and rapid seedling emergence and establishment.

Sowing depth plays a big role in seedling establishment and vigour.

Fertiliser, herbicides (such as trifluralin) and some fungicide seed dressings can also impact on seedling vigour. Pests can lower germination and establishment rates significantly.

3.2.2 Vegetative growth (GS10-GS31)

During the vegetative growth stage, the goal is to set up the wheat crop to support maximum grain production.

Root and leaf area, along with tiller number, underpin the capacity of the crop to access soil nutrients and water and convert sunlight into biomass via photosynthesis.

Western Australian wheat varieties commonly form between eight and 14 leaves on the main stem.

3 Anderson, W and Garlinge, J (2000) The Wheat Book: Principles and Practice, Chapter 3. Western Australian Department of Agriculture, Perth, WA, http://researchlibrary.agric.wa.gov.au/bulletins/6/

However, because continual leaf death and tiller production make leaf counting difficult, it is seldom possible to determine leaf number past GS16 (the six-leaf stage).

The rate at which leaves appear is controlled by daily temperature.

Wheat crops sown in June will typically generate one leaf about every 10 days.[4]

Leaf growth in wheat occurs at temperatures between 0°C and 38°C, but is optimum at 29°C. As temperature drops below this optimum level, leaf growth slows.[5]

The optimum temperature for leaf growth is associated with faster tillering, which is why early-sown crops tend to develop biomass more quickly.

Individual leaves have a limited life span and, as leaves at the base of a stem die, new leaves form and unfold higher up the plant.

The leaf area per unit of ground area (leaf area index — or LAI) determines crop water use. The higher the LAI, the more water is used during the vegetative growth stage. Excessive early season N can result in a large LAI during early vegetative growth which, in turn, can result in insufficient soil moisture for flowering and grain fill (commonly referred to as 'haying off').

3.2.3 Root growth

There is a strong connection between the number of leaves, tillers and nodal roots on a wheat plant.

In southern Australia, root growth rates are typically about 1-1.5 centimetres per day and the wheat root system can reach at least 150 cm by flowering (and even deeper by grain maturity).[6]

The pattern of root elongation and branching means a considerable length of root can develop on each plant.

The total amount of dry matter in roots is substantial. In terms of returning organic matter to the soil, the root dry matter can equal the contribution of stubble remaining after harvest (as shown in Table 2, where there is 2.8 tonnes per hectare equivalent in root material in this example).

Table 2: Root and shoot dry matter (g/m^2) in a wheat crop grown at Merredin, Western Australia.[7]

Dry matter (g/m^2)	34 days	62 days	104 days (flowering)
Roots	22	75	280
Shoots	12	69	509
Root to shoot ratio	2:1	1:1	0.5:1
Root % total dry matter	65	52	35

Depth of soil moisture tends to determine the final rooting depth in wheat crops, but several factors can prevent roots from developing in the subsoil. These include: lack of moisture; chemical constraints, such as salinity, acidity or high aluminium (Al); and physical constraints such as soil density or compaction.

4 NSW Department of Primary Industries (2008) 'Durum Wheat Growth and Development', http://www.dpi.nsw.gov.au/agriculture/broadacre-crops/winter-crops/wheat,-barley-and-other-winter-cereals/durum-wheat-production

5 NSW Department of Primary Industries (2008) 'Durum Wheat Growth and Development', http://www.dpi.nsw.gov.au/agriculture/broadacre-crops/winter-crops/wheat,-barley-and-other-winter-cereals/durum-wheat-production

6 NSW Department of Primary Industries (2008) 'Durum Wheat Growth and Development', http://www.dpi.nsw.gov.au/agriculture/broadacre-crops/winter-crops/wheat,-barley-and-other-winter-cereals/durum-wheat-production

7 Anderson, W and Garlinge, J (2000) The Wheat Book: Principles and Practice, Chapter 3. Western Australian Department of Agriculture, Perth, WA, http://researchlibrary.agric.wa.gov.au/bulletins/6/

3.2.4 Tillering (GS20-26)

Tillers are lateral branches, or shoots, that emerge from buds in the axil of the leaves at the base of the main stem.

Primary tillers are produced from the leaves of the main stem and can form their own secondary tillers.

Not all tillers produce an ear (head). Non-productive tillers can provide nutrient and carbohydrate reserves for grain-bearing tillers.

In dryland wheat production systems, about 100 heads per square metre are required to produce 1 t/ha.[8]

Typically, only 70-75 percent of tillers will produce a head. So, for a target yield of 3 t/ha, about 400 tillers/m^2 would be needed by the end of tillering (typically around the stage of stem elongation).[9]

Tiller production is very sensitive to environmental and nutritional stresses and tiller development can slow or stop in response to poor N supply or water stress.

Tillers are produced until about the start of stem elongation, when numbers reach a maximum. Tiller numbers then decline until flowering and remain more or less constant until harvest.

Tillers cannot survive alone until they have about three leaves and have started to produce their own nodal roots. Typically only the first two to three tillers reach this stage before tillering and leaf production stops.

3.2.5 Reproductive growth (GS14-69)

Final grain yield is predominantly a function of grain number which, in turn, is set by floret production and survival.

Florets are produced on spikelets, which collectively make up the wheat ear (head). Ear or head number is set by tiller number which, in turn, is a function of wheat variety and environmental conditions — particularly N.

Floret number per spikelet rises and then falls so that by flowering, typically about two to five florets per spikelet remain. The exact reason for this floret death is uncertain, but could be the result of competition between the stem and the ear for carbohydrate reserves.

In a typical wheat crop, only 30-40 percent of florets will set grain.[10]

Water stress and high temperatures two to three weeks before flowering (GS61-69) can seriously reduce floret production and survival. Pollen formation is also highly vulnerable to water deficit and excessive temperatures.

Frost damage can occur at all stages of crop development, but is particularly damaging to floret production and survival between flag leaf emergence and 10 days after flowering.

Floret survival is highest when there is an adequate supply of water and nutrients, optimum temperature and high solar radiation.

8 NSW Department of Primary Industries (2008) 'Durum Wheat Growth and Development', http://www.dpi.nsw.gov.au/agriculture/broadacre-crops/winter-crops/wheat,-barley-and-other-winter-cereals/durum-wheat-production

9 NSW Department of Primary Industries (2008) 'Durum Wheat Growth and Development', http://www.dpi.nsw.gov.au/agriculture/broadacre-crops/winter-crops/wheat,-barley-and-other-winter-cereals/durum-wheat-production

10 NSW Department of Primary Industries (2008) 'Durum Wheat Growth and Development', http://www.dpi.nsw.gov.au/agriculture/broadacre-crops/winter-crops/wheat,-barley-and-other-winter-cereals/durum-wheat-production

3.2.6 Terminal spikelet

The terminal spikelet signals the end of the wheat head development phase.

The total number of spikelets produced per ear typically varies between 18 and 22.[11]

After the terminal spikelet is initiated, rapid head growth begins and the stem elongates.

3.2.7 Head at 1 cm (GS30)

The developing head is not visible until it is at least 1 cm above the ground. Once the terminal spikelet is formed, rapid stem growth brings the well-developed head from below ground to above ground.

Any grazing stock must be removed from the crop before 'head at 1 cm' (GS30), or stock will remove heads and cause extensive yield loss.

3.2.8 Stem elongation (GS31-GS36)

Stem growth is the result of the elongation of the internodes.

The wheat crown (base of stem) consists of eight to 14 nodes stacked closely above one another, separated by internodes less than 1 millimetre in length. The growth of the first five or six internodes pushes the head higher and elongates the stem.[12]

Lower internodes remain compressed at the base, with the number depending on sowing rate and variety.

When the internodes elongate, the individual nodes become detectable.

Stem elongation represents a period of rapid dry matter production and high N demand. About 60 percent of total crop N uptake occurs during stem elongation.[13]

3.2.9 Flag leaf extension (GS39)

The flag leaf is located just below the head and is the last leaf to develop.

The flag leaf plays an important role in producing carbohydrates for grain fill, particularly in higher rainfall areas. Protecting the flag leaf from fungal disease is an important management requirement in medium-high rainfall areas.

The emergence of the tips of the awns (awn peep) is an indicator that the flag leaf is fully extended (GS39).

3.2.10 Flowering and grain fill

Flowering (GS61-69) is a short phase, tending to last only a few minutes in an individual floret, a couple of hours in a head and about three to four days across a wheat crop.

The vast majority of florets self-pollinate, with the empty anthers appearing on the outside of the head following fertilisation.

Grain enlargement starts after floret fertilisation and continues for 10 to 14 days.[14]

Grain fill follows the period of grain enlargement and tends to last for 15 to 35 days.[15] During this stage, grain weight increases at a constant rate as carbohydrate and protein are deposited into the grain.

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11 NSW Department of Primary Industries (2008) 'Durum Wheat Growth and Development', http://www.dpi.nsw.gov.au/agriculture/broadacre-crops/winter-crops/wheat,-barley-and-other-winter-cereals/durum-wheat-production

12 NSW Department of Primary Industries (2008) 'Durum Wheat Growth and Development', http://www.dpi.nsw.gov.au/agriculture/broadacre-crops/winter-crops/wheat,-barley-and-other-winter-cereals/durum-wheat-production

13 NSW Department of Primary Industries (2008) 'Durum Wheat Growth and Development', http://www.dpi.nsw.gov.au/agriculture/broadacre-crops/winter-crops/wheat,-barley-and-other-winter-cereals/durum-wheat-production

14 NSW Department of Primary Industries (2008) 'Durum Wheat Growth and Development', http://www.dpi.nsw.gov.au/agriculture/broadacre-crops/winter-crops/wheat,-barley-and-other-winter-cereals/durum-wheat-production

15 NSW Department of Primary Industries (2008) 'Durum Wheat Growth and Development', http://www.dpi.nsw.gov.au/agriculture/broadacre-crops/winter-crops/wheat,-barley-and-other-winter-cereals/durum-wheat-production

The grain moves from what is known as 'milk' stage through to 'dough' stage. The exact stage is determined by the amount of solids in the grain 'milk' or the stiffness of the grain 'dough'.

Once filled, the wheat grain is 70 percent carbohydrate, with 97 percent of this carbohydrate being starch. The protein content is typically between 8 and 15 percent, depending on final grain weight (which can range from 2.5-4.5 milligrams).[16]

3.3 Grain yield

The four components to wheat grain yield are:

- Number of ears (heads)/m^2
- Number of spikelets per ear
- Number of grains per spikelet
- Weight per grain.

Ear and spikelet numbers are set well before flowering. Grain numbers are set at around flowering and grain weight is set between flowering and maturity.

Grain weight is the least variable of the yield components because it is largely determined by the genetic potential of the variety.

Grain yield is, therefore, most closely related to the number of grains produced by the crop.

3.3.1 Yield compensation

Wheat yield can respond to seasonal conditions almost to maturity due to the capacity of the wheat plant to increase or decrease some — or all — of its yield components.

For example, low tiller numbers caused by stress during tiller formation can be compensated for by a larger number of spikelets per head and more grains per spikelet.

Similarly, an excessive number of ears/m^2 might result in smaller ears or lower grain weight.

3.3.2 Estimating grain yield

The yield of a wheat crop can be estimated by:

Grain yield (kg/ha) = ears/m^2 x grains/spikelet x weight/grain (g) x 10.

Ears per square metre

Count the ears in 1 m^2 of crop, or count the number of ears in a 1 m row length and multiply by 5.6 (there are 5.62 m of row in 1 m^2 for a 7-inch or 17.8 cm row spacing). For 12-inch (or 30 cm) row spacing, multiply by 3.3.

Spikelets per ear

Count the number of spikelets on an average ear – for most crops it will be between 16 and 20.

Grains per spikelet

Count the grains in spikelets at the top, middle and bottom of the ear. More and heavier grains are usually set in the central spikelets. The number should be between two and four.

16 NSW Department of Primary Industries (2008) 'Durum Wheat Growth and Development', http://www.dpi.nsw.gov.au/agriculture/broadacre-crops/winter-crops/wheat,-barley-and-other-winter-cereals/durum-wheat-production

Grain weight

Grain weight depends on growing conditions and variety, but will typically be between 0.025 and 0.045 g/grain (2.5-4.5 mg). To determine grain weight – count and weigh 1000 grains and divide by 1000 to get weight/grain.[17]

If it is not possible to weigh grain, a good average figure to use is 0.0356 g/grain (3.56 mg/grain), which is equivalent to 28 grains/g.[18]

Using the components above, the grain yield can be calculated as:

Yield = 100 (ears/m^2) x (18 spikelets x 2 grains/spikelet x 0.03 g/grain) = 100 x 1.08 = 108 g/m^2 or 1.08 t/ha

This leads to the very simple rule of thumb that 100 ears/m^2 will generate about 1 t/ha of grain.[19]

17 NSW Department of Primary Industries (2008) 'Durum Wheat Growth and Development', http://www.dpi.nsw.gov.au/agriculture/broadacre-crops/winter-crops/wheat,-barley-and-other-winter-cereals/durum-wheat-production

18 Anderson, W.K. The Wheat book: principles and practice, 2000, http://researchlibrary.agric.wa.gov.au/cgi/viewcontent.cgi?article=1005&context=bulletins

19 Anderson, W.K. The Wheat book: principles and practice, 2000, http://researchlibrary.agric.wa.gov.au/cgi/viewcontent.cgi?article=1005&context=bulletins

MORE INFORMATION

GRDC-DPIRD MySoil https://agric.wa.gov.au/n/638

GRDC 'Managing Soil Organic Matter: A Practical Guide': https://grdc.com.au/resources-and-publications/all-publications/publications/2013/07/grdc-guide-managingsoilorganicmatter

DPIRD 'Diagnosing Nitrogen Deficiency in Wheat': https://agric.wa.gov.au/n/1995

DPIRD 'Diagnosing Phosphorus Deficiency in Wheat': https://agric.wa.gov.au/n/1996

Nutrition and fertiliser

4.1 Overview

The bulk of Western Australia's soils are sandy in nature, with typically lower nutrient and water holding capacity than in other grain growing regions of Australia. These soils require addition of nutrients such as nitrogen (N) and phosphorus (P) because of their low natural fertility.

Balancing the supply of fertiliser with the nutrients removed by high-yielding crops is a constant challenge.

Water, nutrients and soil acidity (measured in pH) need careful management to maintain optimum growth conditions.

Crop N requirements depend on expected yield and protein, particularly for durum wheat.

The amount of fertiliser N required to supplement N mineralisation from the soil and the timing of its application needs to match the stage of greatest N demand from the crop.

Trace element deficiencies can be corrected with fertilisers containing micronutrients or through foliar applications.

4.2 Western Australian soils

Most WA cropping soils are ancient and were formed from granitic parent rock. Weathering over geological time has leached minerals and clay from the topsoils, leaving these chemically infertile and prone to nutrient leaching and rapid acidification.

Many WA soil profiles are duplex, consisting of a thin sandy or loamy topsoil overlaying a thicker clay layer. The sandy topsoils have a weak structure and are prone to compaction and a low water and nutrient holding capacity.

The clay subsoil can store large amounts of water, but poor structure and small pore size distribution can make it difficult for crop roots to access this moisture. WA also has large areas of deep, sandy soils.

The positive aspect of low-fertility soils is that crop nutrient supply and timing is almost entirely in the hands of the grower.

4.2.1 Organic soil components

Organic matter makes up about 2-10 percent of the soil mass and has a critical role in the physical, chemical and biological function of agricultural soils.[1]

It contributes to nutrient turnover and cation exchange capacity, soil structure, moisture retention and availability and soil buffering.

Soil organic matter is difficult to measure directly, so laboratories tend to measure and report soil organic carbon (SOC) levels, which make up about 58 percent of soil organic matter.[2]

1 GRDC, Managing Soil Organic Matter: A Practical Guide, (2013), https://grdc.com.au/resources-and-publications/all-publications/publications/2013/07/grdc-guide-managingsoilorganicmatter

2 GRDC, Managing Soil Organic Matter: A Practical Guide, (2013), https://grdc.com.au/resources-and-publications/all-publications/publications/2013/07/grdc-guide-managingsoilorganicmatter

Globally, SOC is typically between 0.5 and 4 percent in dryland agricultural topsoils, with the highest amounts in cool, moist environments that have clay-rich soils and the lowest levels in warm, dry environments with sandy soils such as WA[3].

The SOC content in WA cropping soils typically ranges from 0.8 to 2 percent in surface (0-10 centimetre) layers – or the equivalent of 8-20 tonnes of carbon per hectare (t C/ha) – assuming a bulk density of 1.0 grams per cubic centimetre. This is among the lowest of agricultural soils anywhere in the world.[4]

There is typically a fixed ratio of carbon (C), N, P and sulphur (S) in soil organic matter. Each tonne of C is associated with about 80 kilograms of N, 20 kg of P and 14 kg of S.[5]

When soil organic matter is broken down, these amounts of nutrients are potentially available to crops.

Managed optimally, WA's continuous cropping systems that predominantly produce wheat are likely either to just maintain – or lose – SOC.

4.2.2 Soil test critical values

Tests of the top 10 cm of soil are the best way to estimate the status of potassium (K), P and S.

Nitrogen status is better estimated with models, deep soil nitrate tests and plant tissue tests. Micronutrient status is best measured from plant tests.

The critical value of a soil test is the value required to achieve 90 percent of crop yield potential.

The range around the critical value represents the reliability of the test. The narrower the range, the more reliable the data, as highlighted in Table 1.

Table 1: Critical soil test values at two soil-testing depths for phosphorus, potassium and sulphur according to WA soil types.[6]

Soil sampling depth (cm)	Nutrient*	Soil type	Critical value (mg/kg)	Critical range (mg/kg)
0-10	Phosphorus	Grey sands	10	10-16
		Other soils	23	22-24
	Potassium	All	41	39-45
		Yellow sands	44	34-57
		Loams	49	45-52
		Duplexes	41	37-44
	Sulfur	All	4.5	3.5-5.9
0-30	Phosphorus	All	11	10-11
	Potassium	All	N/A	N/A
	Sulfur	All	4.6	4.0-5.3

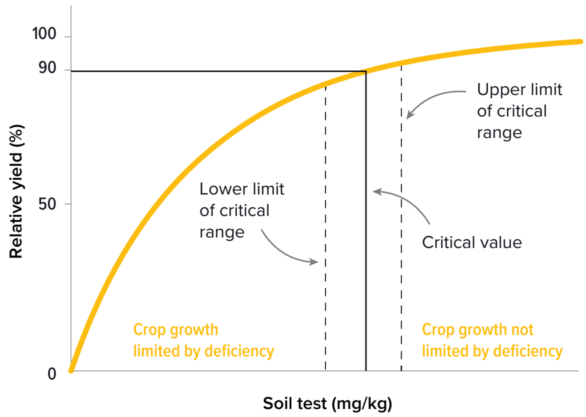
*Micronutrient status is more reliably measured using plant tissue rather than soil testing (see micronutrient section below).

Nitrogen soil tests are a poor indicator of nitrogen requirements and need to be used in conjunction with potential yield outlooks (see nitrogen section below).

If a soil test value is less than the lower critical value limit, wheat yield is likely to respond to a nutrient application, as shown in Figure 1. Soil test critical values do not predict optimum fertiliser rates.

3 DPIRD, Soil Organic Matter hub, 2017, https://www.agric.wa.gov.au/soil-carbon/soil-organic-matter-frequently-asked-questions-faqs
4 DPIRD, Soil Organic Matter hub, 2017, https://www.agric.wa.gov.au/soil-carbon/soil-organic-matter-frequently-asked-questions-faqs
5 DPIRD, Soil Organic Matter hub, 2017, https://www.agric.wa.gov.au/soil-carbon/soil-organic-matter-frequently-asked-questions-faqs
6 Anderson, G, Chen, W, Bell, R, Brennan, R (2016) Critical values for soil P, K and S for near maximum wheat, canola and lupin production in WA: www.giwa.org.au

Figure 1: *A generalised soil test-crop response relationship defining the relationship between soil test value and percent grain yield expected. A critical value and critical range are defined from this relationship. The relative yield is the unfertilised yield divided by maximum yield, expressed as a percentage. Typically 90 percent of maximum yield is used to define the critical value but critical values and ranges at 80 percent and 95 percent of maximum yield can also be produced.*[7]



To determine how much fertiliser to apply, soil test results need to be considered in combination with information about potential crop yield, soil type, gross margin analysis and nutrient removal in previous seasons.

4.3 Nutrient movement

Nutrients arrive at the wheat root by the processes of mass flow, root interception and diffusion.

Mass flow occurs when soluble and mobile nutrients are swept along in the flow of water moving from the soil towards the wheat root in the transpiration stream.

The nutrients that tend to be taken up in mass flow are nitrate (NO_3^-), calcium (Ca), magnesium (Mg) and sulphate (SO_4^{2-}) and these soluble nutrients are the most susceptible to leaching. About 80 percent of nitrate-N reaches wheat roots in this way.[8]

Research and experience in WA indicates splitting N applications can reduce leaching risk and help to maintain high concentrations of nitrate-N in the soil solution during periods of rapid crop growth.

Less soluble nutrients move to plant roots along a concentration gradient by a process called diffusion. Nutrients move from an area of high concentration (the bulk soil solution) towards an area of lower concentration (the root surface).

About 90 percent of P and 80 percent of K taken up by wheat is typically via diffusion.[9] Banding K and P fertilisers can promote high nutrient concentrations in the active root zone.

Root interception is responsible for less nutrient uptake. For example, just 1-2 percent of the uptake of N, P and K is due to interception by roots as these grow through the soil.

Immobile nutrients, such as zinc (Zn) and P are taken up when intercepted by roots or arbuscular mycorrhizal fungi (AMF). The activity of AMF tends to be reduced by canola crops and high levels of P fertiliser. Additional Zn fertiliser may be needed for wheat after canola or when fertilised with high levels of P.

7 Anderson, G, Chen, W, Bell, R, Brennan, R (2016) Critical values for soil P, K and S for near maximum wheat, canola and lupin production in WA: www.giwa.org.au

8 Anderson, W.K. The Wheat Book: Principles and Practice, DAFWA, 2000, http://researchlibrary.agric.wa.gov.au/bulletins/6/

9 Anderson, W.K. The Wheat Book: Principles and Practice, DAFWA, 2000, http://researchlibrary.agric.wa.gov.au/bulletins/6/

4.4 Nitrogen

Figure 2: *Growers are advised to consider tactical application of N fertiliser in response to expected crop requirements, seasonal conditions and commodity and fertiliser prices.*

(SOURCE: GRDC)

Nitrogen supply should be matched to crop requirements, which may vary as the season progresses – particularly as WA's sandy soils are prone to N leaching. Growers are advised to consider tactical application of N fertiliser in response to expected crop requirements, seasonal conditions and commodity and fertiliser prices.

Crop N requirements are related to grain yield, which in turn is driven by rainfall, crop density, root disease, weeds and the status of other nutrients.

Most N in the soil profile is in an organic form that must be mineralised before becoming available for crop uptake.

The goal of N management is to supplement mineralised soil N with fertiliser N to match crop requirements.

Tools and models, such as Yield Prophet®, NULogic and N Broadacre, can estimate N supply from the various pools available and be used to calculate N fertiliser requirements as the season progresses. See section 4.47 for more detail.

Soil testing prior to sowing is key to developing an effective N budget for durum wheat crops during the growing season.

When conducting soil tests, it is important to test for N to the depth of anticipated crop root growth.

Applications of N at sowing, or up to the start of stem elongation, significantly contribute to crop biomass and grain yield response.

Later applications of N, from booting to flowering, tend to facilitate greater grain protein responses.

Pasta manufacturers prefer durum wheat with 13 percent grain protein and growers can use late-season, topdressed N to help meet this target.

When applying N, yield will typically increase to a maximum point, whereas grain protein levels may continue to increase beyond this level with further applications.

In high yielding situations and in favourable conditions, grain protein levels in many new durum varieties may still fall below 13 percent.

Applications of N at sowing, or up to the start of stem elongation, contribute more to wheat crop biomass and grain yield response than later applications of N, which tend to facilitate greater protein responses.

4.4.1 Nitrogen triggers tillers

The number of tillers for a particular variety provides a good indication of crop N status. For example, in a typical crop, the first tiller emerges from the base of leaf-one at the same time that leaf-three emerges on the main stem. Absence of this tiller is a symptom of N deficiency if other inputs are adequate.

Nitrogen demand then increases significantly during stem elongation – a period of rapid leaf area expansion and crop growth.

Nitrogen taken up during stem elongation helps build crop yield by increasing head and grain numbers and provides N reserves for grain protein.

There is a direct relationship between N supply (from all sources), grain yield and grain protein content.

Soil N status and potential yield dictate a paddock's N supply zone – whether it is deficient, moderate or excessive – as outlined below:

- **Zone 1:** Extreme N deficiency
  When N supply is deficient, adding N will increase grain yields markedly. But it is likely grain protein levels will remain unchanged, or even decline slightly, with additional N. Crop yield is only half, or less, of potential and cereal protein levels will be as low as 7-8 percent.[10]
- **Zone 2:** Moderate N supply
  As N supply increases to moderate levels, both crop yield and grain protein increase with additional N fertiliser. Crop yields are 60-80 percent of potential but grain protein is still below 10 percent. In general, returns on applied N are maximised at grain protein levels between 10-11 percent. Fertiliser strategies to produce grain protein levels above this range need to be calculated against the profitability of supplying durum wheat to market at 13 percent protein.[11]
- **Zone 3:** Excessive N supply
  Nitrogen supply in excess of crop yield potential can cause yield decline, high screenings and low test weight – even while grain protein continues to increase. For example, grain protein levels of 14 percent can result in a drop in grain yield of about 10 percent. In general, the efficiency of N conversion to grain decreases as N supply increases.

  Grain protein levels above 10-11 percent usually indicate excess N has been applied because yield and protein payments for durum wheat will offset the extra cost of the N.

  Conversely, if grain protein levels are consistently below 10-11 percent – provided other inputs and management are satisfactory – it is likely the N strategy is forgoing yield potential and could be adjusted upwards.[12]

4.4.2 Nitrogen pools

Wheat crops access N from three main soil pools. The first is stable organic N (SON), which is:

- The biggest source of soil N
- Released as microbes break down organic matter (mineralise)

10 Anderson, W.K. The Wheat Book: Principles and Practice, DAFWA, 2000, http://researchlibrary.agric.wa.gov.au/bulletins/6/

11 Anderson, W.K. The Wheat Book: Principles and Practice, DAFWA, 2000, http://researchlibrary.agric.wa.gov.au/bulletins/6/

12 Anderson, W.K. The Wheat Book: Principles and Practice, DAFWA, 2000, http://researchlibrary.agric.wa.gov.au/bulletins/6/

- Provided to plants in a form of ammonium (NH_4^+) and NO_3^-
- Mineralised most rapidly when the soil is moist and warm
- Increased with cultivation
- Reduced with incorporation of residues that contain a high ratio of C to N, as this causes N immobilisation (the opposite of mineralisation).

During a typical season, about 2 percent of the SON pool becomes available to crops. With significant rain in summer and autumn, mineralisation can be as high as 3 percent.[13]

SON is estimated by measuring organic carbon percentage (OC%) in the profile.

A continuously cropped loamy soil with an OC% of 1 percent can supply as much as 48 kg/ha of N (the equivalent of 1 t/ha of grain yield) from the SON pool.

Residue organic N (RON) is another pool for plants to access.

This is significant when wheat crops follow grain legumes, such as lupins, field peas, chickpeas and faba beans, or legume-based pastures.

This source of N is mineralised rapidly to NH_4^+ and then NO_3^- before and during the growing season.

RON is mostly depleted within two or three years of the legume phase, as shown in Table 2.

Table 2: Approximate quantity of legume nitrogen available to a wheat crop in the years following the legume rotation.[14]

	Legume nitrogen supplied to wheat in the years after legume rotation (kgN/ha)				
Legume crop/pasture yield	**Year 1**	**Year 2**	**Year 3**	**Year 4**	**Total**
1t/ha legume crop	16	7	4	2	29
2t/ha legume crop	30	15	7	4	56
4t/ha pasture (80% legume content)	23	11	4	3	42

*Soil type: loamy sand. Legume crop harvest index: medium.

Fertiliser N is required when SON and RON sources are insufficient to supply crop requirements.

This is typically in the forms of urea, NH_4^+ and NO_3^-.

Urea rapidly changes to NH_4^+, which in turn changes to NO_3^- and both reactions are more rapid when the soil is warm and moist.

Residual mineral N can be available from mineralisation or fertiliser applied in previous years, particularly from low-yielding crops.

Residual mineral N is measured by soil testing down the profile, for example to a depth of 60 cm.

In years following leaching rain, it is recommended to undertake deeper soil testing to get a good indication of this pool.

4.4.3 Wheat uptake of nitrogen

Wheat takes up both NH_4^+ and NO_3^- by its roots. Ammonium is an intermediate product in the mineralisation of organic matter to NO_3^- and is immobile in the soil due to its positive electric charge. It is usually found in the topsoil and at lower concentrations than NO_3^-.

13 GRDC Western Wheat GrowNotes™, www.grdc.com.au/grownotes

14 Quinlan, R (2012) Planfarm, How to get more nitrogen from pasture legumes delivered to crops, www.giwa.org.au/

The negative charge of nitrate gives it the ability to move in solution to the plant roots and to leach into the subsoil – and sometimes below the root zone after heavy rain.

When small amounts of NH_4^+ and NO_3^- are taken up by the crop, these are quickly converted to amino acids and then proteins.

When a large amount of NO_3^- is taken up by a vegetative crop, it remains as NO_3^- in the plant for several weeks.

The NO_3^- content of young plants is a good indication of the short-term supply of N. Nitrate is not typically found in the crop after stem elongation.

Applying urea makes the topsoil alkaline in the short term. Plant uptake of NH_4^+ formed from the urea reverses this reaction when roots excrete a hydrogen ion (proton H+) in exchange for the NH_4^+.

The process of nitrification, converting NH_4^+ to NO_3^-, also tends to acidify the topsoil.

Crop uptake of NO_3^- makes the soil more alkaline because roots exchange a hydroxyl ion (OH^-) for nitrate.

Production of NO_3^- has the effect of making the topsoil more acidic and, if it is then leached, the subsoil becomes more alkaline when NO_3^- is taken up by roots.

The upshot of these reactions is that N supplied to crops, whether from fertiliser or legume N fixation, can lead to topsoil acidification, which can be managed/neutralised by liming.

4.4.4 Nitrogen use efficiency

Figure 3: *Fertiliser nitrogen, such as urea, is required when soil N is insufficient to supply crop requirements.*

(SOURCE: GRDC)

Nitrogen use efficiency (NUE) is a measure of how well N is retrieved by the crop from the soil profile and converted into grain. Wheat crop management practices that can help to increase NUE include:

- Sowing early or into dry soil – ensures roots keep up with N being leached down the profile by the wetting front
- Minimising incidence of root disease – break crops or applied seed fungicides
- Ensuring yield is not limited by deficiencies of other nutrients

» Correcting acidity by liming – optimises root growth
» Reducing risks of take-all disease using a break crop
» Correcting soil compaction to increase the speed of root growth down the profile – potentially using deep ripping to promote root growth
» Cautiously using chlorsulfuron, triasulfuron and trifluralin herbicides that can prune crop roots and reduce NUE
» Banding N below or beside the rows rather than topdressing.

4.4.5 Nitrogen for protein response

A key risk for durum wheat growers is applying too much N, too early in the season. An over-supply of N prior to stem elongation can result in increased crop biomass, more water use and a tendency for durum wheat to set an unattainable yield potential (more grains per square metre).[15]

Durum wheat will reach yield potential when protein levels are between 10.5-11 percent.[16]

It is often difficult to get N requirements exact at the beginning of the season, but soils with available N of more than 50 kg/ha will typically sustain durum wheat crops until stem elongation.

This level of N is typically best applied early in the crop's development and then more N applied later to boost protein to the 13 percent required, as highlighted in Table 3.

Table 3: Comparison of grain protein (%) across different nitrogen application timings*[17]

Nitrogen treatment	Tamaroi	Caparoi⍉	Saintly⍉	Tjilkuri⍉	Hyperno⍉	Yawa⍉
Nil	11.9	11.9	11.9	11.6	11.3	11.4
80 kg N/ha @ GS30**	13.1	13.1	12.9	12.9	12.4	12.5
40 kg N/ha @ GS30** and 40 kg N/ha @ GS47**	13.2	13.4	13.2	13.2	12.5	11.9
80 kg N/ha @ GS47**	13.3	13.4	13.0	13.0	12.4	12.3
LSD (5%)	0.2%					

* Results expressed as a percentage of dry basis (db) and averaged across three years of trial work at Paskeville from 2009 to 2011. The shaded treatments achieved premium grade classification based on protein for DR1.
** GS30 (onset of stem elongation), GS47 (flag leaf emergence)

4.4.6 Nitrogen timing and late season topdressing

Grain protein can be increased and grain size maintained when N application is appropriately timed.

Topdressing durum wheat from booting stage to mid-flowering has been shown to be the most effective time to increase protein and minimise the risk of high grain screenings.[18]

As a general rule-of-thumb, to increase grain protein by 1 percent, it is advised to apply 6-8 kg/ha of N for every 1 t/ha of yield potential on many soil types[19].

For example, a crop with 4 t/ha yield potential will need an extra 24-32 kg/ha of N applied after stem elongation to increase grain protein by one percent.

But late season application is not always easy because rain after application is needed to move N into the root zone and minimise volatilisation losses.

15 GRDC (2014) Fact Sheet 'Durum Quality and Agronomy — Southern Region', GRDC, www.grdc.com.au/GRDC-FS-Durum
16 GRDC (2014) Fact Sheet 'Durum Quality and Agronomy — Southern Region', GRDC, www.grdc.com.au/GRDC-FS-Durum
17 GRDC (2014) Fact Sheet 'Durum Quality and Agronomy — Southern Region', GRDC, www.grdc.com.au/GRDC-FS-Durum
18 GRDC (2014) Fact Sheet 'Durum Quality and Agronomy — Southern Region', GRDC, www.grdc.com.au/GRDC-FS-Durum
19 GRDC (2014) Fact Sheet 'Durum Quality and Agronomy — Southern Region', GRDC, www.grdc.com.au/GRDC-FS-Durum

In more marginal durum wheat growing areas, it may be better to target an earlier application of N.

In higher rainfall areas with good subsoil moisture and a strong chance of follow-up rain, applications at early flowering stage may have more success.

Applying N at strategic times throughout the season to match crop demand and soil moisture supply can increase durum wheat yield and water use efficiency above that of a single application at sowing, as highlighted in Table 4.

Table 4: Grain yield response and water use efficiency of 100 kg/ha nitrogen applied either at sowing or at various growth stages throughout the season.[20]

Nitrogen treatment	Grain yield (t/ha)	Water use efficiency
Nil	2.25	7.1
Sowing	2.86	9.1
3.5 leaf	3.00	9.5
1st node	3.02	9.6
3.5 leaf + 1st node	3.17	10.1
3.5 leaf + awn peep	3.05	9.7
1st node + awn peep	2.96	9.4
Sowing + 3.5 leaf + awn peep	2.95	9.4
$LSW_{0.05}$	0.14	

Mineralised soil N can be a major source of crop N and in some seasons little if any fertiliser N will be required to meet wheat yield potential.

Crop requirements for fertiliser N are a function of demand (yield potential) and supply (soil N supply).

The goal is to put on enough early N to achieve a low or average yield and then monitor conditions as the season unfolds, adding more N at early stem elongation (Zadoks Growth Scale stage GS31-33) if yield potential (demand) requires it.

In higher rainfall areas, if the season continues to progress well above average, further N can be added a few weeks later.

In most southern WA areas, cereal stem elongation (stages GS31-GS33) is the best time for later N application, which typically occurs sometime in July — depending on season and sowing date.

Using moderate N rates early in the season enables a low to average yield potential to be established, without compromising the prospect of higher yields if spring conditions are favourable.

A deferred approach to N also limits the amount of N that is put at risk of loss from denitrification (waterlogging) or leaching.

As shown in Figures 4 and 5, there is increased demand for N as yield potential increases.

20 GRDC (2014) Fact Sheet 'Durum Quality and Agronomy — Southern Region', GRDC, www.grdc.com.au/GRDC-FS-Durum

Figure 4: *Relationship between nitrogen requirement and grain yield for increasing yield potential in a high rainfall area (with 50 kg/ha mineralised N).*[21]

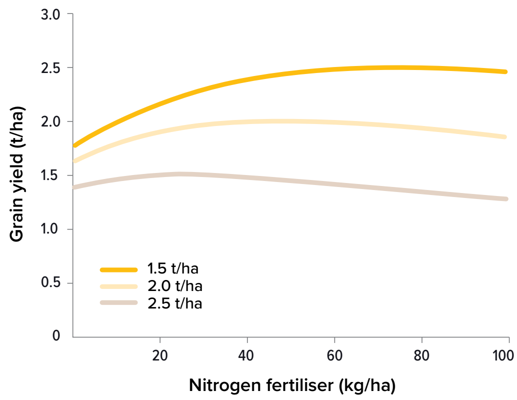
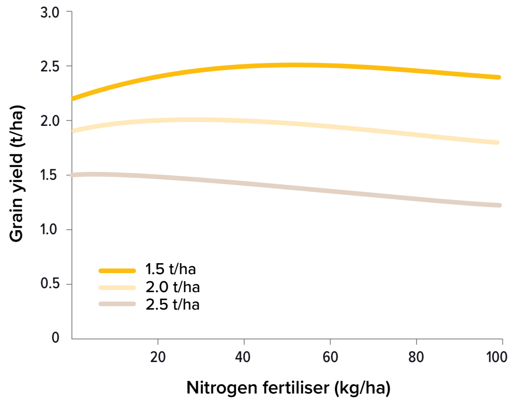


Figure 5: *Relationship between nitrogen requirement and grain yield for increasing yield potential in a low rainfall area (with 70 kg/ha mineralised N).*[22]



These Figures are outputs from the decision support tool 'Select Your Nitrogen' (SYN), developed by the Department of Primary Industries and Regional Development (DPIRD) with Grains Research and Development Corporation (GRDC) funding.

The assumption for the high rainfall example is a dry start to the season (no NO_3^- leaching) and a wheat-legume-wheat rotation delivering about 50 kg of mineralised N/ha.

For the low rainfall example, the assumption is a wheat-fallow-fallow rotation (two years of drought) delivering 70 kg of mineralised N/ha.

4.4.7 Late nitrogen top-ups

The impact of late-applied N on grain yield and protein depends on the wheat growth stage at which the N is applied, previous N history and soil moisture status.

Later applications of N can increase tiller survival and longevity of green leaf area (season permitting) and can also contribute to yield through larger grains or, depending on time of application, more grains per ear.

Nitrogen taken up after flowering is more likely to increase grain protein and less likely to increase grain numbers or grain size.

21 DPIRD 'Select Your Nitrogen' model, http://www.climatekelpie.com.au/manage-climate/decision-support-tools-for-managing-climate/syn-select-your-nitrogen

22 DPIRD 'Select Your Nitrogen' model, http://www.climatekelpie.com.au/manage-climate/decision-support-tools-for-managing-climate/syn-select-your-nitrogen

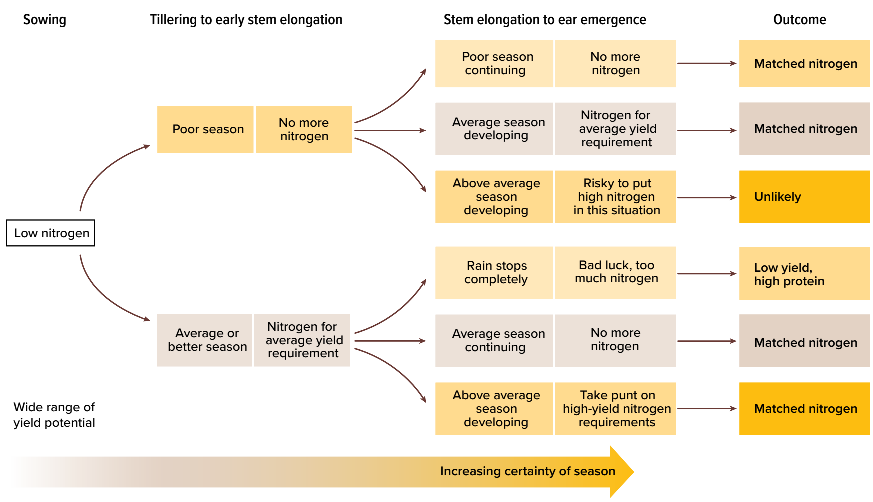
Decision support tools, such as N Broadacre, NUlogic and Yield Prophet®, can be used to explore the economics of late-season N use strategies for a range of seasonal outlooks.

Applying late N in anticipation of a follow-up rain is risky because if the season end does not deliver sufficient rain, yield can decline due to 'haying-off'.

But if N is applied after a rain that exceeds about 20 millimetres across two days, this can result in significant yield increases.[23]

During the period from stem elongation to ear emergence (stages GS30 to 39), a further assessment of crop N requirements can be made according to the season outlook, as shown in Figure 6.

Figure 6: *Decision tree for in-season nitrogen applications according to the progress of the season and crop developmental stages.*[24]



Later applications of N can increase tiller survival and longevity of green leaf area (where the season permits) and can contribute to yield.

But, when the season ends more abruptly, later N (in excess of yield potential) can cause increases in grain protein at the expense of yield.

Late season N applications are typically only warranted for wheat crops in high rainfall areas — although rainfall amount and pattern in some seasons in lower and medium rainfall areas can also deliver yield responses to late season N.[25]

Even in a season tracking above average, the recommendations for in-season N application can still be observed. There should be enough soil moisture and a reasonable prospect of follow-up rain to convert the applied N into yield.

4.4.8 Premiums for protein

Premiums available in the market for protein can influence the decision to apply N late in the season for durum wheat crops.

The protein percentage must exceed 13 percent in durum wheat to reach DR1 classification and optimise grain returns.

High protein wheat is more likely to be produced in the northern and eastern WA grainbelt on heavy soil types.

23 GRDC (2014) Fact Sheet 'Durum Quality and Agronomy — Southern Region', GRDC, www.grdc.com.au/GRDC-FS-Durum

24 Palta, J, Bowden, W, and Asseng, S (2003) Timing of late applications of N fertiliser and season on grain yield and protein in wheat, CSIRO and DAFWA, www.regional.org.au/au/asa/2003/p/5/palta.htm

25 Palta, J, Bowden, W, and Asseng, S (2003) Timing of late applications of N fertiliser and season on grain yield and protein in wheat, CSIRO and DAFWA, www.regional.org.au/au/asa/2003/p/5/palta.htm

However, fertiliser and application costs will be critical to chasing protein premiums from late N applications.

For example, if the N costs $20/ha and application costs $10/ha, the premium must be at least $15/t to break even at a yield of 2 t/ha.

4.4.9 Matching nitrogen to yield potential

Crop yield potential is the major driver of N requirements in durum wheat. Yield forecasting is crucial to optimising N rates in all wheat crops.

Most of the N decision support models outlined in this chapter incorporate various methods of estimating crop yield potential.

Wheat crops typically require about 40-45 kg/ha of N for every 1 t of grain produced. Nitrogen losses due to poor root growth, NO_3^- leaching or volatilisation into the atmosphere need to be accounted for and added to this figure.

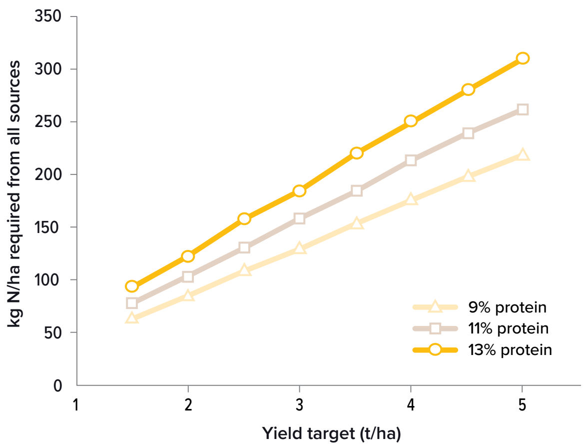
These losses are considered in the common rule-of-thumb estimate that half of soil and fertiliser N is taken up by the crop.

Light soils, especially in higher rainfall areas, are likely to cause crops to have lower nitrogen use efficiency (NUE) than medium and fine textured soils.

The N required from all sources (soil, legume residues and fertiliser) to achieve a grain yield at a range of protein levels is illustrated in Figure 7, which shows an increasing amount of N is required to achieve higher protein as yield increases.

The goal is to determine the value of the extra yield and protein relative to the fertiliser costs of achieving it.[26]

Figure 7: *The amount of nitrogen required from all sources (soil, legume residues and fertiliser) to achieve a grain yield at a range of protein levels (derived from the Nitrogen Calculator).*[27]



4.4.10 Decision support tools for calculating crop nitrogen requirements

Due to many processes involved in delivering N to the wheat crop, models can be used to estimate crop requirements, soil supply and, therefore, the fertiliser N required to reach yield potential.

26 GRDC (2014) Fact Sheet 'Durum Quality and Agronomy — Southern Region', GRDC, www.grdc.com.au/GRDC-FS-Durum

27 Palta, J, Bowden, W, and Asseng, S (2003) Timing of late applications of N fertiliser and season on grain yield and protein in wheat, CSIRO and DAFWA, www.regional.org.au/au/asa/2003/p/5/palta.htm

Models for calculating crop N requirements include:

N Broadacre

- A user-friendly iTunes app
- Based on the Select Your Nitrogen (SYN) model developed by DPIRD
- Incorporates expected value of the grain
- Accounts for cost of the extra N to determine economics of application.

NUlogic

- Developed by CSBP
- Available with paid and accredited access
- Can determine the yield and profit response from applied N
- Can be used to interpret soil and tissue tests.

Yield Prophet®

- Based on the Agricultural Production Simulation (APSIM) model
- Examines agronomic and economic responses to N rates and timing
- Provides a range of possible yield outcomes based on historical weather data
- Available through agronomists or directly through the Yield Prophet® website
- Requires calibration to soil type.

iPaddockYield

- An iPhone and iPad app
- Available through the iTunes app store
- Designed by a WA grain grower
- Estimates wheat yield throughout the season
- Provides a basic N requirement to match yield estimates.

GreenSeeker®

- Simpler support system based on crop reflectance methods
- Requires an N-rich strip set up at the start of season to assess N status
- Involves observation of crop response to the various strips — visually or using infrared GreenSeeker® technology
- If there is significant response to these strips, crop yields are likely to respond to topdressed N.

4.5 Phosphorus

Phosphorus (P) is important in wheat plants for growing tissue where cells are actively dividing, including at seedling root development, flowering and seed formation.

It is advised to undertake soil testing to determine the P status of a paddock.

Soil P tests are best interpreted in association with the soil's capacity to absorb or fix P, which is estimated by the phosphorus buffering index (PBI).

The higher the PBI, the more difficult it is for the plant to access P and the higher the P concentration required to optimise yields.

Phosphorus does not typically move readily in soils, except in very light sandy soils in high rainfall areas.

Soil P test critical ranges for wheat are 10-16 mg P/kg for grey sands and 22-24 mg P/kg for other soils (for a depth of 0-10 cm). But research has shown a single critical value of 11 mg P/kg is suitable for wheat on all soil types when testing to a depth of 0-30 cm.

Results from more than 100,000 soil tests indicate most WA growers are operating at or above the soil P levels required for near-maximum crop production – with 85 percent of tests returning soil P test values higher than the critical Colwell-P value (14-23 mg P/kg).[28]

Research has shown WA grain growers are, on average, applying almost twice the amount of P required and could cut applications without losing productivity or reducing soil P levels.

This has led to further analysis of the economic and agronomic benefits of diverting P fertiliser dollars into liming for soil acidity amelioration.

Some WA soils have been shown to be responsive to fertiliser P even when soil test P levels show that P is adequate. This is particularly the case for water-repellent soils where the soil surface does not wet-up evenly and the P on dry patches remains unavailable to the crop and with soils that have a high PBI.

Preliminary results suggest that when soil pH is below 5 (measured in calcium chloride, or $CaCl_2$), soil P is about 20 percent less available than when soil pH is above 6.

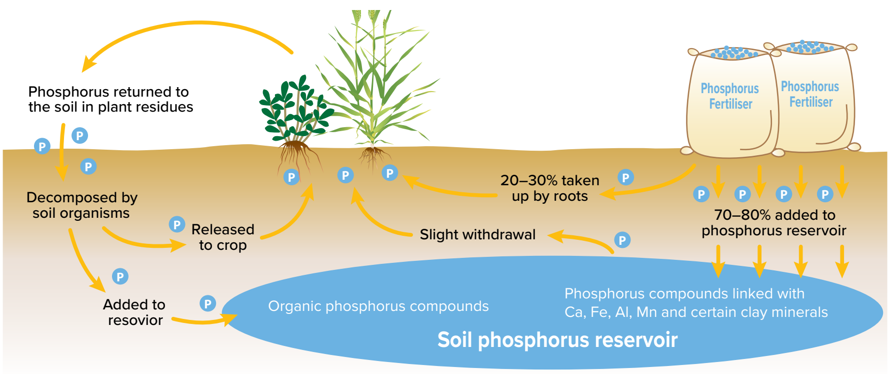
In acidic soils, aluminium (Al) is released into the soil solution, causing root pruning. This reduces the volume of soil that can be explored by the roots and the opportunity to intercept soil P, which is highly immobile in soil.

The Crop Phosphorus Model, developed by DPIRD, enables users to quantify the yield and economic response of broadacre crops to applications of P fertiliser in WA. It can be accessed via this link https://www.agric.wa.gov.au/crop-phosphorus-model.

4.5.1 Soil phosphorus

Soil P is present in soil as either undissolved P in old fertiliser granules, P that is sorbed onto soil constituents or P that is bound-up in organic matter, as shown in Figure 8.

Figure 8: *The phosphorus cycle in a typical cropping system is particularly complex, where movement through the soil is minimal and availability to crops is severely limited.*[29]



Phosphorus fertiliser is typically applied in a water-soluble form that can be readily taken up by plants. But, in this form, P is not stable and rapidly reacts in the soil (principally with iron (Fe), Al and Ca) to form insoluble, more stable compounds.

28 GRDC (2016) Western Wheat GrowNotes™, Section 5.7 Pg 15 Phosphorus, GRDC, www.grdc.com.au/GrowNotes

29 GRDC (2016) Western Wheat GrowNotes™, Section 5.7 Pg 15 Phosphorus, GRDC, www.grdc.com.au/GrowNotes

This means there is strong competition for water-soluble P from the soil and from plant roots, with only 5-30 percent of the P applied typically taken up by the crop in the year of application.[30] Phosphorus is relatively immobile in soils and P applied to the 0-10 cm layer of most WA soils tends to remain in that layer, especially in no-tillage systems.

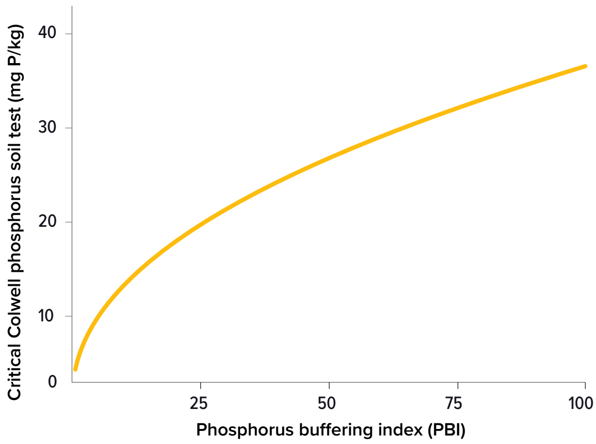
However, grey sands have low P sorption capacity and P in these soils can leach from the 0-10 cm soil layer and accumulate in layers below 10 cm.[31]

4.5.2 Soil testing for phosphorus

Determining the soil ability to fix P can underpin P fertiliser decisions.

A high P-fixing soil will require significantly more P fertiliser than a low P-fixing soil, as shown in Figure 9.

Figure 9: *Relationship between phosphorus required to meet 90 percent wheat yield potential (Critical Colwell P) and the P-fixing capacity of a soil (phosphorus buffering index).*[32]



Commercial tests have been developed to determine the P fixing capacity of soils.

Results from these tests can be used in conjunction with other soil and crop traits to optimise fertiliser P applications. Key features of P testing for P include:

- Phosphorus retention index (PRI) — direct measure of P-sorption and soil ability to fix P
- Phosphorus buffering index (PBI) — index is adjusted for pH (becoming the Australian standard for measuring soil P-sorption)
- Reactive iron test (RIT) — measures amount of iron extracted from soil as an indirect measure of soil ability to fix P
- Diffuse gradient technology phosphorus (DGT-P) — relatively new method that mimics the action of the plant roots in accessing available P.

30 GRDC (2016) Western Wheat GrowNotes™, Section 5.7 Pg 15 Phosphorus, GRDC, www.grdc.com.au/GrowNotes

31 GRDC (2016) Western Wheat GrowNotes™, Section 5.7 Pg 15 Phosphorus, GRDC, www.grdc.com.au/GrowNotes

32 Quinlan, R (2012) Planfarm, Phosphorus WA Fact Sheet, soilquality.org.au/factsheets/phosphorus

4.6 Potassium

Sandy soils in WA are prone to K deficiency. This can cause shrivelled grain and exacerbate frost and leaf disease impacts, as native and fertiliser applied K are held poorly and subject to leaching.

In most sandy soils, K concentration is highest in the surface layer where the organic matter is higher. Soil types of WA's west midlands and southern sandy soils are commonly K deficient.

Most clay and clay-loam WA soils contain sufficient K for optimum wheat and pasture production, but K deficiency is starting to show up in some duplex and loam soils.

Until the early 1990s, duplex soils rarely showed responses to K.

But responses to the application of K on these soils are now well documented in the central and southern grainbelt.

Potassium deficiency has also been identified on York gum and red loam soils near Moora.

Subsoil K can be a significant K store in some soils.

The economically optimum rate for K fertiliser will vary between paddocks and relative to yield potential, soil K test value and the fertiliser being used.

Research has found stubble contains up to three times as much K as grain — making it important to account for K export after harvest when calculating nutrient budgets.[33]

Potassium deficiency diagnosed in-crop cannot typically be corrected until the following season.

Early season K deficiency can be more detrimental to crop yield than late season deficiency.

Deficiency tends to occur initially in older leaves and can be mistaken for leaf diseases, such as yellow spot (*Pyrenophora tritici-repentis*) and Septoria nodorum blotch, or SNB (*Stagonospora nodorum blotch*).

Soil acidity, soil compaction and waterlogging modify root growth and lower the capacity of wheat to extract subsoil nutrients, including K. As a result, there is a poor relationship between soil test K (and other nutrient) values and crop yield response in wheat across all soil types.

The critical range for K across soil types in WA is 39-45 mg K/kg to achieve a relative yield of 90 percent for wheat.[34]

Loams have a higher critical range of 45-52 mg K/kg at depth.[35] In paddocks with high yield potential, profitable responses have been measured where the soil test result was up to 45 mg K/kg. Topdressing test K strips in soils above 30 mg K/kg can help determine economic responses.[36]

Windrow burning and canola swathing can concentrate K in some cases — causing big spatial variations in K content across paddocks. It is, therefore, advised to use soil K tests in conjunction with tissue testing and visual crop symptoms to determine application rates for paddocks.

However, tissue testing only determines K deficiency — not requirements — and is useful for determining K requirements for following seasons.

Potassium lost through product removal should be replaced when paddocks reach a responsive situation, as shown in Table 5.

33 GRDC (2016) Western Wheat GrowNotes™, Section 5.8 Pg 18 Potassium, GRDC, www.grdc.com.au/GrowNotes

34 GRDC (2016) Western Wheat GrowNotes™, Section 5.8 Pg 18 Potassium, GRDC, www.grdc.com.au/GrowNotes

35 GRDC (2016) Western Wheat GrowNotes™, Section 5.8 Pg 18 Potassium, GRDC, www.grdc.com.au/GrowNotes

36 GRDC (2016) Western Wheat GrowNotes™, Section 5.8 Pg 18 Potassium, GRDC, www.grdc.com.au/GrowNotes

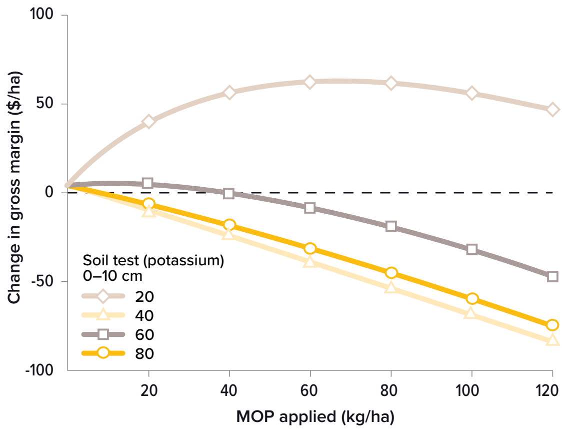
Table 5: Potassium removal per tonne of produce.[37]

Crop	Annual K removal (kg)
Wheat	4
Barley	5
Oats	5
Canola	5
Lupins	10
Oaten hay	25

The economically optimum rate of K fertiliser to apply will differ between paddocks and depend on crop yield potential, soil K test value and fertiliser being used.

Soil tests for K can be used in conjunction with the K model developed by DAFWA to determine the predicted gross margin from applying muriate of potash (MOP), as shown in Figure 10.

Figure 10: *Economic response to applying muriate of potash (at a cost of $800 per tonne) for wheat (estimated return of $240/t) with a potential yield of 2 t/ ha.*[38]



4.6.1 Potassium fertiliser placement and timing

Muriate of potash (MOP) is the cheapest form of K (with a potassium chloride (KCL) concentration of 49.5 percent K) and is typically applied by topdressing either at seeding or up to five weeks after seeding.[39]

Using MOP rates higher than 30 kg/ha sown directly with seed (at 22 cm row spacing) has been found to have potential to significantly reduce crop germination and establishment. For this reason, it is recommended K is banded away from the germinating seed.[40]

Sulphate of potash is less damaging than MOP and can be drilled directly with seed, but can be considerably more expensive per unit of K.

Banded K has been shown to be twice as accessible to crops as topdressed K, potentially because the crop is able to access this source before weeds can.

37 GRDC (2016) Western Wheat GrowNotes™, Section 5.8 Pg 18 Potassium, GRDC, www.grdc.com.au/GrowNotes

38 GRDC (2016) Western Wheat GrowNotes™, Section 5.8 Pg 18 Potassium, GRDC, www.grdc.com.au/GrowNotes

39 Quinlan, R, and Wherret, (2016) WA Potassium – Fact Sheet, Soilquality.org.au, http://www.soilquality.org.au/factsheets/potassium

40 Quinlan, R, and Wherret, (2016) WA Potassium – Fact Sheet, Soilquality.org.au, http://www.soilquality.org.au/factsheets/potassium

However, it is advised not to drill K at rates higher than 15 kg/ha and to band fertiliser away from seed.[41]

In paddocks with severe K deficiency (over 30 mg/kg), K is best applied early in the season (up to four weeks after seeding) to maximise crop response, as shown in Figures 11 and 12.

Figure 11: *Impact of potassium supplied at different wheat growth stages on the number of wheat heads per pot.*[42]

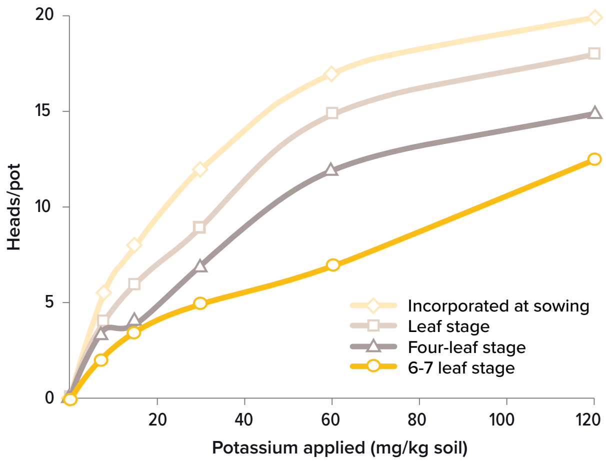
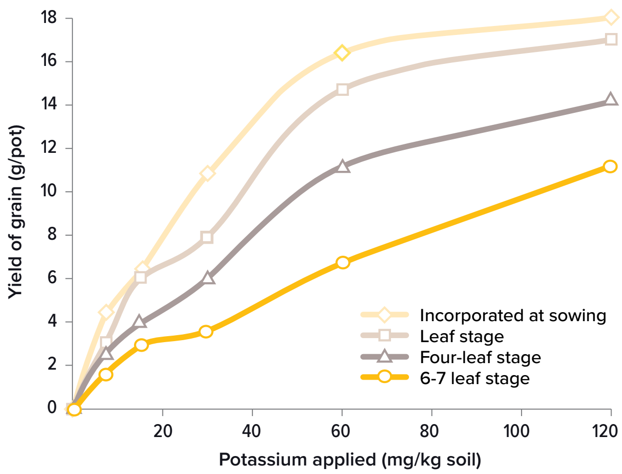


Figure 12: *Impact of potassium supplied at different wheat growth stages on wheat grain yield per pot.*[43]



41 GRDC (2016) Western Wheat GrowNotes™, Section 5.8 Pg 18 Potassium, GRDC, www.grdc.com.au/GrowNotes

42 GRDC (2016) Western Wheat GrowNotes™, Section 5.8 Pg 18 Potassium, GRDC, www.grdc.com.au/GrowNotes

43 GRDC (2016) Western Wheat GrowNotes™, Section 5.8 Pg 18 Potassium, GRDC, www.grdc.com.au/GrowNotes

4.7 Sulfur

Sulfur is part of all living cells and an important part of three of the 21 amino acids that form proteins.[44]

It is also a critical component in the enzyme responsible for converting the NO_3^- form of N to amino acids and is essential for N fixation in legumes and chlorophyll formation.

Sulfur deficiency is rare in WA wheat systems due to previous widespread use of superphosphate (which contains 10 percent S). But it can occur when organic matter mineralisation slows during cold weather and following high rainfall on acidic sandy soils.

Continual use of compound fertilisers that contain little or no S will also increase the risk of S deficiency.

Research has found addressing visual S deficiency in wheat with use of sulphate of ammonia can quickly address the problem without significant yield loss.[45]

There is a poor relationship between the critical soil S test value measured in the 0-10 cm layer and wheat yield response, however a better relationship exists between the critical soil S test value measured in the 0-30 cm layer and wheat yield.[46]

A tissue test for N to S ratio higher than 19:1 often indicates S deficiency.[47]

Early deficiency is occasionally seen in crops growing on sandy soils in wetter areas, but plants generally recover without any yield loss.

Continual use of compound fertilisers that contain little or no S will increase the risk of S deficiency.

WA grainbelt soils typically have soil pH values of less than 5.5 in the 0-10 cm layer. Nevertheless, sulphate sorption is generally low for WA soils in the 0-10 cm soil layer due to low clay content.

Also, the presence of P — which is more strongly adsorbed than S — reduces the capacity of the soil to adsorb S.

Sulphate adsorption is known to increase with soil depth due to increasing clay content of the soil and decreasing P and pH. As a result, there can be significant amounts of S contained in the subsoil — especially in soil profiles with soil pH of less than 5.0.

Crop S requirements are closely linked to the amount of available N — a reflection of the similar role the nutrients have in protein and chlorophyll formation.

Sulfur deficiency is typically unlikely to be an issue when the bulk of crop N is sourced from mineralised N rather than fertiliser N.

As a general rule, fertiliser N and S should be supplied in a ratio of 5:1 (N:S) on sandy textured soils.[48]

Tissue testing of the youngest emerged leaf can determine crop S status. Levels below 0.3 percent are indicative of a deficiency.[49]

If using a whole-top plant test, levels below 0.15 percent in whole shoots at the boot stage are likely to be deficient.

Nitrogen to S tissue test ratios higher than 19:1 are also indicative of S deficiency.[50]

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44 GRDC (2016) Western Wheat GrowNotes™, Section 5.8 Pg 18 Potassium, GRDC, www.grdc.com.au/GrowNotes

45 GRDC (2015) Hot Topic Sulfur strategies for the western region, GRDC, www.grdc.com.au/Media-Centre/Hot-Topics/Sulfur-strategies-for-western-region

46 GRDC (2016) Western Wheat GrowNotes™, Section 5.8 Pg 18 Potassium, GRDC, www.grdc.com.au/GrowNotes

47 GRDC (2016) Western Wheat GrowNotes™, Section 5.8 Pg 18 Potassium, GRDC, www.grdc.com.au/GrowNotes

48 GRDC (2016) Western Wheat GrowNotes™, Section 5.8 Pg 18 Potassium, GRDC, www.grdc.com.au/GrowNotes

49 GRDC (2016) Western Wheat GrowNotes™, Section 5.8 Pg 18 Potassium, GRDC, www.grdc.com.au/GrowNotes

50 GRDC (2016) Western Wheat GrowNotes™, Section 5.8 Pg 18 Potassium, GRDC, www.grdc.com.au/GrowNotes

Topdressing 10-15 kg/ha of S as gypsum or ammonium sulphate tends to overcome deficiency symptoms. Foliar sprays tend to be unable to supply enough S for plant needs.

MORE INFORMATION

GRDC-DPIRD MyCrop and MyCrop app: https://www.agric.wa.gov.au/mycrop

4.8 Micronutrients

The most likely limiting micronutrients in WA wheat systems are copper (Cu), manganese (Mn), molybdenum (Mo) and zinc (Zn).[51]

Inadequate supplies can reduce wheat growth and grain yields and lead to inefficient use of N and soil moisture.

Traditionally, cultivation tended to distribute micronutrients through the topsoil. But the introduction of no-tillage and one-pass seeding equipment has led to more limited physical distribution.

Tissue tests are the best way to identify micronutrient deficiencies.

Soil tests typically have low reliability because micronutrients are present in such low quantities.

Visual crop symptoms can be a guide to micronutrient deficiencies, but some symptoms may mimic other unrelated problems.

For example, symptoms of a Cu deficiency in cereals can resemble symptoms of frost, disease or drought — and even a Mo deficiency can produce white heads. Micronutrient deficiencies may also be temporary or transient due to cold weather, drought or slow root growth.

51 GRDC (2016) Western Wheat GrowNotes™, Section 5.8 Pg 18 Potassium, GRDC, www.grdc.com.au/GrowNotes

MORE INFORMATION

GRDC 'Tips and Tactics Crown Rot in Cereals — Western Region, GRDC': www.grdc.com.au/TT-CrownRotWinterCereals

NSWDPI 'Crown Rot, an Update on Latest Research': https://grdc.com.au/Research-and-Development/GRDC-Update-Papers/2015/07/Crown-rot-an-update-on-latest-research

Diseases

5.1 Crown rot

Figure 1: *Severe crown rot affecting wheat plants.*

(SOURCE: GRDC)

Crown rot, caused by the fungus *Fusarium pseudograminearum*, is a major disease of durum and bread wheat in eastern Australia.

While it is not as significant in Western Australian wheat crops, its incidence appears to be increasing.[1]

The crown rot fungus enters the plant through the roots and blocks water movement from root to stem, causing grain to shrivel or fail to form.

Crown rot infection in wheat crops is characterised by a light honey-brown to dark brown discolouration of the base of infected tillers.

Major yield loss that results from the production of whiteheads is related to moisture stress post-flowering.

There are three distinct and separate phases of crown rot disease in wheat — survival, infection and expression. Management strategies can differentially affect each phase, as outlined below:[2]

1 Huberli, D (2014) Relative Yield Loss of Wheat Varieties to Crown Rot 2014 Trial Report, DAFWA, https://www.agric.wa.gov.au/wheat/yield-loss-response-curve-trial-crown-rot-2016-trial-report

2 Simpfendorfer, S (2015) Crown Rot an Update on Latest Research, NSW DPI Tamworth, GRDC 2015 Update Papers, https://grdc.com.au/Research-and-Development/GRDC-Update-Papers/2015/07/Crown-rot-an-update-on-latest-research

Survival

- Crown rot fungus survives as mycelium (cottony growth) in crop residues
- Hosts are winter cereals (wheat, barley, durum, triticale and oats)
- Grass weed residues also host disease
- Fungus will survive as inoculum inside stubble while intact
- This will vary due to soil and weather conditions
- Stubble decomposition is a slow process.

Infection

- Fungus will grow out of stubble residues
- It infects new winter cereal plants if there is soil moisture
- Infection occurs through the coleoptile, sub-crown internode or crown tissue (sub-surface)
- Fungus can infect plants above ground through outer leaf sheathes
- This requires direct contact with the previously infected residues
- Infections can occur right through the season if there is soil moisture
- Wet seasons favour increased infection
- High stubble loads tend to build-up inoculum levels.

Expression

- Yield loss is related to moisture/temperature stress
- This is particularly around flowering and grain fill
- Fungus proliferates in the base of infected tillers
- This restricts water movement from the roots through the stems
- Whiteheads are produced
- These contain either no grain or lightweight shrivelled grain
- Whiteheads can increase with moisture/temperature stress at grain fill
- Crops near trees in paddocks and along tree lines likely to show whiteheads.

Crown rot is often not detected until after heading, when whiteheads (those that are prematurely ripened) are seen scattered through a crop .

Most wheat varieties are susceptible or very susceptible to crown rot and it is recommended to avoid growing durum wheat immediately after a bread wheat crop to avoid this disease.

5.1.1 Durum wheat crown rot resistence

A five-year research program, to be carried out until 2018, has been established to transfer crown rot resistance genes from bread wheat and other tetraploid wheat sources into durum wheat varieties.[3]

Crossing durum wheat lines with bread wheat lines presents technical challenges because of the different genomics of the two species.

Bread wheat has three genomes and durum wheat has only two, so making successful crosses and then back-crossing to ensure the progeny are pure durum wheats takes some time.

Bread wheat crosses to three elite durum wheat breeding lines, including EGA Bellaroi⟨PBR⟩, have been advanced to the point where stable resistance has been identified over several generations in multiple families within these crosses.

3 Paterson, J (2014) Crown Rot Resistance in Cereal Breeding Pipeline: Durum Crown Rot Resistance, GRDC Ground Cover, Issue 111, GRDC, https://grdc.com.au/Media-Centre/Ground-Cover-Supplements/GCS111/Crown-rot-resistance-in-cereal-breeding-pipeline

MORE INFORMATION

NSWDPI 'Guide to Producing Durum Wheat': http://www.nvtonline.com.au/wp-content/uploads/2013/03/Crop-Guide-NSW-Durum-Wheat-Production.pdf

5.1.2 Tackling crown rot on-farm

A summary of diagnosis and management strategies that can be used for crown rot in cereal crops is outlined in Table 1.

Table 1: Diagnosing and managing crown rot in wheat.[4]

Diagnosis	Symptoms	Management
Use PREDICTA® B to monitor soil inoculum levels and guide wheat management decisions: http://www.sardi.sa.gov.au/diagnostic_services/predicta_b/why_test/crown_rot	To diagnose crown rot incrop use the GRDC-DPIRD MyCrop web tool: https://agric.wa.gov.au/n/2131	High nitrogen environments create large crops that can collapse with a large crown rot outbreak. A grass-free break from cereals is the best way to lower crown rot inoculum levels. There are no registered post-emergent chemical treatments to control crown rot. A registered fungicide-based seed treatment is available. More information on managing crown rot: www.grdc.com.au/GRDC-FSCrownRotCerealsSW New GRDC-funded research by DPIRD is evaluating the crown rot resistance of new and upcoming wheat varieties: https://agric.wa.gov.au/n/3774

There are no registered post-emergent chemical treatments to control crown rot in durum wheat crops.

The registered fungicide-based seed treatment for durum wheat is Rancona® Dimension, containing the Group 3 active ingredient ipconazole.

If disease levels are high and there is moisture and/or evaporative stress during grain fill, yield losses from crown rot can be up to 90 percent in durum wheat and 50 percent in bread wheat.[5]

The crown rot fungus can persist in infected cereal residues for up to two years and be carried into wheat crops from infected grass weeds.

Rotating cereals with non-susceptible crops, such as pulses, oilseeds, lupins or grass-free pastures — and maintaining good grass weed control — can reduce crown rot inoculum.

Inter-row sowing using GPS guidance in no-tillage systems has been shown to halve the number of plants infected with crown rot, resulting in a 5-10 percent yield increase.[6]

Cultivation (even when this is shallow) distributes infected residue more evenly across paddocks and into the infection zones below ground for crown rot management.

PREDICTA® B tests

Soil testing using the PREDICTA® B DNA-based diagnostic service is a good tactic to identify level of risk for crown rot (and other soil-borne pathogens) prior to sowing wheat.

4 GRDC 'Tips and Tactics Crown Rot in Cereals — Western Region, GRDC': www.grdc.com.au/TT-CrownRotWinterCereals

5 GRDC (2016) Tips and Tactics, Crown Rot in Cereals — Western Region, GRDC, www.grdc.com.au/TT-CrownRotWinterCereals

6 GRDC (2016) Tips and Tactics, Crown Rot in Cereals — Western Region, GRDC, www.grdc.com.au/TT-CrownRotWinterCereals

However, this requires a dedicated sampling strategy and is not a simple add-on to a soil nutrition test.[7]

PREDICTA® B detects levels of a range of cereal pathogens, including the main *Fusarium* species that cause crown rot.

It is accessed through accredited advisers and agronomists and correct sampling guidelines include:

- Collect three soil sample cores of 1 centimetre diameter and at 10 cm soil depth
- If the core is wider, take fewer cores per location
- Core at 15 different locations in the target paddock or production zone
- Take the soil cores from along/in the rows of previous cereal crop if still visible
- Retain any stubble collected by the core
- If the rows can't be seen, take the cores at random
- Add one piece of cereal stubble (if present) to the sample bag at each of the 15 sample sites
- Each stubble piece should be from the base of the plant and include the crown to the first node
- Maximum sample weight should not exceed 500 grams.

A commercial plant disease diagnosis service is also available through the Department of Primary Industries and Regional Development (DPIRD) Diagnostic Laboratory Services (DDLS)-Plant Pathology service at https://www.agric.wa.gov.au/bacteria/ddls-plant-pathology-services for crown rot and other pathogens.8

Crown rot paddock assessment

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 or three years in stubble and soil.

Growing a non-host crop for at least two seasons is recommended to reduce inoculum levels.[9]

This allows time for decomposition of winter cereal residues that host the crown rot fungus.

Stubble decomposition varies with:

- » Type of break crops grown
- » Canopy density
- » Rate of canopy closure
- » Row spacing
- » Amount of soil water used
- » Seasonal rainfall.

Check cereal crops for crown rot between grain filling to harvest.

It is recommended to collect plant samples in the paddock by walking in a large W pattern and picking out five plants at 10 different locations, as shown in Figure 2.[10]

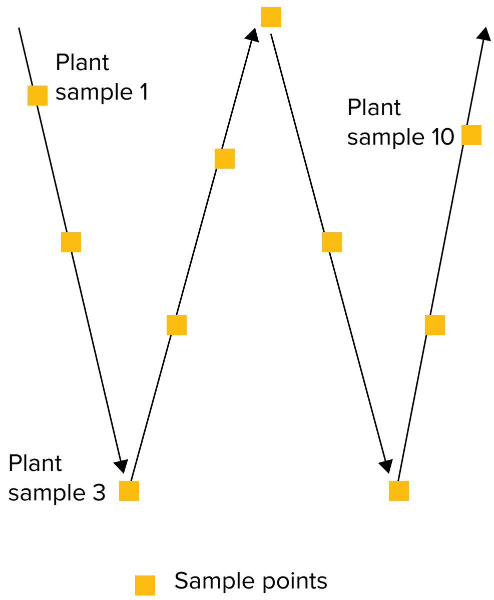
7 Simpfendorfer, S (2015) Crown Rot an Update on Latest Research, NSW DPI Tamworth, GRDC 2015 Update Papers, https://grdc.com.au/Research-and-Development/GRDC-Update-Papers/2015/07/Crown-rot-an-update-on-latest-research

8 GRDC (2016) Tips and Tactics, Crown Rot in Cereals — Western Region, GRDC, www.grdc.com.au/TT-CrownRotWinterCereals

9 Simpfendorfer, S (2015) Crown Rot an Update on Latest Research, NSW DPI Tamworth, GRDC 2015 Update Papers, https://grdc.com.au/Research-and-Development/GRDC-Update-Papers/2015/07/Crown-rot-an-update-on-latest-research

10 GRDC (2016) Tips and Tactics, Crown Rot in Cereals — Western Region, GRDC, www.grdc.com.au/TT-CrownRotWinterCereals

Figure 2: *The W pattern recommended for plant sampling to check for disease in cereal crops.*[11]



When sampling, examine each plant for basal browning, record the percentage that show the symptom and then put in place appropriate measures for the next year.

As a general rule, the risk for a cereal crop in the subsequent season will be:

- Low — less than 10 percent of plants infected
- Medium — 11-24 percent of plants infected
- High — more than 25 percent of plants are infected.[12]

If crown rot has caused yield loss, or is suspected to have caused loss, there are several ways to minimise disease risk for the coming season. But actual yield loss will be mostly determined by seasonal conditions.

For example, a paddock may have a high inoculum load but the cereal crop may only suffer small yield losses if there is good spring rainfall and mild temperatures.

Paddock history can also provide clues. Risk of crown rot tends to be high in paddocks following:

- High infection levels in a winter cereal crop in the past three years
- High frequency of winter cereals in the rotation
- Stubble retention with no tillage
- Low rainfall during the last fallow or break crop from cereals (where dry conditions have made residue decomposition slow)
- Poor grass weed control
- Stubble cultivated close to sowing
- Paddocks with low stored soil moisture at sowing/soil types with low water holding capacity.[13]

Stubble and crown rot fungus survival

- Stubble decomposition is a microbial process
- It is driven by temperature and moisture

11 GRDC (2016) Tips and Tactics, Crown Rot in Cereals — Western Region, GRDC, www.grdc.com.au/TT-CrownRotWinterCereals

12 GRDC (2016) Tips and Tactics, Crown Rot in Cereals — Western Region, GRDC, www.grdc.com.au/TT-CrownRotWinterCereals

13 GRDC (2016) Tips and Tactics, Crown Rot in Cereals — Western Region, GRDC, www.grdc.com.au/TT-CrownRotWinterCereals

- Cultivating stubble can increase rate of decomposition
- Cultivation reduces stubble particle size
- It will bury stubble particles in the soil where microbial activity is higher
- Cultivation dries out the soil in the cultivation layer
- This limits the potential for decomposition of the incorporated stubble
- Decomposition of cereal stubbles is a very slow process
- It requires adequate moisture for an extended period of time
- A summer fallow tends to be too short.

Stubble and crown rot infection

- The bulk of crown rot infection sites are below ground
- Infection requires physical contact between infected residue and plant parts
- Stubble cultivation breaks the inoculum into smaller pieces
- It spreads these more evenly through the cultivation layer across the paddock
- The fungus may contact the major infection sites below ground as the next winter cereal crop germinates and develops
- In a no-tillage system, fungus is confined to the previous cereal rows
- Fungus is more reliant on infection through outer leaf sheathes at the soil surface
- Inter-row sowing with GPS guidance can halve the number of plants infected with crown rot when used in a no-till cropping system.[14]

Stubble and crown rot expression

- Cultivation dries out the soil to the depth of cultivation
- This reduces water infiltration rate due to the loss of structure
- Lack of cereal stubble cover can increase soil evaporation
- With poorer infiltration and higher evaporation, fallow efficiency is reduced (cultivated systems compared to no-tillage stubble retention)
- Moisture availability can buffer against crown rot expression late in the season
- Cultivation is a balancing act between perceived benefits and costs.

Burning stubble removes the above-ground portion of crown rot inoculum, but the fungus typically survives in infected crown tissue below ground and this is not a quick fix for high inoculum situations.[15]

Removal of stubble through burning can increase evaporation from the soil surface and impact on fallow efficiency.

A cooler autumn burn is preferable to an earlier hotter burn, as this minimises the negative impacts on soil moisture storage while still reducing inoculum levels.

Inoculum level is important in limiting the potential for yield loss from crown rot. But the overriding factor dictating the extent of yield loss is moisture/temperature stress during grain fill.[16]

Soil moisture conservation tactics

Any management strategy that limits storage of soil water, or creates constraints that reduce the ability of roots to access this water, will tend to increase the probability and/or severity of moisture stress during grain fill and exacerbate the impact of crown rot.

14 Simpfendorfer, S (2014) Cultivation Can Exacerbate Crown Rot, NSW DPI Tamworth, GRDC Ground Cover, Issue 111, GRDC, https://grdc.com.au/Media-Centre/Ground-Cover-Supplements/GCS111/Cultivation-can-exacerbate-crown-rot

15 Simpfendorfer, S (2015) Crown Rot an Update on Latest Research, NSW DPI Tamworth, GRDC 2015 Update Papers, https://grdc.com.au/Research-and-Development/GRDC-Update-Papers/2015/07/Crown-rot-an-update-on-latest-research

16 Simpfendorfer, S (2015) Crown Rot an Update on Latest Research, NSW DPI Tamworth, GRDC 2015 Update Papers, https://grdc.com.au/Research-and-Development/GRDC-Update-Papers/2015/07/Crown-rot-an-update-on-latest-research

Grass weeds are ideally controlled in fallow periods and in-crop. This is especially important in break crops, as these host the crown rot fungus and can significantly reduce soil moisture storage.

In pasture situations, grass weeds are best controlled well in advance of a following cereal crop, as these are a host for the crown rot fungus.

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 a key reason inter-row sowing with GPS guidance has been found to reduce the number of plants infected with crown rot by up to 50 percent when used in a no-till cropping system.[17]

Further research has also demonstrated the benefits of row placement in combination with crop rotation and the relative placement of break crop rows and winter cereal rows within the sequence to limit disease and maximise yield.[18]

Sowing break crops between standing wheat rows, that are kept intact, and then sowing the following wheat crop directly over the row of the previous year's break crop tends to result in there being four years' break between wheat rows being sown in the same row space.

This has been found to substantially reduce the incidence of crown rot in wheat crops, improve establishment of break crops (especially canola) and benefit chickpeas from reduced virus incidence in standing wheat stubble.

In WA, inter-row sowing using accurate ±2 cm differential GPS autosteer has been shown to reduce the number of infected plants by about 50 percent, resulting in a 5-10 percent yield advantage in the presence of crown rot.[19]

Soil type does not appear to differentially affect the survival or infection phases of crown rot.

However, the inherent water holding capacity of each soil type interacts with expression by potentially buffering against moisture stress late in the season. Yield loss can be worse on red soils due to their generally lower water holding capacities.[20]

Any other subsurface constraint, such as sodicity, salinity or shallower soil depth, effectively reduces the level of plant available water which can increase the expression of crown rot.

Cereal crop and variety choice for crown rot management

All winter cereal crops host the crown rot fungus. Yield loss in subsequent crops varies between crop type. The approximate order of increasing loss from disease is oats, barley, triticale, bread wheat and durum wheat.

Bread wheat varieties appear to vary significantly in the level of yield loss to crown rot. Varietal resistance and tolerance to crown rot exist but are not the only solutions, according to researchers.[21]

Resistance is the plant's ability to limit the development of the crown rot fungus in living tissue. Tolerance is the plant's ability to maintain yield in the presence of crown rot infection.

Some of the new durum wheat lines show promise of improved resistance to crown rot compared to current commercial varieties.

MORE INFORMATION

'Crown Rot Resistance and Yield Loss': http://www.hartfieldsite.org.au/media/2013%20TRIAL%20RESULTS/21_Crown_rot_resistance__yield_loss_2013HartTrialResultsBook.pdf

17 Simpfendorfer, S (2015) Crown Rot an Update on Latest Research, NSW DPI Tamworth, GRDC 2015 Update Papers, https://grdc.com.au/Research-and-Development/GRDC-Update-Papers/2015/07/Crown-rot-an-update-on-latest-research

18 Verrell, A (2014) Managing Crown Rot Through Crop Sequencing and Row Placement, NSW DPI, GRDC 2014 Update Paper, https://grdc.com.au/Research-and-Development/GRDC-Update-Papers/2014/07/Managing-crown-rot-through-crop-sequencing-and-row-placement

19 GRDC (2016) Tips and Tactics, Crown Rot in Cereals — Western Region, GRDC, www.grdc.com.au/TT-CrownRotWinterCereals

20 Simpfendorfer, S (2015) Crown Rot an Update on Latest Research, NSW DPI Tamworth, GRDC 2015 Update Papers, https://grdc.com.au/Research-and-Development/GRDC-Update-Papers/2015/07/Crown-rot-an-update-on-latest-research

21 GRDC (2016) Tips and Tactics, Crown Rot in Cereals — Western Region, GRDC, www.grdc.com.au/TT-CrownRotWinterCereals

Further field screening is needed to validate these findings, but the progress toward improved resistance to crown rot being made in durum breeding programs is encouraging, according to researchers.[22]

Crop Variety Guides and the National Variety Trials (NVT) website at: www.nvtonline.com.au provide crown rot ratings that are predominantly based on the evaluation of resistance.

The latest information about the relative yield of varieties in the presence of crown rot can be found on the GRDC website at www.grdc.com.au

However, researchers advise variety choice is not a solution to this disease. Even the best varieties tend to suffer up to 40 percent yield loss from crown rot under high infection levels and when there is a dry/hot seasonal finish in many areas of southern Australia.[23]

Sowing time and crown rot

Earlier sowing in the recommended window of a given wheat 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 also increase plant root length/depth and provide more access to deeper soil water later in the season, which can buffer against crown rot expression.

This has been shown in previous research across seasons to reduce yield loss from crown rot. However, earlier sowing can place a crop at risk of frost damage during its most susceptible time.

Sowing time for cereal crops in WA is a balancing act between the risk of frost and heat stress.

However, when managing crown rot, increased disease expression due to delayed sowing can have just as big an impact on yield as frost.

There is the additional detrimental impact of later sowing on grain size in the presence of crown rot infection.

5.1.3 Crop nutrition and crown rot

Bulky crops are more likely to experience moisture stress during grain filling than less bulky crops, which makes these more vulnerable to yield losses from crown rot.

It is advised to match nitrogen (N) rates and timing to stored soil moisture and targeted potential yield. This can avoid excessive early crop growth that can diminish soil water reserves prior to the critical grain filling period.

Zinc (Zn) nutrition is important, as the expression of whiteheads in tillers infected with crown rot can be more severe in Zn deficient crops. But applying Zn above recommended rates will not typically provide further protection from crown rot.[24]

If a cereal must be sown, but there is a risk of yield loss from crown rot, it is recommended to:

- Select a cereal type with lowest potential yield loss
- Select wheat varieties with improved tolerance[25]
- Match N nutrition to stored moisture and seasonal forecast
- Ensure Zn nutrition is adequate
- Sow on the inter-row on loams and heavier soil types if possible (not an option for water repellent sandy soils)
- Avoid sowing late in the planting window.

22 Evans, M and Wallwork, H (2013) Hart Field Site 2013 Results: Crown Rot Resistance and Yield Loss, SARDI, http://www.hartfieldsite.org.au/media/2013%20TRIAL%20RESULTS/21_Crown_rot_resistance__yield_loss_2013HartTrialResultsBook.pdf

23 GRDC (2016) Tips and Tactics, Crown Rot in Cereals — Western Region, GRDC, www.grdc.com.au/TT-CrownRotWinterCereals

24 GRDC (2016) Tips and Tactics, Crown Rot in Cereals — Western Region, GRDC, www.grdc.com.au/TT-CrownRotWinterCereals

25 GRDC (2016) Tips and Tactics, Crown Rot in Cereals — Western Region, GRDC, www.grdc.com.au/TT-CrownRotWinterCereals

Registered fungicide seed dressings alone are unlikely to provide consistent or significant yield improvements, but may be beneficial when used with other management options.

Note that growing a cereal, particularly a susceptible variety, may increase inoculum levels for subsequent crops.

5.2 Take-all root disease

Figure 3: *Take-all disease can stunt root growth of wheat plants.*

(SOURCE: GRDC)

- Seed, fertiliser or in-furrow applied fungicides are registered
- Actives include flutriafol, fluquinconazole and triadimefon
- Acidifying fertilisers may slightly reduce disease severity
- Disease severity may increase after liming
- Control volunteer grasses and cereals
- Delay sowing following opening rains by implementing a short chemical fallow
- High rainfall in winter can increase disease pressure.

Take-all is a soil-borne disease of cereal crops and, in WA, is caused by two variants of the *Gaeumannomyces graminis* fungus. These are *G. graminis var. tritici* (Ggt) and *G. graminis var. avenae* (Gga).

Take-all restricts water and nutrient flow up the crop's root system and, under periods of moisture stress, causes infected plants to die prematurely.

While it remains a relatively minor disease in WA, take-all is most severe in high rainfall areas, including southern cropping regions and areas close to the coast.

Currently there are no available resistant wheat or barley varieties to take-all.

The most effective management strategy to control take-all is to deny the fungus the ability to survive in the paddock by eliminating hosts, using tactics summarised in Table 2.[26]

26 GRDC (2014) Hot Topic — Take All, GRDC, https://grdc.com.au/Media-Centre/Hot-Topics/Take-all

Table 2: Diagnosing and managing take-all in wheat.[27]

Monitor	Diagnose	Manage
Use PREDICTA® B to monitor take-all inoculum levels and guide wheat management decisions: www.sardi.sa.gov.au/diagnostic_services/predicta_b/why_test/take-all PREDICTA® B take-all map: www.sardi.sa.gov.au/diagnostic_services/predicta_b/disease_distribution	To diagnose take-all in crop use the GRDC-DPIRD MyCrop web tool: https://www.agric.wa.gov.au/n/2153	The most effective way to reduce take-all is to use a non-cereal break crop, grass-free pasture or chemical fallow to remove grasses in the year before wheat: www.soilquality.org.au/factsheets/take-all-disease There are no post-emergent fungicide treatments to control take-all. Check current registered seed dressings at: https://www.agric.wa.gov.au/n/1794

Take-all management tactics include using a non-cereal break crop, such as lupins, canola or field peas, and ensuring effective grass weed control during autumn.

Pastures containing low levels of grass species will also have reduced take-all carry-over levels in the following season.

Widespread adoption of no-till tillage has significantly increased the time required for stubble residue to break down and disease management should take this into account.

Burning stubbles can reduce the amount of surface residue infected with the take-all fungus, but typically the burn is not hot enough to affect the infected material below ground.

High rainfall in winter can increase take-all disease pressure.

If there is a soft finish to the season, cereal yield losses from take-all might not be as high. But the fungus will keep developing until the crop matures and pose an even greater risk to subsequent cereals.

27 GRDC (2014) Hot Topic — Take All, GRDC, https://grdc.com.au/Media-Centre/Hot-Topics/Take-all

5.3 Pythium root rot

Figure 4: *Using DNA analysis, CSIRO researchers Dr Paul Harvey and Rosemary Warren have identified that different crops are selecting to host different strains of pythium.*

(SOURCE: GRDC)

- No post-emergent treatments registered for suppression
- There are registered pythium-selective seed dressings
- Seed dressing actives are flutriafol and metalaxyl
- Diagnosis based on above-ground symptoms is difficult
- Moderate-severe disease often misdiagnosed as rhizoctonia.[28]

All major grain crops and pastures can host and be infected by pythium root rot. Wheat and barley are significantly less susceptible than pulses and canola.

Disease incidence tends to be higher after long-term legume pastures and repetitive wheat-canola rotations.

Pythium is often distributed relatively evenly in soils. This means that, in the absence of a protective treatment, all plants can be affected by pythium to a similar extent and severe infection can go undetected.[29]

Pythium is more prevalent in regions with an annual average rainfall above 350 millimetres and is often associated with waterlogging damage.

The effects of pythium root rot are often underestimated.

Guidelines for diagnosing, monitoring and managing pythium in wheat crops are outlined in Table 3.

28 GRDC (2010) Fact Sheet, Root Disease — Pythium Root Rot, GRDC, www.grdc.com.au/GRDC-FS-PythiumRootRot

29 GRDC (2010) Fact Sheet, Root Disease — Pythium Root Rot, GRDC, www.grdc.com.au/GRDC-FS-PythiumRootRot

Table 3: Diagnosing and managing pythium root rot in wheat.[30]

Monitor	Diagnose	Manage
PREDICTA® B pythium map: www.sardi.sa.gov.au/diagnostic_services/predicta_b/disease_distribution	Pythium is frequently misdiagnosed as rhizoctonia. To diagnose pythium in-crop use the GRDC-DPIRD MyCrop tool: https://www.agric.wa.gov.au/n/2142	Good weed control and the use of diverse rotations and fungicide seed dressings can help manage pythium: www.grdc.com.au/GRDC-FSPythiumRootRot Check currently registered fungicides or pythium at: https://www.agric.wa.gov.au/n/1794

5.4 Leaf spot, rust and other fungal diseases

Early sown wheat crops, including durum wheat varieties, can be particularly vulnerable to leaf spot and rust fungal diseases.

High disease pressure in continuous and early sown wheat crops before stem elongation can make it economical to apply a fungicide at — or before — early stem elongation (Zadoks Growth Scale stage GS31, or first node), particularly in medium and high rainfall areas.

Registered seed dressing and in-furrow fungicides can suppress leaf or stripe rust on wheat seedlings for four to six weeks, depending on the product and rate and — in some cases — can replace the need for a foliar spray before flag leaf emergence.[31]

Severe late season *septoria nodorum* blotch (SNB) can be an issue in WA wheat crops, as disease can spread from the leaves to infect wheat heads during grain fill to cause glume blotch.[32]

In these late-season infections, fungicide needs to be applied before crop heading is complete to reduce risks of head infection.

Spraying after heading is sub-optimal and spraying after crop flowering has finished is generally not economical.

Glume blotch results in dark patches on the glumes and can result in shrivelled grain and even complete loss of seed. Care needs to be taken to distinguish glume blotch from other causes of glume darkening, including pseudo black chaff, loose smut, frost and copper deficiency.

It is advised to send suspected glume blotch samples to DPIRD Diagnostic Laboratory Services (DDLS)-Plant Pathology at https://www.agric.wa.gov.au/bacteria/ddls-plant-pathology-services-for-diagnosis.

30 GRDC (2010) Fact Sheet, Root Disease — Pythium Root Rot, GRDC, www.grdc.com.au/GRDC-FS-PythiumRootRot

31 GRDC (2016) Western Wheat GrowNotes™, Section 5.8 Pg 18 Potassium, GRDC, www.grdc.com.au/GrowNotes

32 DPIRD (2016) Septoria Nodorum Blotch of Wheat, https://www.agric.wa.gov.au/crops/grains/wheat

5.4.1 Leaf spot disease treatment options

Yellow spot

Figure 5: *Yellow spot symptoms on a wheat leaf.*

(SOURCE: GRDC)

The registered in-furrow fungicide for the leaf spot disease yellow spot (caused by the fungus *Pyrenophora tritici-repentis*), is Uniform® (with the actives azoxystrobin and metalaxyl-M).

Foliar fungicides registered for control of yellow spot in wheat include:

- Azoxystrobin
- Tebuconazole
- Propiconazole
- Sulphur
- Prothioconazole
- Cyproconazole.

Septoria nodorum blotch, or spot-type net blotch

Figure 6: *Spot-type net blotch on leaf.*

(SOURCE: GRDC)

There are no registered seed treatments or in-furrow fungicides registered for control of SNB in wheat.

Foliar fungicide options for SNB control include:

» Azoxystrobin
» Tebuconazole
» Propiconazole
» Epoxiconazole
» Sulphur
» Prothioconazole
» Cyproconazole.

Septoria tritici blotch

Figure 7: *Septoria tritici blotch.*

(SOURCE: Evan Collis Photography)

Seed treatments registered for suppression of *septoria tritici* blotch (STB) are fluquinconazole-based.

Foliar fungicides that can be used for STB in wheat include the actives:

» Azoxystrobin
» Tebuconazole
» Propiconazole
» Sulphur
» Cyproconazole.

All wheat crops are vulnerable to air-borne spores of yellow spot and SNB.

Early sown crops are exposed to infection before later sown crops, which can provide these diseases with a head start.

Typically, milder conditions usually experienced in April and May also enable fungal diseases to mature more quickly on earlier sown crops.

Moderate to severe leaf disease in young wheat crops can reduce early growth, but the main impact of early disease is as a source of infection later in the season.

Leaf spot diseases are difficult to distinguish in wheat.

Yellow spot and SNB symptoms appear as irregular or oval-shaped spots that are initially small and yellow and then enlarge to form brown dead centres with yellow edges.[33]

33 GRDC (2011) Fact Sheet, Yellow Spot, Western Region, GRDC, https://grdc.com.au/Resources/Factsheets/2011/08/Yellow-Spot-Fact-Sheet-Western-Region

Being stubble-borne, leaf spot diseases are a particular a problem in continuous wheat crops where stubble retention is practised.

These diseases have the capacity to reduce yield by up to 30 percent and compromise grain quality in medium-high rainfall areas and in above-average seasons in lower rainfall areas.[34]

Management practices for leaf spot diseases are outlined in Table 4.

Table 4: Characteristics and management of wheat leaf spot diseases.[35]

***Septoria nodorum* blotch**	**Yellow spot**
Primary infection from wheat stubble.	Primary infection from wheat stubble.
Infection requires heavy and frequent rain with warm weather (20-25°C) that results in leaves remaining wet for more than six hours.	Infection requires at least six hours of leaf wetness with temperatures of 15-28°C and periods of dew.
Air-borne spores can spread kilometres.	Air-borne spores are heavier than *septoria nodorum* blotch and spread only metres.
Secondary infection results from splash dispersed spores spreading the disease through the crop. Disease can spread from leaves to heads in a wet spring, this is known as glume blotch.	Secondary infection (leaf to leaf) occurs via air-borne spores and is favoured by leaf wetness (dew, fog or rain), high relative humidity and temperatures above 10°C.
Integrated disease management options	
Crop rotation.	
Avoid very susceptible or susceptible wheat varieties.	
Ensure crop has adequate nutrition; particularly nitrogen and potassium.	
No seed treatments or in-furrow fungicides are registered for control of yellow spot.	
A fluquinconazole based seed dressing is now registered for suppression of *septoria nodorum* blotch.	
Apply foliar fungicides when evidence of disease moving up the canopy.	

5.4.2 Rusts

MORE INFORMATION

'Australian Cereal Rust Control Program': http://sydney.edu.au/agriculture/plant_breeding_institute/cereal_rust/index.shtml

Figure 8: *Wheat seedling showing infection with leaf rust.*

(SOURCE: GRDC)

34 GRDC (2011) Fact Sheet, Yellow Spot, Western Region, GRDC, https://grdc.com.au/Resources/Factsheets/2011/08/Yellow-Spot-Fact-Sheet-Western-Region

35 GRDC (2011) Fact Sheet, Yellow Spot, Western Region, GRDC, https://grdc.com.au/Resources/Factsheets/2011/08/Yellow-Spot-Fact-Sheet-Western-Region

Leaf, stripe and stem rusts are among the major constraints to durum wheat and bread wheat production in Australia.

These rusts are also distributed across the world and have diverse race structures that continuously evolve and form new strains.

The most significant shifts in rust response ratings in Australia have been due to a series of changes in the pathotypes of wheat leaf rust, including the movement of two pathotypes from the eastern grains belt to WA in 2013 and 2015.[36]

The characteristics of the various wheat rust diseases found in Australia are outlined in Table 5.

Table 5: Characteristics of stem, leaf and stripe rust diseases of wheat.[37]

Characteristics	Stem rust	Leaf rust	Stripe rust
Colour	Reddish brown	Orange brown	Yellow
Shape of pustules	Oval to elongated with tattered edges	Circular to oval	Small circular in yellow stripes running along leaf
Location on plant	Both sides of leaf, leaf sheaths, stems and external head	Mostly on upper surface of leaf	Mostly on upper surface of leaf in characteristic stripes along leaf veins. Also on leaf sheaths, awns and inside glumes
Optimal conditions	Warm, humid (18-30˚C)	Moist with temperature between 10-20˚C	Cool, moist conditions (8-15˚C)
Potential yield loss	Usually 10-50% (but can be up to 90%)	Up to 30%	60%

Managing rust involves avoiding (where possible) the use of very susceptible or susceptible wheat varieties. Growing varieties with some level of rust resistance is the key to controlling disease outbreaks.

Knowing both the seedling and adult rust resistance characteristics of wheat varieties underpins effective fungicide management.

It is more effective to use fungicides to protect a crop from rust infection, rather than to control an already occurring rust outbreak, and crop monitoring is key to ensuring timely fungicide applications.

The rust fungi continually mutate and some of these mutations are capable of overcoming wheat rust resistance. The more rust there is in the environment, the higher the possibility that mutations with new virulence will develop.

Removing the 'green bridge' of weeds and volunteer cereal (and other) crops between seasons is a major control tactic, as the rust fungus cannot survive without a living host.

This will reduce the amount of pathogen that survives over summer and the amount of rust present at the start of the next growing season.

The green bridge must be totally removed at least four weeks before sowing to minimise the risk of carrying rust into new season crops.[38]

If high levels of rust are present in a green bridge when crops are sown, research has found even crops with moderate levels of rust resistance can potentially be severely

36 University of Sydney (2016) University of Sydney Plant Breeding Institute 2016 Cereal Rust Report, Vol 14 Issue 4, http://sydney.edu.au/agriculture/documents/pbi/cereal_rust_report_2016_14_4.pdf

37 University of Sydney (2016) University of Sydney Plant Breeding Institute 2016 Cereal Rust Report, Vol 14 Issue 4, http://sydney.edu.au/agriculture/documents/pbi/cereal_rust_report_2016_14_4.pdf

38 GRDC (2010) Fact Sheet, Green Bridge, GRDC, www.grdc.com.au/GRDC-FS-GreenBridge

affected. The rust tends to infect crops during the very susceptible establishment phase before adult plant resistance traits have had a chance to develop.

Wheat leaf rust

A new wheat leaf rust strain, originating in eastern Australia, was detected in WA in 2013 and a second in October 2015. This has altered disease ratings for some prominent WA bread wheat varieties.

The introduction of these two wheat leaf rust pathotypes to WA had radically shifted the leaf rust response of many bread wheat varieties towards increased susceptibility.[39]

All durum wheat varieties tested by researchers ranged from highly resistant, resistant or moderately resistant to the two new strains, as shown in Table 6.

Table 6: Disease response of Australian durum varieties to three rust diseases.[40]

	Rust Response				
	Leaf Rust		Stem Rust	Stripe Rust	
	Eastern States	WA		WA	Yr17+27+
Carparoi⌽	RMR	R	R	MR	MR
DBA Aurora⌽	R	RMR	R#	RMR	RMR
EGA Bellaroi⌽	RMR	RMR	MR	MR	MR
Hyperno	R	RMR	RMR	MR	MR
Jandaroi⌽	RMR	MR	MR	MR	MR
Penne⌽	R	RMR	MR	MR	MR
Rotini⌽	R	RMR	RMR	MR	MR
Tjilkuri⌽	R	RMR	MR	MR	MR
WID802⌽	R	RMR	RMR	MR	MR
Yawa⌽	R	MR	RMR	MR	MR

# indicates the variety may be more susceptible to alternate pathotypes, e.g. when the reaction to a new or rare pathotype is unknown.

Seed dressings containing fluquinconazole or triticonazole and the in-furrow fungicide triadimefon are registered for suppression of wheat leaf rust.

These can be particularly important for early sown and long season crops and, in some cases, can replace the need for a foliar spray before flag leaf emergence.

Wheat plants treated with at-sowing fungicides may still display minor levels of infection, but infection will tend to be significantly lower than that in untreated crops.

Treating leaf rust early can also make the disease easier to manage in spring if follow-up spraying is required.

Wheat stripe rust

Flutriafol or triadimenol seed dressings suppress stripe rust in seedling crops. Longer-term control can be achieved with fluquinconazole-based seed dressings (depending on application rate) and flutriafol in-furrow fungicides.

Wheat stem rust

There are no seed dressing or in-furrow fungicides currently registered for control of wheat stem rust.

39 University of Sydney (2016) University of Sydney Plant Breeding Institute 2016 Cereal Rust Report, Vol 14 Issue 4, http://sydney.edu.au/agriculture/documents/pbi/cereal_rust_report_2016_14_4.pdf

40 University of Sydney (2016) University of Sydney Plant Breeding Institute 2016 Cereal Rust Report, Vol 14 Issue 4, http://sydney.edu.au/agriculture/documents/pbi/cereal_rust_report_2016_14_4.pdf

MORE INFORMATION

The University of Sydney Plant Breeding Institute '2016 Cereal Rust Report': http://sydney.edu.au/agriculture/documents/pbi/cereal_rust_report_2016_14_4.pdf

Rust resistance testing

If rust outbreaks are detected in wheat varieties with rust resistance, it is advised to send samples for testing to the Australian Cereal Rust Survey. The outbreak may indicate a new virulent rust strain has developed.[41]

Rust samples should be sent in paper envelopes (not plastic bags), marked with name and contact details, date, location and variety. Leaves and stems with active pustules are required.

Post as soon as possible to: Australian Cereal Rust Survey, Private Bag 4011, Narellan, NSW 2567.

Sampling instructions, posting details and further information about new pathotypes can be found on the Australian Cereal Rust Control Program website at http://sydney.edu.au/agriculture/plant_breeding_institute/cereal_rust/index.shtml

5.4.3 Nutrition interaction with leaf spot and rust diseases

Research has shown wheat crops deficient in N and/or potassium (K) can be more vulnerable to leaf spot infections.[42]

It has found N and fungicide use can have an additive effect in reducing leaf spot diseases until ear emergence, resulting in significant yield increases in susceptible varieties.

Nitrogen increases wheat vigour and tiller numbers to lift yield — and possibly enable more effective fungicide application — particularly on susceptible wheat varieties.

Addition of K does not necessarily control disease, but can help plants meet yield potential.[43]

5.4.4 Smut diseases in wheat

Figure 9: *Wheat flag leaf showing smut disease in the field.*

(SOURCE: GRDC)

Wheat smut diseases are caused by fungi that parasitise the host plant and produce masses of soot-like spores in the leaves, grains or ears and reduce grain yield and quality.[44]

Smut diseases, outlined in Table 7, have one of two distinct life cycles — internally seed-borne or externally seed-borne. It is important to know the type of smut and its life cycle to determine effective control options.

41 University of Sydney (2016) University of Sydney Plant Breeding Institute 2016 Cereal Rust Report, Vol 14 Issue 4, http://sydney.edu.au/agriculture/documents/pbi/cereal_rust_report_2016_14_4.pdf

42 DPIRD (2016) Managing Yellow Spot and Septoria Nodorum Blotch in Wheat, https://agric.wa.gov.au/n/2196

43 DPIRD (2016) Managing Yellow Spot and Septoria Nodorum Blotch in Wheat, https://agric.wa.gov.au/n/2196

44 DPIRD (2016) Smut and Bunt Diseases of Cereal — Biology, Identification and Management, https://agric.wa.gov.au/n/326

Table 7: Smut diseases that infect wheat.[45]

Disease	Location	Management	Notes
Covered smut (common bunt)	Seed and soil-borne	Seed dressing Some variety resistance is available Use only clean seed and thoroughly clean contaminated machinery Rotate contaminated paddocks out of wheat and into barley, oats and broadleaf crops for at least one year Destroy any wheat regrowth in the break crop year	Extremely difficult to detect infield; low levels can remain undetected in harvested grain. Seed can be tested at DPIRD DDLS https://www.agric.wa.gov.au/n/1766 Zero tolerance for common bunt in wheat delivered to CBH Group Barley, oats and broad leaf crops are not affected by common smut To diagnose covered smut in the field use GRDC-DPIRD MyCrop: https://agric.wa.gov.au/n/2129
Flag smut	Seed and soil-borne	Correct seed dressing – especially for susceptible varieties Resistant varieties	Barley, oats and broad leaf crops are not affected by flag smut To diagnose covered smut in the field use GRDC-DPIRD MyCrop: https://agric.wa.gov.au/n/2136
Loose smut	Internally seed-borne. Carried as a small colony of fungus inside the seed embryo rather than as spores on the seed coat	No resistant varieties yet Seed dressings reduce incidence – correct application of seed dressings is critical to ensuring adequate control In-furrow and foliar fungicide applications are not effective	Infected seed shows no symptoms and appears normal Machinery and soil do not transmit loose smut Prevalent in areas receiving more than 450 mm average annual rainfall Frequent rain showers and high humidity at flowering favour infection To diagnose covered smut in the field use GRDC-DPIRD MyCrop: https://agric.wa.gov.au/n/2140

Smut diseases commonly occur at low levels but, without fungicide seed dressings, can increase rapidly to cause significant yield loss. There are no registered in-furrow fungicides for smut diseases.

Smuts can be controlled by specific seed dressings applied at the correct label rate. It is critical that every seed is covered with seed dressing for effective control.

45 DPIRD (2016) Smut and Bunt Diseases of Cereal — Biology, Identification and Management, https://agric.wa.gov.au/n/326

MORE INFORMATION

DPIRD 'Diagnosing Fusarium Head Blight in Cereals': https://www.agric.wa.gov.au/mycrop/diagnosing-fusarium-head-blight-cereals

5.5 Fusarium head blight

Figure 10: *Wheat with varying levels of fusarium infection, resulting in poor germination, contrasts with disease-free seed (lower right).*

(SOURCE GRDC)

Fusarium head blight (FHB) is a rare fungal disease that occurs mainly in high rainfall areas. It can significantly reduce grain yield and quality and produces toxins affecting marketability.[46]

Durum wheat varieties are particularly susceptible to FHB and crops show scattered, bleached spikelets or heads several weeks after flowering, with pink or orange spores at the edge of glumes.

Seedlings can be blighted in young crops sown with infected seed.

FHB can commonly be mistaken for frost damage, copper (Cu) and molybdenum (Mo) deficiency, spring drought, crown rot or take-all.

But the disease can be distinguished by the common symptoms outlined above, combined with shrivelled grain that can be discoloured as white or pink.

Head infection is favoured by moisture or high humidity around flowering time.

There is no treatment available and preventative measures are key to control.

It is recommended to avoid sowing multiple winter cereal crops in sequences, which can promote the disease once it is established, and to not sow winter cereals into summer crop paddocks until all summer residues have broken down. It is also advisable to avoid sowing winter cereals adjacent to those paddocks.

46 GRDC-DPIRD (2015) MyCrop: Diagnosing Fusarium Head Blight in Cereals, https://agric.wa.gov.au/n/2138

MORE INFORMATION

GRDC 'Tips and Tactics – Root Lesion Nematodes – Western Region': https://grdc.com.au/Resources/Factsheets/2015/03/Root-Lesion-Nematodes

5.6 Root lesion nematodes

Figure 11: *The effect of root lesion nematodes (right) stunting root growth in wheat grown at Dumbleyung, WA.*

(SOURCE: GRDC)

Figure 12: *Root lesion nematodes are microscopic, worm-like organisms.*

(SOURCE: GRDC)

Root lesion nematodes, or RLN (caused by *Pratylenchus* species), are significant pests that feed on the roots of crop plants and cause yield loss.

These microscopic, worm-like organisms are less than 1 mm in length and cannot be seen with the naked eye.

RLN levels are increasing across the WA grainbelt according to research and survey work.[47]

RLN species were found in 90 percent of 130 paddocks surveyed in 2013 and levels in almost half of the surveyed paddocks were high enough to cause 15-50 percent yield loss.[48]

It is estimated RLN are now found on 5.74 million hectares (or more than 65 percent) of WA's cropping areas. Populations potentially limit yields in at least 40 percent of these infested paddocks.[49]

The main species of RLN found in broadacre cropping systems in WA are *P. neglectus*, *P. quasitereoides* (formerly known as *P. teres*), *P. thornei* and *P. penetrans*.

The host range of RLN is broad and includes cereals, oilseeds, grain legumes and pastures, as well as many broadleaf and grass weeds.

Knowing which species of nematode is present in paddocks is key to management, which is underpinned by the choice of crop rotations used.

5.6.1 Symptoms of RLN

Above-ground symptoms of RLN are often indistinct and difficult to identify.

Initial signs can be poor wheat crop establishment, stunting of plants, poor tillering and plants possibly wilting despite moist soil.

Nematodes are usually distributed unevenly across a paddock, resulting in irregular crop growth. Symptoms can be confused with nutrient deficiency and exacerbated by a lack of nutrients.[50]

When roots are damaged by RLN, the plant becomes less efficient at taking up water and nutrients and less able to tolerate stresses, such as drought or nutrient deficiencies.

Depending on the extent of damage and the growing conditions, affected plants may partly recover if the rate of new root growth exceeds the rate at which nematodes damage the roots.

Underground symptoms of nematode damage include a general browning or discolouration of primary and secondary cereal roots and there may be fewer, shorter lateral roots branching from the main roots. The root cortex (or outer root layer) can be damaged and may disintegrate.

Diagnosis of RLN and the specific species is difficult and can be confirmed only with laboratory testing, as all RLN species cause identical symptoms.

The PREDICTA® B soil test is a useful tool for identifying several nematode species and is available through accredited advisers and agronomists. Sampling guidelines are outlined below.

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47 Collins, S (2013) WA Root Lesion Nematode Causes Yield Losses, GRDC-DAFWA 2013 Agribusiness Crop Updates, DAFWA, https://agric.wa.gov.au/n/724

48 Collins, S (2013) WA Root Lesion Nematode Causes Yield Losses, GRDC-DAFWA 2013 Agribusiness Crop Updates, DAFWA, https://agric.wa.gov.au/n/724

49 GRDC (2015) Tips and Tactics, Root Lesion Nematodes, Western Region, GRDC, www.grdc.com.au/TT-RootLesionNematodes

50 GRDC (2015) Tips and Tactics, Root Lesion Nematodes, Western Region, GRDC, www.grdc.com.au/TT-RootLesionNematodes

Plant samples

- Collect plants from several locations towards the margins of poor crop growth
- Use a trowel or shovel to keep the root system intact
- Keep the soil ball intact to protect the roots in transit.

Soil samples

- Use a soil corer or trowel to sample to 0-10 cm
- Take samples in crop rows and close to root systems
- Collect from 6-12 locations towards the margins of poor crop growth
- Put soil samples in a bucket and mix gently but thoroughly
- Remove a 500 g sample and seal in a plastic bag
- Collect a second sample from healthy areas in the crop
- Label all bags
- Include notes on relevant paddock symptoms.

NOTE: SARDI PREDICTA® B is available through accredited advisers.

5.6.2 Impact of the RLN lifecycle

RLN are migratory plant parasites that move freely between roots and soil if the soil is moist.

In WA, the lifecycle of RLN begins after opening rains in autumn. Juvenile and adult nematodes rehydrate, become active and invade plant roots, where they feed and multiply as they move through the root.

RLN lay individual eggs in the plant root, from which juvenile nematodes hatch and grow to adults — which in turn lay more eggs.

The nematodes develop from an egg to adult in 40-45 days (typically about six weeks), depending on soil temperature and host, and there may be three to five lifecycles in the plant host each season.

As plants and soil dry out in late spring, RLN enter a dehydrated state called anhydrobiosis and can survive high soil temperatures and desiccation over summer.

As the nematodes feed and multiply, lesions and/or sections of brown discoloration are formed on the plant root.

5.6.3 Paddock management for RLN

Implementing an effective management strategy for RLN relies on observation and monitoring the above and below-ground symptoms of nematode damage and diagnosis of the cause(s).[51]

If RLN infestation is suspected, it is advised to firstly check crop roots by carefully digging them up, washing off the soil and — if there is evidence of infestation — sending them for laboratory analysis.

Testing services are available at DPIRD DDLS-Plant Pathology and the SARDI DNA-based soil testing service PREDICTA® B for detection of the RLNs *P. neglectus*, *P. thornei* and *P. quasitereoide*.

Although little can be done in a current cropping season to ameliorate nematode symptoms, diagnostic test information is crucial in planning effective rotations of crop species and varieties in following seasons.

Well-managed rotations incorporating resistant or non-host break crops are vital.

The GRDC-DPIRD Crop Variety Guides are useful resources for choosing crop types and varieties with high resistance ratings, which can result in fewer nematodes remaining in the soil to infect subsequent crops.

51 GRDC (2015) Tips and Tactics, Root Lesion Nematodes, Western Region, GRDC, www.grdc.com.au/TT-RootLesionNematodes

Reducing RLN can lead to higher yields in following cereal crops.

Healthy soils and good crop nutrition can partly alleviate RLN damage through good crop establishment and healthier plants may recover more readily from infestation under more suitable growing conditions.

It is advised to observe crop roots to monitor development of symptoms.

Weeds can host parasitic nematodes within and between cropping sequences, so choice of pasture species and control of host weed species and crop volunteers is important.

Nematicides are not recommended for control of RLN on broadacre crops due to cost and potential mammalian toxicity — and because rotation crop options are available to help in nematode management.

There is limited information available about the effect of time of sowing on yield loss in intolerant crops in the presence of RLN.[52]

Adequate nutrition (especially N, P and Zn) can help cereal crops to compensate for the loss of root function caused by RLN, although this does not necessarily lead to lower nematode reproduction.

In field trials in areas infested with *P. neglectus*, yield losses for intolerant wheat varieties ranged from 12-33 percent when minimal levels of P were applied, but losses were reduced to only 5 percent with a high rate of P (50 kg/ha).[53]

Weeds can play an important role in increased incidence or persistence of nematodes in cropping soils. Poor control of susceptible weeds can compromise the use of crop rotations for RLN management.

Wild oats (*Avena fatua*), barley grass (*Hordeum vulgare*), brome grass (*Bromus*) and wild radish (*Raphanus raphanistrum*) are susceptible to *P. neglectus*.

There are several pasture species and varieties suitable to include in rotations to reduce RLN when these are targeted to the RLN species in the paddock, but weed control is vital as this can strongly influence nematode populations at the end of the pasture phase.

Nematodes cannot move across long distances unaided but can be spread by surface water, in soil adhering to vehicles and farm machinery and in summer dust (when in a dehydrated state). In uninfested areas, it is advised to use good hygiene to reduce these risks.[54]

52 GRDC (2015) Tips and Tactics, Root Lesion Nematodes, Western Region, GRDC, www.grdc.com.au/TT-RootLesionNematodes

53 GRDC (2015) Tips and Tactics, Root Lesion Nematodes, Western Region, GRDC, www.grdc.com.au/TT-RootLesionNematodes

54 GRDC (2015) Tips and Tactics, Root Lesion Nematodes, Western Region, GRDC, www.grdc.com.au/TT-RootLesionNematodes

MORE INFORMATION

WeedSmart: www.weedsmart.org.au

GRDC 'Integrated Weed Management Manual': www.grdc.com.au/IWMM

Hart Field Trials: http://www.hartfieldsite.org.au/pages/trials-results/2014-trial-results.php

GRDC Ground Cover Supplement 'Herbicide Resistance': https://grdc.com.au/Media-Centre/Ground-Cover-Supplements/GCS104

WeedSmart App: https://grdc.com.au/apps

DPIRD 'Crop Weeds': https://www.agric.wa.gov.au/pests-weeds-diseases/weeds/crop-weeds

Weeds and herbicides

6.1 Overview

Durum wheat is typically less competitive with weeds than other crops, including bread wheat and barley.

Effective weed control is essential for durum wheat crops to make full use of stored summer rainfall, minimise grain yield losses and prevent weed seed contamination at harvest. Some tactics that can be used include:

- Variety and crop type choice (influencing herbicide options)
- Controlling weeds in preceding crops and fallow
- Rotating crops and herbicides
- Growing more competitive durum wheat crops
- Judicious use of herbicides at registered rates.

In many broadacre crops, there are varieties that vary in sensitivity to commonly used herbicides and tank mixes.

To review herbicide tolerance ratings for newer durum wheat varieties, go to http://www.nvtonline.com.au/wp-content/uploads/2016/04/SA-Wheat-Advanced-2015.pdf[1] (Note these ratings are based on South Australian information).

There are limited options available for safe and effective pre-emergent herbicide use in durum wheat nationally, including Western Australia, which further increases the importance of alternative weed control strategies.

Trials at South Australia's grower-led Hart agronomic field site in 2014 investigated crop competition aspects of seeding rate, seed bed utilisation, variety selection and row spacing for some of the newest durum wheat varieties compared to current bread wheat lines.

The trial aimed to identify the most effective of these techniques in terms of weed control, crop yield and grain quality. Key findings included:

- DBA-Aurora⊕ durum wheat and Mace⊕ bread wheat had similar ability to compete with weeds
- Use of higher seeding rates improved weed control
- Increased crop seeding rates resulted in less crop screenings.[2]

The trial plots were planted on May 28, 2014 and received fertiliser applications of diammonium phosphate (DAP, at a ratio of 18:20) plus 2 percent zinc (Zn) at a rate of 70 kilograms per hectare and Urea Ammonium Nitrate (UAN, at a ratio 42:0) at a rate of 95 Litres/ha on August 15.

Annual ryegrass (*Lolium rigidum*) was spread over the trial area at a rate of 10 kg/ha and gently 'tickled' in (using light cultivation) prior to seeding. Selected plots were also treated with a pre-emergent herbicide to create plots with varying weed pressure.

The pre-emergent herbicide used was IBS trifluralin (1.2 L/ha) + triallate (1.2 L/ha) applied on May 28, 2014.

1 GRDC (2016) National Variety Trials: Wheat variety response to herbicides in South Australia, SARDI, GRDC and Government of South Australia Primary Industries and Resources, http://www.nvtonline.com.au/wp-content/uploads/2016/04/SA-Wheat-Advanced-2015.pdf

2 Goss, S and Wheeler, R (2014) Hart Field Trials: Weed competition — determining best management practices in durum wheat, SARDI Waite campus, http://www.hartfieldsite.org.au/media/2014%20Trial%20Results/2014_Results_Weed_competition_determining_best_management_preactices_in_durum_wheat.pdf

The trial found for DBA-Aurora⁽ᴰ⁾ durum wheat and Mace⁽ᴰ⁾ bread wheat, the use of a higher seeding rate gave the best annual ryegrass control in 2014, as highlighted in Table 1.

Table 1: The effect of seed rate and normal or spreader seeding boots on grain yield (t/ha) and grass seed set (heads/m^2) for DBA-Aurora⁽ᴰ⁾ durum wheat and Mace⁽ᴰ⁾ wheat at Hart, 2014. (Yield loss percentage is the difference between plots with high weed pressure compared to no weed pressure).[3]

Variety	Seeding boot	Seeding rate (seeds/m^2)	Ryegrass heads/m^2	Yield t/ha	Yield loss %
DBA Aurora⁽ᴰ⁾	Normal Boot	100	138	2.29	9.2
DBA Aurora⁽ᴰ⁾		200	90	2.44	12.2
DBA Aurora⁽ᴰ⁾		300	29	2.95	8.2
Mace⁽ᴰ⁾		100	100	3.02	9.6
Mace⁽ᴰ⁾		200	79	3.52	11.5
Mace⁽ᴰ⁾		300	52	3.75	3.9
DBA Aurora⁽ᴰ⁾	Spreader Boot	100	104	2.41	18.3
DBA Aurora⁽ᴰ⁾		200	67	2.75	10.8
DBA Aurora⁽ᴰ⁾		300	54	3.02	9.2
Mace⁽ᴰ⁾		100	138	3.19	8.3
Mace⁽ᴰ⁾		200	90	3.75	8.7
Mace⁽ᴰ⁾		300	29	3.83	7.4
LSD ($P \le 0.05$)			**ns**	**0.27**	**2.6**

There was no benefit in weed control in the trials from using a spreader boot compared to a 'normal' boot typically used in SA. Trials in 2013 had found the use of a spreader boot reduced annual ryegrass numbers.

Using medium and low seeding rates progressively increased annual ryegrass head numbers.

The trials found DBA-Aurora⁽ᴰ⁾ and Mace⁽ᴰ⁾ were similar in ability to compete with annual ryegrass. This highlights the improved ability of DBA-Aurora⁽ᴰ⁾ to compete with weeds, compared to the durum wheat variety Tjilkuri⁽ᴰ⁾, which was less competitive with weeds than Mace⁽ᴰ⁾ in 2013 trials.[4]

The addition of pre-emergent herbicides provided very good annual ryegrass control (data not shown), which was also found in 2013 trials.

The addition of other management strategies was unable to improve the weed control further, according to the researchers.

Mace⁽ᴰ⁾ wheat had lower yield losses (on average 8.2 percent) compared to DBA-Aurora⁽ᴰ⁾ (on average 11.3 percent) when under high weed pressure in 2014.[5]

The lowest yielding treatments were those sown at a rate of 100 seeds per square metre.

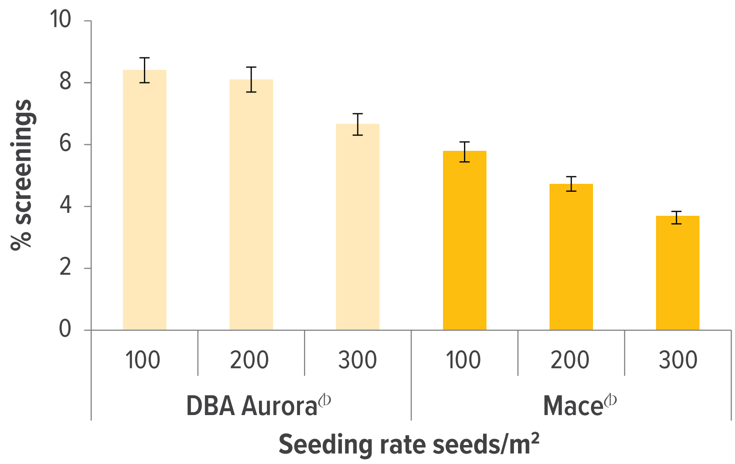
In Mace⁽ᴰ⁾ and DBA-Aurora⁽ᴰ⁾, increasing seeding rate reduced annual ryegrass head set and grain screening percentage, as shown in Figure 1.

3 Goss, S and Wheeler, R (2014) Hart Field Trials: Weed competition — determining best management practices in durum wheat, SARDI Waite campus, http://www.hartfieldsite.org.au/media/2014%20Trial%20Results/2014_Results_Weed_competition_determining_best_management_preactices_in_durum_wheat.pdf

4 Goss, S and Wheeler, R (2014) Hart Field Trials: Weed competition — determining best management practices in durum wheat, SARDI Waite campus, http://www.hartfieldsite.org.au/media/2014%20Trial%20Results/2014_Results_Weed_competition_determining_best_management_preactices_in_durum_wheat.pdf

5 Goss, S and Wheeler, R (2014) Hart Field Trials: Weed competition — determining best management practices in durum wheat, SARDI Waite campus, http://www.hartfieldsite.org.au/media/2014%20Trial%20Results/2014_Results_Weed_competition_determining_best_management_preactices_in_durum_wheat.pdf

Figure 1: *Effect of seeding rate and crop variety on screenings percentage (percent less than 2.00 mm) when grown in presence of annual ryegrass.*[6]



The results from the Hart Field Trials in 2013 and 2014 indicated increasing wheat seeding rates can lessen the impact of suppressed grain yields that can result from high weed pressure.

The trials also found having a high seeding rate not only restricts annual ryegrass growth, but can reduce the amount of grain screenings at harvest.

Results from 2014 show very similar levels of response to weed competition from Mace⁽ᴰ⁾ and DBA-Aurora⁽ᴰ⁾.[7]

6.2 Herbicide resistance

Herbicides act by targeting specific plant processes and this activity is termed mode-of-action (MOA).

In Australia, all herbicides are classified into groups based on their MOA and named with a group letter from A to Z.

MOA groups are ranked according to the risk of weed populations becoming resistant to those herbicides. Groups A and B are high risk and Groups C to Z are moderate risk. There are no low-risk herbicides.

Herbicide weed control in WA cropping systems is heavily reliant on six MOAs and multiple herbicide resistance is now the 'normal' status for the State's two most costly cropping weeds — annual ryegrass and wild radish (*Raphanus raphanistrum*).

Glyphosate resistant annual ryegrass, wild radish and brome grass (*Bromus rubens*) have also been found in winter cereal crops in WA.[8]

A 2013 pre-harvest and targeted statewide survey found more than 40 percent of 172 annual ryegrass samples tested had some level of resistance to glyphosate.[9]

The herbicide resistance status of major weeds found in WA is outlined in Table 2.

MORE INFORMATION

AHRI Ryegrass Surveys, 2010. http://ahri.uwa.edu.au/research/surveys/ryegrass-2/

GRDC 'Integrated Weed Management Manual': www.grdc.com.au/IWMM

6 Goss, S and Wheeler, R (2014) Hart Field Trials: Weed competition — determining best management practices in durum wheat, SARDI Waite campus, http://www.hartfieldsite.org.au/media/2014%20Trial%20Results/2014_Results_Weed_competition_determining_best_management_preactices_in_durum_wheat.pdf

7 Goss, S and Wheeler, R (2014) Hart Field Trials: Weed competition — determining best management practices in durum wheat, SARDI Waite campus, http://www.hartfieldsite.org.au/media/2014%20Trial%20Results/2014_Results_Weed_competition_determining_best_management_preactices_in_durum_wheat.pdf

8 GRDC (2012) Fact Sheet — Herbicide resistance, Western Region, GRDC, https://grdc.com.au/GRDC-FS-HerbicideResistance

9 Peltzer, S (2014) eWeed It's time — implement your glyphosate resistance management plan now, DAFWA, https://www.agric.wa.gov.au/newsletters/eweed-volume-152-april-2014

Table 2: Characteristics and herbicide status of major weeds of winter cereals in Western Australia.[10]

Weed and WA herbicide resistance status	Biological strengths and weaknesses
WILD RADISH	
Group B — sulfonylureas	Prolific seeder and highly competitive can cause yield losses of 10-90%.
Group B — sulfonamides	Wild radish has significant seedbank dormancy: one year of seed allowed to escape into the soil can mean more than seven years of subsequent weed germinations.
Group B — imidazolinones	Up to 70% of the seeds are still dormant at the start of the next cropping season: many seeds will not germinate until the second season after their formation (about 18 months later).
Group C — triazines	Wild radish seeds become viable within three weeks from the appearance of first flowers: important to kill in-crop wild radish while small (less than 5 cm diameter).
Group C — triazinones	Most non-dormant seed germinates during autumn and winter but can emerge throughout the year provided there is sufficient soil moisture.
Group F — nicotinanalides	Produces seed very quickly from germinations late in spring or during summer.
Group I — phenoxys	Easily distributed (along with herbicide resistance) as an impurity in hay, chaff and grain.
Group M — glyphosate	Retains seed at harvest height: late flushes and early survivors can be removed via the harvester.
ANNUAL RYEGRASS	
Group A — 'fops'	Highly competitive – can compete as early as the two-leaf crop stage.
Group A — 'dims'	Less competitive when emerging after crop: competitive crops can out-compete.
Group B — sulfonylureas	Produces up to 45,000 seed/m^2 under ideal conditions: seed bank quickly replenished by uncontrolled survivors.
Group B — imidazolinones	80% of seed germinates at break after two falls of rain exceeding 20 mm: good control possible with early start to season.
Group C — triazines	Can emerge from late autumn-early spring depending on rainfall and seedbank levels: control early survivors and late flushes with harvest weed seed control.
Group C — substituted ureas	Germination drops with increasing seed depth seed, stopping at about 100 mm: strategic mouldboard ploughing can control bad infestations.
Group D — trifluralin	Viable seed relatively short-lived in soil: can reduce seedbank by 75% per year with concerted control.
Group M — glyphosate	Retains seed at harvest height: late flushes and early survivors can be removed during the harvesting operation.
Group Q — triazoles	
*95% of resistant populations are resistant to both Group A and B herbicides.	
WILD OATS	
Group A — 'fops'	Highly competitive when left uncontrolled, can reduce wheat yields by up to 80%.
Group A — 'dims'	Up to 20,000 seeds/m^2 produced in uncontrolled infestations.
	40% germinates with opening rains with further 10-30% germinating during season.
	Viable seed short-lived in soil: can deplete seed bank by 75% per year with concerted control.
BROME GRASS	
Group B — sulfonylureas	Highly competitive in wheat: keep seeding rate high and rows narrow to enable wheat to outcompete.
Group B — imidazolinones	More drought tolerant and responsive to nitrogen than wheat: N can aggravate brome grass problem.
Group C — triazines	Can produce 600-3000 seeds per plant.
	Most seed shed before crop harvest: harvest weed seed control less effective than wild radish and ryegrass.

10 GRDC (2014) Integrated Weed Management Manual, Section 2 Herbicide resistance, GRDC, www.grdc.com.au/IWMM

No new herbicide MOAs are on the horizon and the most recent was commercialised in the early 1990s.

To help manage herbicide resistance, a range of techniques that intercept weed seeds at harvest before they re-enter the soil seedbank are being employed across vast areas of WA and in other parts of southern Australia — as well as being investigated for use in a range of grain growing countries globally.

Research shows it is possible to drive down the seedbank of some weeds by as much 95 percent in three to five years using an integrated approach involving crop competition, herbicide MOA rotation and harvest weed seed control (HWSC).[11]

But integrated weed management (IWM) requires a long-term and committed plan using herbicide, cultural and mechanical control measures, rather than just a year-to-year approach using herbicides alone.

The grains industry-led WeedSmart initiative, funded by GRDC, has a 10-point plan to deal with herbicide resistance and optimise weed control, as shown in Table 3.

11 GRDC (2014) Integrated Weed Management Manual, Section 2 Herbicide resistance, GRDC, www.grdc.com.au/IWMM

Table 3: WeedSmart 10-point plan to prevent weed seeds from entering the soil seedbank.[12]

Tactic	Mechanism	Weed impact	More information
Develop a weed management plan	Understand the biology of your weeds. Be strategic and committed.	Knowledge of a weed's biology helps target its weaknesses.	Section 5 of the Integrated Weed Management Manual www.weedsmart.org.au/10-point-plan/act-now-to-stop-weed-seed-set/
Capture weeds at harvest	Consider your options – chaff cart, narrow windrow burning, baling, Harrington Seed Destructor. Compare the financial cost per hectare.	Research across southern Australia shows, on average, about 80% of annual ryegrass and wild radish seed entering the harvester can be collected via harvest weed seed control methods.	Section 4 of the Integrated Weed Management Manual www.weedsmart.org.au/10-point-plan/capture-weed-seeds-at-harvest/
Rotate crops and herbicide MOAs	Repeated application of effective herbicides with the same MOA is the single greatest risk factor for herbicide resistance evolution.	Crop rotation enables rotation of different herbicides and targeting of specific weeds. For example, sowing field peas enables delayed sowing, swathing and late herbicide application.	http://www.weedsmart.org.au/10-point-plan/rotate-crops-and-herbicide-modes-of-action/
Test for resistance	Measure resistance so you can manage it. Sample weed seeds before harvest for resistance testing.	Knowing your resistance status allows you to choose the most effective herbicides.	http://www.weedsmart.org.au/10-point-plan/test-for-resistance-to-establish-a-clear-picture-of-paddock-by-paddock-farm-status/
Never cut the rate	Always use the label rate. Using low herbicide rates can result in weeds with tolerance/resistance to multiple herbicides.	Herbicide resistance will develop faster in weeds exposed to low chemical rates. AHRI laboratory-based research demonstrated that ryegrass populations developed resistance to Sakura® after only three years of low application rates.	www.weedsmart.org.au/10-point-plan/never-cut-the-rate/ http://ahri.uwa.edu.au/creating-a-cross-resistant-monster/
Don't automatically reach for glyphosate	Diversity, diversity, diversity. Rotate to alternative knockdown herbicides. Consider strategic tillage.	Glyphosate resistance can be slowed by using alternative herbicides and introducing nonchemical weed control tactics.	www.weedsmart.org.au/10-point-plan/dont-automatically-reach-for-glyphosate/ www.glyphosateresistance.org.au/factsheets/Glyphosate_Resistant_weeds-beat_them_before_they_beat_you_DAFWA_Aug2014.pdf
Carefully manage spray events	Use best management practice to stop spray drift and maximise weed kill.	Monitor and destroy all weed escapes. Patch spray resistant weeds if required.	www.weedsmart.org.au/10-point-plan/carefully-manage-spray-events/ Refer to GRDC Fact Sheet series on best practice spray application: www.grdc.com.au/GRDC-FS-SprayPracticalTips
Plant clean seed into clean paddocks with clean borders	Plant weed-free crop seed. The density, diversity and fecundity of weeds is generally greatest along paddock borders and areas such as roadsides, channel banks and fencelines.	Recent AHRI* research showed nearly 75% of cleaned grain samples from 74 WA farms had some level of weed seed contamination. About 25% of the 347 Australian sites documented with glyphosate resistant annual ryegrass are from fence lines.	Section 4 of the Integrated Weed Management Manual http://www.weedsmart.org.au/10-point-plan/plant-clean-seed-into-clean-paddocks-with-clean-borders/ www.grdc.com.au/Resources/Factsheets/2010/11/Glyphosate-Resistance-fact-sheet
Use the double knock technique	Any combination of weed control that involves two sequential strategies (chemical and non-chemical). The second application/tactic is used to control survivors from the first.	The glyphosate/ paraquat double-knock uses different MOAs to eliminate weeds. Ensure the paraquat rate is high and start the double knock shortly after rainfall to tackle weeds while they are small.	Section 4 of the Integrated Weed Management Manual www.weedsmart.org.au/10-point-plan/use-the-double-knock-technique/
Use crop competitiveness to combat weeds	Increase your crop's competitiveness to win the war against weeds. Row spacing, seeding rate and crop orientation can help crops fight weeds and competitive cultivar eg barley.	Narrow rows out-compete weeds and deliver higher yields than wider rows. Sowing crops east-west instead of north-south can halve weed seed set.	Section 3 of the Integrated Weed Management Manual http://www.weedsmart.org.au/consider-narrow-row-spacing/

12 WeedSmart Website: www.weedsmart.org.au/10-point-plan/capture-weed-seeds-at-harvest/

The natural genetic variability of weed populations gives them an inherent capacity to adapt to herbicide and non-herbicide control measures.

If weed densities are kept low, the likelihood of resistance genes evolving within the population is also kept low and herbicide usefulness is extended, according to leading weeds researchers.

6.3 Herbicide resistance in WA

Wild radish, annual ryegrass, wild oats (*Avena fatua*) and brome grass are the most prolific and costly weeds affecting wheat production in WA and each has developed a level of herbicide resistance.

Multiple resistance to selective and non-selective herbicides is now standard for WA's two worst cropping weeds — annual ryegrass and wild radish.

It is estimated only 2 percent of annual ryegrass populations remain fully susceptible to herbicide control, with others resistant to one or more herbicide MOAs. More than 90 percent of wild radish populations are estimated to be resistant to one or more herbicides.[13]

A 2010 weed herbicide resistance survey found 84 percent of 96 wild radish populations tested from Geraldton in the north to Esperance in the south had some level of resistance to the Group B herbicide active chlorsulfuron.[14]

In recent years, WA has experienced a sharp increase in the level of herbicide resistance in wild radish to commonly used herbicides.

Key findings from the 2010 survey included:

- 84 percent of samples had plants resistant to chlorsulfuron (Group B)
- This was a 30 percent increase from 2003 levels
- 49 percent showed resistance to Intervix (Group B)
- 76 percent were resistant to 2,4-D amine (Group I), especially in the northern and central grainbelt
- 49 percent had resistance to Brodal® (Group F)
- One population had atrazine-resistant plants.[15]

Paddocks at high risk of developing herbicide resistance include those where there has been a long history of herbicide use and no management to prevent herbicide survivors from setting seed. These paddocks often have high weed numbers.

The goal is to ensure herbicide resistant weed seed does not enter the seedbank.

The expected time it will take for weeds to develop resistance to applications of the major herbicide groups is outlined in Table 4. The 'years of application' do not need to be consecutive applications.

13 Australian Herbicide Resistance Initiative, UWA (2010) Wild radish surveys, http://ahri.uwa.edu.au/research/surveys/wild-radish/

14 Australian Herbicide Resistance Initiative, UWA (2010) Wild radish surveys, http://ahri.uwa.edu.au/research/surveys/wild-radish/

15 GRDC (2014) Hot Topic — Wild radish control options in WA, GRDC, https://grdc.com.au/Media-Centre/Hot-Topics/Wild-radish-control-options-in-WA

Table 4: Predicted time (years) for weeds to develop resistance to each of the major herbicide groups.[16]

Herbicide group	Years of application
B	4
A 'fop'	6
A 'dim'	8
C	10-15
D	10-15
E	>15
F	10
G	>15
H	10
I	>20
K	>15
L	>15
M	>12

6.3.1 Rotation planning and weed control benefits

Continuous wheat rotations lack diversity in options for weed control using herbicides.

Including break crops in sequence planning opens up weed control options that are unavailable, or not suitable, to use in the wheat phase and can broaden the range of pre-emergent herbicide MOAs that can be used.

Rotating herbicide group MOAs helps to delay the onset of herbicide resistance.

Mixing two or more herbicides is also a sound strategy to prevent and delay the evolution of herbicide resistance.

Growing oaten hay or break crops to control annual ryegrass seedset and including competitive crops, such as barley, are important tools.

Growing field peas, lupins or pasture in the rotation allows for the use of late herbicide applications (for crop or pasture-topping) for weed seedset control.

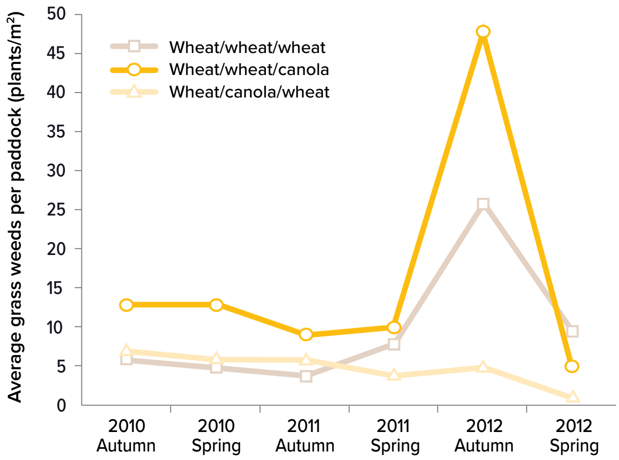
Problem weeds, such as herbicide resistant wild radish and annual ryegrass, can also be targeted with the inclusion of break crops in the cropping rotation — as weeds resistant to one herbicide MOA can be controlled using herbicides with a different MOA.[17]

For example, timely use of canola in the rotation has the ability to reduce the number of grass weeds for following crops using Group C herbicides and imidazolinone-tolerant and Roundup Ready® technologies – in combination with non-herbicide weed control methods, as shown in Figure 2.

16 GRDC (2014) Integrated Weed Management Manual, Section 2 Herbicide resistance, GRDC, www.grdc.com.au/IWMM

17 Harries, M and Anderson, G (2015) Crop and pasture sequences sustain wheat productivity, GRDC 2015 Update Paper, DAFWA, https://grdc.com.au/Research-and-Development/GRDC-Update-Papers/2015/02/Crop-and-pasture-sequences-sustain-wheat-productivity

Figure 2: *Impact of crop rotation on grass weed numbers in paddocks in a range of crop sequences.*[18]



Note: Canola following two years of wheat enabled grass weed numbers to be reduced from a high of 47 plants/m² in autumn to fewer than five plants/m² by spring

6.4 Post-emergent herbicides for wheat crops

Selective post-emergent herbicides often provide more than 98 percent control of common weeds found in WA cropping systems when applied under recommended conditions.[19]

Early removal of grass weeds, such as annual ryegrass and wild oats, reduces competition for resources in the crop.

Nozzle selection, droplet size, sprayer speed and meteorological conditions require careful attention to maximise spray efficacy.

Selective post-emergent herbicides for use in WA wheat crops belong to the herbicide MOA Groups:

- A (diclofop)
- B (metsulfuron)
- C (diuron)
- F (diflufenican)
- G (carfentrazone)
- H (pyrasulfotole)
- I (2,4-D, dicamba, picloram).

Post-emergent herbicides are often more reliable than pre-emergent herbicides, especially in low rainfall conditions, as pre-emergent herbicides rely on moist soil to achieve high levels of weed control.

Dry conditions following sowing often delay weed emergence.

Post-emergent herbicides can be applied after the bulk of weeds have emerged, at a time when the plants are most susceptible to the herbicide being applied.

This allows more flexibility in herbicide choice to control the particular suite of weeds in the crop — and identification of the most appropriate rate of application — compared to when using pre-emergent herbicides.

18 Harries, M and Anderson, G (2015) Crop and pasture sequences sustain wheat productivity, GRDC 2015 Update Paper, DAFWA, https://grdc.com.au/Research-and-Development/GRDC-Update-Papers/2015/02/Crop-and-pasture-sequences-sustain-wheat-productivity

19 GRDC (2014) Integrated Weed Management Manual: Section 4 Tactics for managing weed populations, GRDC, www.grdc.com.au/IWMM

Many post-emergent herbicides (such as bromoxynil and metsulfuron in wheat) have an extended application window due to a wide margin of crop safety.[20]

Depending on application rate, some post-emergent herbicides have a degree of pre-emergent or residual activity on susceptible weeds, which extends their period of weed control.

Residual activity is often related to application rate. Typically, the higher the rate, the longer the residual effect.

Soil moisture, organic matter, clay content, temperature, acidity (pH) and microbial activity can also influence the longevity (or availability) of post-emergent herbicides in the soil.

Hot and dry conditions increase the waxiness of weed leaves, which reduces herbicide absorption.

Plants suffering any kind of stress tend to have lower rates of translocation and the herbicide will take more time to reach sites of action.

Herbicide-tolerant crops can be damaged when stressed due to waterlogging, frost or dry conditions because they cannot produce sufficient levels of the enzymes that can break down the herbicide into harmless compounds.

6.4.1 Movement of post-emergent herbicides in plants

Knowing how a herbicide enters the plant and is translocated is important for determining the most appropriate application volume, adjuvant type and nozzle style. For example, some products (such as the contact herbicide paraquat) do not move/translocate well within plants and an even coverage of herbicide across the weed is required for effective control.

Other products (such as soil-applied herbicides and several fungicides), can only travel upwards in plants through the xylem and must be deposited onto the lower parts of plants to provide effective control above this point.

Some products (such as glyphosate and phenoxy herbicides) can move up and down the plant throughout the phloem and xylem, but only when the target plants are not stressed.

6.4.2 Post-emergent herbicides in integrated weed management plans

Early use of post-emergent herbicides can help maximise yield by removing weed competition when the crop is establishing.

Achieving good crop competition (with high seeding rates and narrow rows) and adopting harvest weed seed control (HWSC) measures, in combination with both pre and post-emergent herbicide use, can significantly reduce weed seed numbers over time.

Controlling herbicide resistant wild radish in WA wheat crops typically requires a two-spray, post-emergent herbicide approach — in combination with crop competition and HWSC.

20 GRDC (2014) Integrated Weed Management Manual: Section 4 Tactics for managing weed populations, GRDC, www.grdc.com.au/IWMM

MORE INFORMATION

GRDC Update Paper 'Why the Obsession with the Ryegrass Seedbank': www.grdc.com.au/Research-and-Development/GRDC-Update-Papers/2015/02/Why-the-obsession-with-the-ryegrass-seed-bank

HerbiGuide 'Annual Ryegrass': http://www.herbiguide.com.au/Descriptions/hg_Annual_Ryegrass.htm

Ryegrass Integrated Management (RIM) model: www.ahri.uwa.edu.au/RIM

6.5 Annual ryegrass

Figure 3: *Annual ryegrass is a scourge of wheat crops in WA and across southern Australia.*

(SOURCE: GRDC)

Annual ryegrass can compete with a crop as early as the two-leaf crop stage.

This weed is active in winter and spring and can emerge from late autumn through to early spring. The number of emergence flushes and the density of plants are related to initial seedbank levels and the frequency and amount of rainfall.

Ideal conditions for germination of annual ryegrass include a significant autumn/winter rain event and seeds located at a soil depth of 20 mm. Germination levels reduce with increasing seed depth, stopping at about 100 mm.[21]

Most shallow seeds tend to germinate during autumn and early winter. Peak germination (80 percent of seeds) occurs at the break-of-season, typically after the first two falls of rain that exceed 20 mm.[22]

Newly-formed seeds of annual ryegrass tend to be dormant for about six months. Plants typically set seed in October and dormancy breaks in April-May in typical WA conditions.

About 20 percent of seed carries over for two seasons and about 5 percent carries over for three years, with seed life sometimes extending to four years.[23]

21 HerbiGuide 'Annual Ryegrass', http://www.herbiguide.com.au/Descriptions/hg_Annual_Ryegrass.htm

22 HerbiGuide 'Annual Ryegrass', http://www.herbiguide.com.au/Descriptions/hg_Annual_Ryegrass.htm

23 HerbiGuide 'Annual Ryegrass', http://www.herbiguide.com.au/Descriptions/hg_Annual_Ryegrass.htm

6.5.1 Annual ryegrass and herbicide resistance

Annual ryegrass produces very high numbers of seeds per plant.

Dense stands can produce up to 1000 kg/ha of seed.[24]

Annual ryegrass also is a host for the bacterium *Clavibacter* spp. that causes annual ryegrass toxicity (ARGT) affecting livestock.

Many populations of annual ryegrass have developed resistance to both selective and nonselective herbicides. Repeated use of herbicides from the same MOAs (particularly high-risk Groups A and B) have led to herbicide-resistant individuals.

Annual ryegrass has developed resistance to the following MOA herbicide groups in WA:

- Group A — 'Fops' (for example, diclofop-methyl)
- Group A — 'Dims' (for example, sethoxydim)
- Group B — sulfonylureas (for example, chlorsulfuron and sulfometuron)
- Group B — imidazolinones (for example imazapic)
- Group C — triazines (atrazine and simazine)
- Group C — substituted ureas (for example, diuron)
- Group D — trifluralin
- Group Q — triazoles (for example, amitrole)
- Group M — glyphosate
- Group L — paraquat.

It is estimated there would be several thousand unconfirmed populations of glyphosate-resistant annual ryegrass — along with many more glyphosate resistant cases in awnless barnyard grass (*Echinochloa colona*) and fleabane (*Conyza* spp.) populations — in Australia.[25]

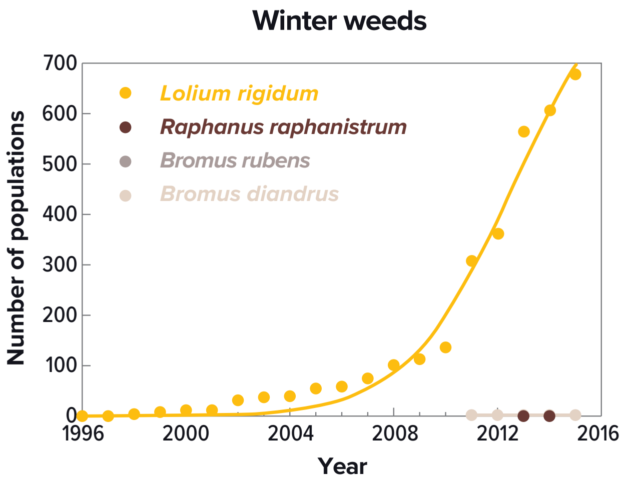
Testing has found more than 600 confirmed cases of glyphosate-resistant annual ryegrass populations in winter crops in WA, New South Wales, Victoria and SA. This is mostly from cropping paddocks and trends in incidence are shown in Figure 4.[26]

24 HerbiGuide 'Annual Ryegrass', http://www.herbiguide.com.au/Descriptions/hg_Annual_Ryegrass.htm

25 Preston, C (2016) Australian Glyphosate Sustainability Working Group — Australian glyphosate register — Glyphosate resistant weeds in Australia, University of Adelaide, http://www.glyphosateresistance.org.au/register_summary.html

26 Preston, C (2016) Australian Glyphosate Sustainability Working Group — Australian glyphosate register — Glyphosate resistant weeds in Australia, University of Adelaide, http://www.glyphosateresistance.org.au/register_summary.html

Figure 4: *The increase in confirmed cases of glyphosate resistance in winter weeds in Australia between 1996 and 2016.*[27]



All confirmed glyphosate-resistant weed populations in Australia have occurred in situations where there has been intensive use of glyphosate (often across 15 years or more), few or no other effective herbicide MOAs used and few other weed control practices put in place. This suggests the following factors are the main risks for glyphosate resistance evolution:

- 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 control used to stop seed set.

In 2013, there was a case of resistance to paraquat and glyphosate in a vineyard in WA's South West.

Flaxleaf fleabane (*Conyza bonariensis*) is the latest species confirmed to have resistance to paraquat in a vineyard in southern New South Wales. This fleabane population had been sprayed multiple times per year with top label rates of paraquat.

All cases of resistance to paraquat are in situations with long histories of use (more than 15 years).[28]

6.5.2 Control of annual ryegrass

There are many tactics that can be considered in an IWM plan to control annual ryegrass in WA cropping systems and in wheat crops in particular.

As outlined in Table 5, these include improved crop competition, burning residue, inversion ploughing, autumn tickle, using herbicides and HWSC tactics.

27 Preston, C (2016) Australian Glyphosate Sustainability Working Group — Australian glyphosate register — Glyphosate resistant weeds in Australia, University of Adelaide, http://www.glyphosateresistance.org.au/register_summary.html

28 Australian Herbicide Resistance Initiative (AHRI) (2013) Double banger — glyphosate and paraquat resistant ryegrass, http://ahri.uwa.edu.au/double-banger-glyphosate-and-paraquat-resistant-ryegrass/

Table 5: Tactics that should be considered when developing an integrated plan to manage annual ryegrass.[29]

Annual ryegrass (*Lolium rigidum*)		Most likely % control (range)	Comments on use
Agronomy	Improve crop competition	50 (20–80)	Optimum sowing rates essential. Row spacing >250 mm to reduce crop competitiveness. Sow on time.
Tactic	Burning residues	50 (0–90)	Avoid grazing crop residues. Use a hot fire back-burning with a light wind.
Tactic	Inversion ploughing	95 (80–99)	Bury seed greater than 100 mm deep. Use of skimmers on the plough is essential for deep burial.
Tactic	Autumn tickle	15 (0–50)	Only effective on last year's seedset. Use in conjunction with delayed sowing.
Tactic	Fallow and pre-sowing cultivation	60 (0–90)	Cultivation may lead to increased annual ryegrass in the crop. Use in combination with a knockdown herbicide. Use cultivators that bury seed.
Tactic	Knockdown (non-selective) herbicides for fallow and pre-sowing control	80 (30–95)	Avoid overuse of the one herbicide MOA group. Wait until annual ryegrass has more than 2 leaves.
Tactic	Double knockdown or 'double-knock'	95 (80–99)	Reduces the likelihood of glyphosate resistance. Use glyphosate followed by paraquat or paraquat + diquat 3 to 10 days later.
Tactic	Pre-emergent herbicides	70 (50–90)	Note incorporation requirements for different products and planting systems.
Tactic	Selective post-emergent herbicides	90 (80–95)	Apply as early as possible after the annual ryegrass has 2 leaves to reduce yield losses in cereals.
Tactic	Spray-topping with selective herbicides	80 (60–90)	Apply before milk dough stage of annual ryegrass.
Tactic	Crop-topping with non-selective herbicides	70 (50–90)	Note stage of crop compared to stage of annual ryegrass. Often not possible to achieve without crop yield loss. Most likely to occur with quick finish to season.
Tactic	Pasture spray-topping	80 (30–99)	Graze heavily in spring to synchronise flowering.
Tactic	Silage and hay – crops and pastures	80 (50–95)	Most commonly used where there is a mass of resistant annual ryegrass growth. Follow up with herbicides or heavy grazing to control regrowth.
Tactic	Manuring, mulching and hay freezing	90 (70–95)	Most commonly used where there is a mass of resistant annual ryegrass growth. Follow up with herbicides or heavy grazing to control regrowth.
Tactic	Grazing – actively managing weeds in pastures	50 (20–80)	Graze heavily in autumn to reduce annual ryegrass plant numbers. Graze heavily in spring to reduce seedset.
Tactic	Weed seed collection at harvest	65 (40-80)	Best results when crop is harvested as soon as possible before ryegrass lodges or shatters.
Tactic	Sow weed-free seed	85 (50-99)	Reduces the risk of introducing resistant annual ryegrass to the paddock with crop seed.

29 GRDC (2014) Integrated Weed Management Manual: Section 4 Tactics for managing weed populations, GRDC, www.grdc.com.au/IWMM

Newly-set seed of annual ryegrass is predominantly dormant. While most of this dormancy is lost over summer, some seed can remain dormant at the season break and limit the proportion of the seedbank that can emerge and be controlled.

Annual ryegrass emergence will be highest at the autumn break when:

- Seed has formed during a hot dry spring in the previous year
- Summer is very hot (faster dormancy release)
- There have been heavy rainfall events during a hot summer
- There is a late break to the growing season.

If these conditions occur simultaneously, there is a valuable opportunity to delay seeding in problem annual ryegrass paddocks to allow maximum weed germination and kill pre-sowing.

Increasing glyphosate resistance levels in annual ryegrass populations makes the double-knock (an application of glyphosate typically followed by an application of paraquat) a highly effective pre-sowing herbicide tactic.[30]

The most effective double-knock interval between the glyphosate and paraquat applications is between two and 10 days for seedling annual ryegrass plants.[31]

Maximum control of annual ryegrass results from an application of herbicide at the three to four-leaf stage. Annual ryegrass treated at the zero to one-leaf stage can potentially regrow from seed reserves.[32]

Herbicide treatments can be highly effective in reducing in-crop annual ryegrass populations within five consecutive growing seasons. But research trials in the northern region found it was only in the paddocks where both early season herbicides and HWSC were routinely practiced that very low weed densities were achieved.

Stubble cover of 50-90 percent has been shown to reduce the performance of pre-emergent herbicides, such as trifluralin, for annual ryegrass control. Increasing the carrier volume of these herbicides can significantly increase weed kill.[33]

Research and experience is indicating that burying annual ryegrass seed deep using a mouldboard plough operation every 10-20 years can reduce the weed seedbank by as much as 99 percent, enabling problem paddocks to be 're-set' in terms of annual ryegrass numbers.[34]

Combining herbicide control with HWSC measures has reduced annual ryegrass seed bank levels to near zero in some northern WA grainbelt paddocks, as outlined in Figure 5.

30 GRDC (2012) Fact Sheet — Herbicide resistance, Western Region, GRDC, https://grdc.com.au/GRDC-FS-HerbicideResistance

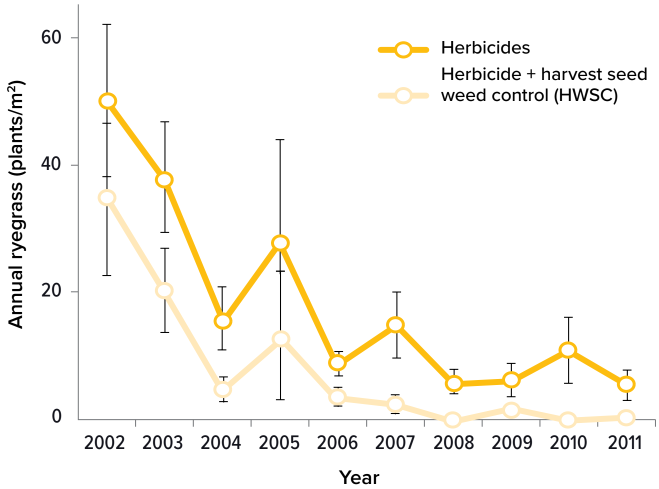
31 GRDC (2012) Fact Sheet — Herbicide resistance, Western Region, GRDC, https://grdc.com.au/GRDC-FS-HerbicideResistance

32 GRDC (2012) Fact Sheet — Herbicide resistance, Western Region, GRDC, https://grdc.com.au/GRDC-FS-HerbicideResistance

33 GRDC (2014) Integrated Weed Management Manual, Section 6 Profiles of common weeds of cropping, GRDC, www.grdc.com.au/IWMM

34 GRDC (2014) Integrated Weed Management Manual, Section 6 Profiles of common weeds of cropping, GRDC, www.grdc.com.au/IWMM

Figure 5: *Influence of the long-term (2002-2011) use of herbicides alone and herbicides plus harvest weed seed control (HWSC) on in-crop annual ryegrass plant densities in northern WA cropping fields.*[35]



NOTE: Capped bars represent the standard error values showing variation around the mean annual ryegrass populations in 17 fields (herbicides) or eight fields (herbicides plus HWSC).

6.6 Wild radish

Figure 6: *Wild radish is a highly competitive weed in wheat crops and can cause yield losses of 10-90 percent.*

(SOURCE: GRDC)

MORE INFORMATION

GRDC Fact Sheet 'Wild Radish': www.grdc.com.au/GRDC-FS-WildRadishManagement

GRDC Hot Topic 'Wild Radish Control Options in WA': www.grdc.com.au/Media-Centre/Hot-Topics/Wild-radish-control-options-in-WA

GRDC 'Herbicide Resistance Testing': www.grdc.com.au/Media-Centre/Media-News/South/2014/04/Herbicide-resistance-testing-autumn-2014

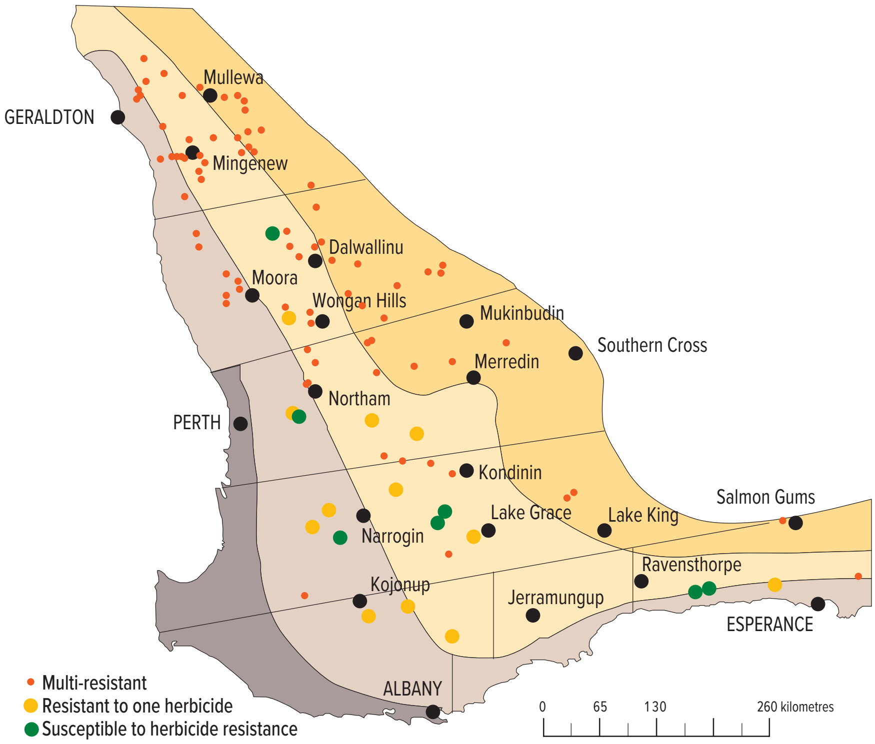
DPIRD 'Wild radish': https://www.agric.wa.gov.au/grains-research-development/wild-radish

35 Newman, P, DAFWA (2013) A systems approach to enhance the adoption of Integrated Weed Management techniques in the Northern Agricultural Region of WA, https://grdc.com.au/research/reports/report?id=1361

Wild radish is a highly competitive weed in wheat crops and can cause yield losses of 10-90 percent. It is an alternative host for several pests and diseases and it can lead to animal health problems when grazed.[36]

Wild radish with multiple herbicide resistance is also increasing in WA, as highlighted in Figure 7.

Figure 7: *Incidence of multi-resistant wild radish across WA's cropping zones.*[37]



SOURCE: AUSTRALIAN HERBICIDE RESISTANCE INITIATIVE, 2010 SURVEY

Wild radish is a prolific seeder and can emerge at any time of the year, providing there is sufficient soil moisture. But most seed germinates during autumn and winter.

Wild radish can produce seed in a very short time from germinations late in spring or during summer, its seedlings establish rapidly and it can grow relatively fast.

This weed is easily distributed as an impurity in hay, chaff and grain. Seed pods often break into segments that are similar in size to wheat seed and removing the contamination can be difficult.

Wild radish plants commonly shed pods before crop harvest in WA conditions, enabling the weed to persist in cropping systems.

Moisture levels of harvested grain can also be affected. In years when there are late rains and wild radish continues to grow and remain green after crop maturity, the moisture from the weed stems at harvest can raise crop grain moisture content above acceptable storage levels.

Wild radish has allelopathic activity and its extracts and residues can suppress germination, emergence and seedling growth of some crops and weeds.

Wild radish dormancy is controlled at three levels — the pod, the seed coat and the embryo.

36 DPIRD 'Wild radish' hub, 2017, https://www.agric.wa.gov.au/grains-research-development/wild-radish

37 DPIRD 'Wild radish' hub, 2017, https://www.agric.wa.gov.au/grains-research-development/wild-radish

The seed pod acts as a sponge to slow water uptake by the seed and contains alkaloids that protect it from microbial attack. This ensures the seed only germinates when there is enough soil moisture.

The seed coat acts as a second barrier to germination, with seeds only germinating once the seed coat has been ruptured to allow water to enter.

Once these physical barriers have broken down, the embryo senses the environment and allows germination only when conditions are right.

For buried seeds, conditions for germination are typically optimal in autumn and early winter in WA and there may be a secondary peak in spring.

The presence of the pod and seed coat mean fresh seed is unlikely to germinate until it has been weathered or physically damaged through harvest, tillage or stock grazing.

This explains why an 'autumn tickle' (or light cultivation) is so effective in promoting wild radish germination, provided there is enough moisture. It also explains why, in no-till systems, seed can remain dormant for longer and make other factors (such as predation and natural seed death) more important in driving down the weed seedbank.[38]

6.6.1 Herbicide resistance and wild radish

Populations of wild radish (mostly in WA) have developed resistance to a range of herbicide MOAs. Group B resistance is the most common, followed by Group F, but resistance also occurs in:

- Group B — sulfonylureas (for example, chlorsulfuron)
- Group B — sulfonamides (for example, metosulam)
- Group B — imidazolinones (for example, imazapic)
- Group C — triazines
- Group C — triazinones (for example, metribuzin)
- Group F — nicotinanalides (for example, diflufenican)
- Group I — phenoxies (2,4-D)
- Group M — glyphosate.[39]

A combination of IWM tactics can work to reduce or control populations of wild radish and help to manage herbicide resistance, as outlined in Table 6.

38 Peltzer, S (2016) Crop weeds: wild radish, DAFWA, https://agric.wa.gov.au/n/214

39 Peltzer, S (2016) Crop weeds: wild radish, DAFWA, https://agric.wa.gov.au/n/214

Table 6: Tactics to consider when developing an integrated plan to manage wild radish in WA cropping systems.[40]

Wild radish (*Raphanus raphanistrum*)		Most likely % control (range)	Comments on use
Agronomy	Herbicide tolerant crops	90 (80–99)	If growing canola in a wild radish infested area it is essential to use a herbicide resistant variety and associated herbicide package.
Tactic	Burning residues	70 (20–90)	In concentrated windrows. Burn when conditions are conducive to a hot burn.
Tactic	Inversion ploughing	98 (20-100)	Plough must be correctly 'set up' and used under the right conditions. Must use skimmers.
Tactic	Autumn tickle	45 (15–65)	Follow-up rain is needed for better response.
Tactic	Knockdown (non-selective) herbicides for fallow and pre-sowing control	80 (70–90)	Add a reliable herbicide spike for more reliable control. Late germinations will not be controlled.
Tactic	Selective post-emergent herbicides	90 (70–99)	Apply to young and actively growing weeds. Repeat if necessary to control late emerging weeds or survivors.
Tactic	Spray-topping with selective herbicides	80 (70–95)	Wild radish may regrow if there are late rains. Good for seedset control. Spray before embryo development for best results.
Tactic	Wiper technology	70 (50–80)	Has potential in low growing pulses such as lentils.
Tactic	Silage and hay – crops and pastures	80 (70–95)	Cut before embryo formation in developing wild radish seed (21 days after first flower). Graze or spray regrowth.
Tactic	Manuring, mulching and hay freezing	95 (90–100)	Brown manuring more efficient than green manuring and more profitable. Grazing before spraying to open sward will improve results. Hay freezing works well and is the most profitable manuring option in most cases.
Tactic	Grazing – actively managing weeds in pastures	70 (50–80)	Rotationally graze and use spray-grazing. Can also use slashing to improve palatability and reduce pasture growth rate in spring.
Tactic	Weed seed collection at harvest	75 (65–85)	Most reliable in early harvested paddocks.
Tactic	Sow weed-free seed	95 (90-100)	Very important as resistance in wild radish is increasing and introduction via crop seed is increasingly likely.

40 Peltzer, S (2016) Crop weeds: wild radish, DAFWA, https://agric.wa.gov.au/n/214

6.6.2 Control strategies for wild radish

The high and complicated seed dormancy of wild radish can make control of this weed difficult. Up to 70 percent of seed set in one season may not germinate for about 18 months.[41]

Exhausting the seedbank completely can take up to a decade of concerted weed management effort.

Any wild radish plants that survive to set seed results in the seedbank being replenished with a new wave of dormant seed.

Unlike annual ryegrass, wild radish seed survives for longer periods the deeper it is buried in the soil.

Wild radish control in WA cropping systems requires a multi-pronged approach consisting of:

- Applying in-crop herbicides twice
- Making the first application while weeds are small (two-leaf) at Zadoks Growth Scale GS12
- Using a second application no later than GS31 (first node)
- Ensuring excellent herbicide application
- Using narrow row spacing
- Considering east-west crop rows to out-compete weeds
- Using HWSC to destroy seedset of surviving weeds.[42]

Research in Geraldton in 2013 confirmed the value of a two-spray approach for wild radish control and improving wheat yields.

A trial was set up in wheat paddocks with a weed burden of 200 wild radish plants/ m^2 that were sprayed twice while small (at the two-leaf stage) with either Bromicide® 200 (Group C), Jaguar® (Group C + F) or Velocity® (Group H + C), followed by one of a range of herbicides at the five-leaf stage.

The twice sprayed areas out-yielded wheat plots sprayed only once (at the later stage) by an average of 0.4-0.5 tonnes/ha.[43]

Spraying wild radish only once at the five or six-leaf stage will typically not kill all plants and seed from the remainder will survive in the seedbank if not captured during harvest. Later sprays can also fail due to poor penetration of herbicide into the crop canopy.

Ensuring wheat crops can out-compete weeds using tactics such as higher seeding rates, narrow row spacing and east-west crop row orientation can help to reduce all in-crop weeds, including wild radish, annual ryegrass, wild oats and brome grass.

Using wheat rows that face east-west, rather than north-south, has been found to significantly reduce weed density in-crop in WA research trials, as shown in Table 7.

41 GRDC (2014) Hot Topic — Wild radish control options in WA, GRDC, https://grdc.com.au/Media-Centre/Hot-Topics/Wild-radish-control-options-in-WA

42 GRDC (2014) Hot Topic — Wild radish control options in WA, GRDC, https://grdc.com.au/Media-Centre/Hot-Topics/Wild-radish-control-options-in-WA

43 Lee, N (2014) Be the early bird on wild radish control, GRDC, https://grdc.com.au/Media-Centre/Media-News/West/2014/05/Be-the-early-bird-on-wild-radish-control

Table 7: Annual ryegrass seed production (seeds/m^2) in east-west or north-south orientated crops of wheat (2010) or wheat and barley (2011), with low or high seeding rates. Means for each factor within each trial are separated by least significant diff (Lsd), where NS indicates that the means were not different.[44]

Treatments	2010			2011		
	Merredin	Wongan Hills	Katanning	Merredin	Wongan Hills	Katanning
East-west	503	24	529	27	260	14113
North-south	910	300	465	125	6155	26276
Lsd (P<0.05)	331	36	NS	35	3469	1342
Barley	*	*	*	19	4420	16410
Wheat	*	*	*	146	4345	23378
Lsd (P<0.05)				18	NS	271
Low seeding rate	1032	130	151	119	5029	24087
High seeding rate	381	21	132	30	3736	15826
Lsd (P<0.05)	275	NS	NS	18	NS	271

"Treatment not included in trial.

Despite increasing herbicide resistance issues, some WA growers are able to keep weed seedbanks low.

Research shows the weed seedbank of wild radish can be reduced by up to 95 percent in five years if there is a concerted and integrated approach to weed control, including collection and destruction of weed seeds at harvest.[45]

44 GRDC (2014) Hot Topic — Wild radish control options in WA, GRDC, https://grdc.com.au/Media-Centre/Hot-Topics/Wild-radish-control-options-in-WA

45 GRDC (2014) Hot Topic — Wild radish control options in WA, GRDC, https://grdc.com.au/Media-Centre/Hot-Topics/Wild-radish-control-options-in-WA

MORE INFORMATION

WeedSmart '10-Point plan': http://www.weedsmart.org.au/10-point-plan/capture-weed-seeds-at-harvest/

GRDC 'Integrated Weed Management Manual': http://www.weedsmart.org.au/bulletin-board/integrated-weed-management-manual/

GRDC Hot Topic 'Integrated Weed Management in WA': https://grdc.com.au/Media-Centre/Hot-Topics/Integrated-Weed-Management-in-WA

6.7 Weed management at harvest

Figure 8: *The integrated Harrington Seed Destructor iHSD system is one way to destroy weed seeds at harvest by pulverising the chaff fraction as it leaves the harvester.*

(SOURCE: McIntosh & Son)

The seed from WA's major cropping weeds does not shatter before harvest and a large proportion is retained above crop height, enabling it to be removed at this time.

Common harvest weed seed control (HWSC) tactics that can be used to capture and/or destroy these seeds, lower the weed seedbank and help manage herbicide resistance issues include:

- Collecting chaff in chaff carts
- Using the Bale Direct system to collect straw and chaff as it exits the harvester
- Depositing chaff on narrow windrows for burning or livestock grazing the next autumn
- Using seed destruction technology to pulverise chaff fraction as it leaves the harvester
- Diverting chaff onto permanent tramlines (in controlled traffic farming systems) or into narrow rows.

Research shows that 75-85 percent of annual ryegrass seed and 85-95 percent of wild radish seed that enters the front of the header during the harvest operation can be collected using these HWSC methods. Some HWSC tactics have been shown to reduce annual ryegrass emergence in the following autumn by up to 60 percent. Combined with effective use of herbicides, HWSC can keep weed numbers at fewer than one plant per square metre — enabling earlier sowing each season.[46]

46 Walsh, M and Powles S, (2012) Harvest Weed Seed Control, Australian Herbicide Resistance Initiative, GRDC Update Papers, www.giwa.org.au

6.7.1 Stubble management and weed control

Figure 9: *Research and experience in WA indicates burning narrow windrows, rather than entire paddocks, can result in higher weed kill and less erosion risk.*

(SOURCE: GRDC)

Narrow windrow burning has been shown to control up to 99 percent of annual ryegrass and wild radish seed present in the windrow.

But narrow windrow burning efficacy is limited by the number of weed seeds that enter the front of the harvester, so total seed set control is in the range of 30 to 90 percent.

When considering burning stubbles, research has found that to kill annual ryegrass seed, a temperature of 400°C for 10 seconds is required. For complete kill of wild radish seed retained in pod segments, a temperature of 500°C for 10 seconds is needed.[47]

During traditional whole paddock stubble burning, the very high temperatures needed for weed seed destruction tend not to be sustained for long enough to kill most weed seeds. There are also risks of wind and water erosion with stubble burning.

By concentrating harvest residues and weed seed into a narrow windrow (of about 0.6-1.5 metres wide), fuel load is increased and the period of high temperatures extends to several minutes. This improves weed seed destruction.

Research and experience in WA indicates burning narrow windrows, rather than entire paddocks, can result in higher weed kill and less erosion risk.

Best results are typically achieved when windrows are burned during light cross or head winds (at a strength of about 5-10 km/hour), as the wind fuels the fire all the way to the soil surface where the bulk of weed seeds are located.

It is recommended to consult the local shire or fire warden for burning regulations, have firefighting equipment on hand and burn under ideal wind, temperature and humidity conditions.

A useful tool to determine suitability of burning conditions is the McArthur Grassland Fire Danger Index (GFDI). More information about this and the CSIRO Grassland Fire Danger Meter is available at http://www.csiro.au/en/Research/Environment/Extreme-Events/Bushfire/Fire-danger-meters/Grass-fire-danger-meter

47 Walsh, M and Newman, P (2007) Burning narrow windrows for weed seed destruction, Western Australian Herbicide Resistance Initiative/The University of Western Australia, ScienceDirect, http://ahri.uwa.edu.au/windrow-burning-a-good-place-to-start/

6.7.2 Timing of burns

Although burning early in the season is likely to achieve the best weed seed control, in many instances this is not practical due to weather conditions creating high risk of fire spread. As mentioned, it is recommended to consult the local shire or fire warden for burning regulations.

Premature removal of stubble can also increase erosion risk and reduce the efficiency of water conservation.

It is recommended to burn the outside two laps of the paddock first before starting on the rest of the paddock.

As a general rule-of-thumb, it is recommended burning is carried out with a grass fire index of:

- Less than 15 (will give a reasonable windrow burn)
- Ideally 8-10
- Not less than two (too cold and humid)
- No more than 15 (high risk of fire getting out of control).[48]

For narrow windrow burning, it can be important not to 'over-thresh' the straw at harvest — as this can become too fine and not burn well the next autumn.

It is recommended to light the windrows when the wind is at 90 degrees across, or diagonal to, the windrow (rather than parallel) as this prevents the fire developing a 'face' that can carry between the rows.

Another tip for burning windrows is to light up across the windrows every 75 m in good conditions — and closer as conditions cool down. The fires will tend to burn to meet each other.

It is advisable to start burning just on dark, when it is cooler, and plan to have the burning finished when the dew falls. This will limit stubble smouldering and flare-ups during the next day.

Summer rain will lower the burning temperature achieved in narrow windrows, but effective weed seed kill is possible if windrows are left for two weeks or more to dry before burning.

48 Walsh, M and Newman, P (2007) Burning narrow windrows for weed seed destruction, Western Australian Herbicide Resistance Initiative/The University of Western Australia, ScienceDirect, http://ahri.uwa.edu.au/windrow-burning-a-good-place-to-start/

MORE INFORMATION

GRDC 'Summer Fallow Weed Management Guide': www.grdc.com.au/GRDC-Manual-SummerFallowWeedManagement

GRDC Hot Topic 'Summer Fallow Weed Management': www.grdc.com.au/Media-Centre/Hot-Topics/Summer-fallow-weed-management

6.8 Summer weed control

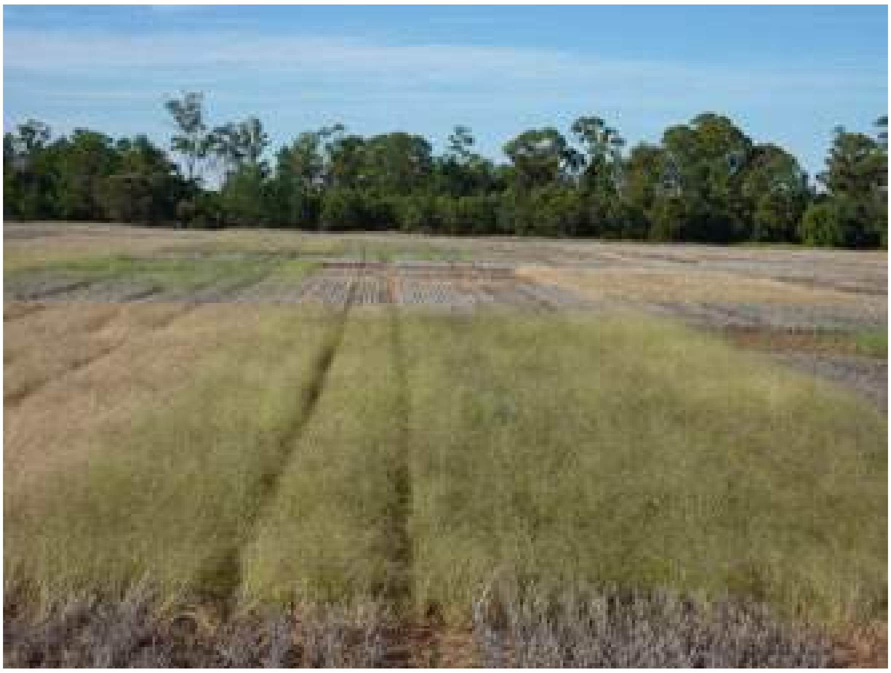


Figure 10: *Summer weeds are a scourge of WA crops.*

(SOURCE: DPIRD)

Summer weeds are best destroyed soon after emergence, when plants are small and actively growing. Weeds will stress fast in hot summer growing conditions and become more difficult to control.[49]

Summer weeds often germinate in winter crops after final post-emergent herbicides have been applied and then grow through to the summer fallow after the winter crop is harvested.

Tactics for effective summer weed control in WA include:

- Using a well-timed double-knock
- Determining rain fast periods for effective herbicide use
- Ensuring high water rates (at least 60 L/ha)
- Adding a surfactant and/or spraying oil to all post-emergent treatments (unless otherwise directed on the label)
- Avoiding treatment of stressed plants
- Considering residual herbicides (noting plant-back intervals when using pre-emergent herbicides)
- Not sowing susceptible crops before the plant-back period is complete
- Careful use of night spraying — consider inversion and drift conditions
- Considering WeedSeeker® and WeedIT® technologies.

Research has demonstrated weed management has the biggest impact on the amount of plant available water stored during a fallow period. Early and total control of summer weeds optimises soil moisture storage.[50]

49 GRDC (2014) Summer fallow weed management: A reference manual for grain growers and advisers in the southern and western grains regions of Australia, GRDC, www.grdc.com.au/GRDC-Manual-SummerFallowWeedManagement

50 Seymour, M, Kirkegaard, J. A, Peoples, M. B, White, P. F and French, R. J (2012) Break-crop benefits to wheat in Western Australia — insights from over three decades of research, CSIRO and DAFWA, http://www.publish.csiro.au/paper/CP14097.htm

Researchers have found 20-30 percent of moisture from summer rain events of more than 25 mm is typically still available in the soil in WA conditions at seeding if fallows are kept weed-free.[51]

As much as 30 mm (or even up to 80 mm on some soil types) of soil moisture can be available at the start of the growing season after weed-free fallows. Such deeply stored soil water can produce more grain per millimetre than from growing season rainfall.[52]

Growing season rainfall has dropped by 10 percent since the mid-1970s in WA's South West, with the amount and intensity of summer rain events (December-February) increasing during the same period.[53]

These rainfall trends highlight the importance of summer weed control to conserve soil moisture for use during below-average rainfall seasons. Results from modelling highlighting the profitability of summer weed control can be seen in Table 8.

Table 8: The percentage of years in WA in which modelled summer weed control was necessary, the percentage of those years where weed control was profitable, and the mean profit from summer weed control.[54]

Location	Propotion of years in which weed control was necessary	Proportion of years in which weed control was profitable	Mean profit
	(%)	(%)	($/ha)
Buntine	43	73	118
Mingenew	34	34	2
Morawa	43	88	156
Wongan Hills	45	44	17
Kellerberrin	48	82	129
Borden	53	58	34
Salmon Gums	62	92	213

Analysis shows summer weed control is profitable in 30-40 percent of years in lower rainfall areas and in 50-60 percent of years in wetter areas that have a higher crop yield potential. Research across southern Australia has also demonstrated an average $3.50 return in higher crop yields for every $1 spent on summer weed control.[55]

In all locations investigated, the mean return on investment from summer weed control was positive, but there were years in which control was not profitable.

Benefits from increased soil water storage at sowing were more likely to occur on soils with a larger water holding capacity and in drier locations.

Fallow weeds are more difficult to control in mid-summer, due to size and temperature stress, and require top label herbicide rates and/or a double-knock strategy.

It is advised to control summer weeds early and completely. The timing for effective control of various summer weed species is illustrated in Table 9.

51 Seymour, M, Kirkegaard, J. A, Peoples, M. B, White, P. F and French, R. J (2012) Break-crop benefits to wheat in Western Australia — insights from over three decades of research, CSIRO and DAFWA, http://www.publish.csiro.au/paper/CP14097.htm

52 Seymour, M, Kirkegaard, J. A, Peoples, M. B, White, P. F and French, R. J (2012) Break-crop benefits to wheat in Western Australia — insights from over three decades of research, CSIRO and DAFWA, http://www.publish.csiro.au/paper/CP14097.htm

53 Seymour, M, Kirkegaard, J. A, Peoples, M. B, White, P. F and French, R. J (2012) Break-crop benefits to wheat in Western Australia — insights from over three decades of research, CSIRO and DAFWA, http://www.publish.csiro.au/paper/CP14097.htm

54 Seymour, M, Kirkegaard, J. A, Peoples, M. B, White, P. F and French, R. J (2012) Break-crop benefits to wheat in Western Australia — insights from over three decades of research, CSIRO and DAFWA, http://www.publish.csiro.au/paper/CP14097.htm

55 GRDC (2016) Paddock Practices — Summer weed control, saving soil nitrogen and water to boost crop profits, GRDC, https://grdc.com.au/Media-Centre/GRDC-E-Newsletters/Paddock-Practices/Summer-weed-control-saving-soil-nitrogen-and-water-to-boost-crop-profits

Table 9: Latest spray timing for summer weeds to avoid seed set and problems with seeder blockages.[56]

Weed	Latest time to spray
Fleabane	Spray as early as possible after harvest; fleabane very difficult to control when large.
Melons	Important to distinguish between paddy melons and Afghan melons as paddy melons more difficult to kill and require higher herbicide rate. Spray pre-vine when plant is about saucer plate size.
Caltrop	Spray at flowering; very quickly develops viable seed so monitor closely. Alleopathic: can reduce wheat emergence.
Button grass	Spray from three-leaf to tillering; high rates required.
Wire weed/tar vine	Spray early; very difficult to control when large and causes seeder bloackages.
Iceplant	Spray while small. Becomes palatable and poisonous to stock as it dries off so if sprayed late remove stock.
Small crumbweed (mintweed/ goosefoot	Atrazine in many mixes can be used in southern areas to provide good control and ongoing residual control following summer rain.
Wild radish	Spray when pods are the thickness of a lead pencil.
Winter grasses – ryegrass	Spray when first heads fully emerged.

56 Seymour, M, Kirkegaard, J. A, Peoples, M. B, White, P. F and French, R. J (2012) Break-crop benefits to wheat in Western Australia — insights from over three decades of research, CSIRO and DAFWA, http://www.publish.csiro.au/paper/CP14097.htm

Pests and Insects

7.1 Overview

Insects are not typically a major problem in Western Australia's winter cereal crops. But several pests can cause serious damage to wheat, potentially including durum wheat, in some seasons, locations and farming systems.

The types of pests affecting WA's crops have changed in recent years as a result of:

» Increased use of broad spectrum insecticides
» Widespread adoption of stubble retention and minimum tillage
» Increased plantings of vulnerable crops (such as canola)
» Drier conditions exacerbated by climate change.

Incidence of pest resistance to insecticides is also increasing on the back of widespread use of prophylactic, or 'insurance', insecticide applications.

Parasitic wasps (*Hymenoptera*), ladybeetles (*Coccinella*), lacewings (*Chrysopidae*) and hoverflies (*Syrphidae*) can provide useful biological control of some crop pests. Monitoring of both pest and beneficial insect populations can reduce the need to apply insecticides.

The Department of Primary Industries and Regional Development (DPIRD) MyPestGuide application (app) has comprehensive information about pest identification and management in WA cropping systems and is available at https://mypestguide.agric.wa.gov.au/#/. It covers more than 200 crop and grain storage pests, beneficial and biological control agents and biosecurity pest threat alerts specific to WA.

A key feature of the app is that it enables users to send pest reports and photographs direct to entomologists at DPIRD for diagnosis.

MORE INFORMATION

DPIRD 'MyPestGuide': https://mypestguide.agric.wa.gov.au/#/

DPIRD 'Aphid Feeding Damage to Cereal Crops': https://www.agric.wa.gov.au/barley/aphid-feeding-damage-cereal-crops

DPIRD 'Pest Insects': https://www.agric.wa.gov.au/pests-weeds-diseases/pests/pest-insects

DPIRD 'Mites and Spiders': https://www.agric.wa.gov.au/pests-weeds-diseases/pests/mites-spiders

7.2 Integrated pest management

Prophylactic, or 'insurance', insecticide applications can be an unnecessary cost and speed the development of insect resistance.

It is advisable to closely analyse the need for insecticides, as there may be beneficial insects that can help control pests if crops are left untreated.

Integrated pest management (IPM) plans can include monitoring, identification, cultural, chemical, genetic and biological tactics to prevent crop pests from reaching damaging levels.

It is recommended to only apply insecticides after monitoring and correctly identifying pest species.

If insecticides are used, minimising chemical impact on beneficial insects can be helped by selective spraying and limiting the number of applications.

When using insecticides, it is best practice to:

» Rotate products
» Use different modes of action (MOA)
» Use recommended label rates
» Ensure good coverage
» Consider economic thresholds for pest control.

7.3 Insect and pest monitoring in cereal crops

- Monitoring insect incidence and numbers is key to IPM
- Correctly identify immature and adult stages
- Monitor and identify both pest and beneficial insects
- Use good sampling and recording techniques.

Knowledge of the pests and beneficial insects likely to be present during the year, their lifecycles and typical location on crop plants are essential when conducting monitoring as part of an IPM plan.

Monitoring frequency and pest focus should be targeted at crop stages likely to incur economic damage, such as at seedling emergence and flowering/grain formation.

Using appropriate sampling technique is important to ensure that a representative portion of the crop has been monitored — as pest activity is often patchy.

Defining sampling parameters (such as number of samples per paddock and number of leaves per sample) helps achieve 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, considering time constraints and distance covered.

It is recommended random sampling be balanced with sampling in areas of obvious damage.

Random sampling aims to give an overall picture of what is happening in the paddock, but any obvious 'hot spots' of insect activity should also be investigated.

7.3.1 Monitoring — keeping good records

Accurately recording the results of insect and pest sampling is key to good decision making and being able to review the success of control measures.

It is advised monitoring record sheets should show:

» Numbers and types of insects found
» Details of adults and immature stages
» Size of insects (particularly important for larvae)
» Date and time
» Crop stage and any other relevant information — such as row spacings, weather conditions.

It can be useful to collate insect monitoring data into a visual form that enables analysis of trends in pest numbers and plant conditions over time.

Being able to track whether an insect population is increasing, static or decreasing can be useful in deciding whether an insecticide treatment may be required and/or if a treatment has been effective.

Records of insecticide use can 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 of application
» Nozzle types and spray pressure.

7.3.2 Monitoring — optimal times to inspect for insect and pests

It is advised to check cereal crops for signs of pest and beneficial insects or eggs every week during the vegetative stage.

Caterpillar pests are typically not mobile in the canopy and some, such as cutworm (*Agrotis* ssp.), reside below the ground during the day. It is advised to check for these with a torch at night in wheat crops — at the emergence to seedling stage.

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.

Most thresholds for insect control are expressed as pests per square metre (pests/m^2).

It is recommended to separate leaflets or flowers when looking for eggs or small larvae and to 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 progressing in terms of average growth stage, pod retention and other agronomic factors.

Sweep net sampling can be used for flighty insects and is also useful if the field is wet. This works well for smaller pests found in the tops of smaller crops, but is less efficient against larger pests, such as pod-sucking bugs, and tends not to be practical in tall crops with a dense canopy.

It is recommended by DPIRD researchers that at least 20 sweeps are taken along a single 20 metre row.

Monitoring with traps (such as pheromone, volatile and light traps) can provide general evidence about pest activity and the timing of peak egg-laying events for some species. But this is considered a poor substitute to in-paddock monitoring of actual pests and beneficial insect numbers.

7.4 Aphids (*Aphidoidea*)

Figure 1: *Aphids can significantly damage wheat crops.*

(SOURCE: GRDC)

- Occasional pests of wheat crops
- Affect wheat during tillering and from flowering to maturity
- Adults and nymphs suck sap
- Big populations can limit grain yield and size
- Especially damaging with winter and spring infestations.

Cereal aphid numbers can build up on volunteer cereals and grass weeds (the 'green bridge') before sowing and then migrate to infest new season crops.

Damaging populations can typically develop in three out of five years and there are no obvious signs or symptoms of cereal aphid damage in wheat.

The two main cereal aphid species affecting wheat crops in WA are corn aphid (*Rhopalosiphum maidis*) and oat aphid (*R. padi*).

A potential future risk is the Russian wheat aphid, or RWA (*Diuraphis noxia*), which was identified for the first time in Australia in May 2016 and quickly became widespread across Victorian and South Australian cereal-growing areas. It has since been detected in southern New South Wales and the WA grains industry is monitoring crops closely for any incursions.

As part of an integrated approach to future RWA management, GRDC is making investments into:

- » Determining aphid biotype
- » Chemical control options (seed treatment and foliar)
- » Plant resistance activities (screening, germplasm access)
- » Importance of natural enemies
- » Biology and population dynamics
- » Yield loss and thresholds for control
- » Communication and extension activities — including the 'Find, identify, threshold approach, enact (FITE)' strategy.

MORE INFORMATION

DPIRD MyCrop Diagnostic Tool 'Aphids'': https://agric.wa.gov.au/n/2157

GRDC Ute Guide 'Crop Insects': https://grdc.com.au/Resources/Ute-Guides/Insects

GRDC Tips and Tactics 'Reducing Aphid and Virus Risk': https://grdc.com.au/Resources/Factsheets/2015/02/Reducing-aphid-and-virus-risk

GRDC Back Pocket Guide 'Crop Aphids': https://grdc.com.au/Resources/Bookshop/2015/02/Crop-Aphids-Back-Pocket-Guide

DPIRD 'Russian Wheat Aphid': www.agric.wa.gov.au/rwa2016

7.4.1 Control of aphids

It is advised to check crops from late tillering onwards for feeding damage by corn aphids in the furled growing tips and for oat aphids on stems, ears and the backs of leaves. Infestations of both aphid species simultaneously can cause more damage than either species in isolation.

Cereal aphids also spread Barley yellow dwarf virus (BYDV), which reduces cereal yield.

The spread of BYDV by aphids is typically economically damaging if aphids transmit the virus early, in the first eight to 12 weeks after crop emergence.[1]

Such early BYDV infection tends to occur mainly in high rainfall areas, especially where early season grass and cereal weeds have been present.

Insecticide treatment for aphid feeding damage is considered worthwhile if about 50 percent of tillers have at least 15 aphids and crops are expected to yield 3 tonnes per hectare or more.[2]

Registered insecticides for aphids in WA wheat crops include (but are not restricted to) products containing:

- Dimethoate
- Esfenvalerate
- Gamma-cyhalothrin
- Lambda-cyhalothrin
- Pirimicarb
- Sulfoxaflor.

Registered seed treatments for aphids in WA wheat crops include products containing:

- Imidacloprid
- Thiamethoxam + lambda-cyhalothrin.

Crops treated with insecticides for aphid control before stem elongation (Zadoks Growth Scale stage GS30) may need re-treating between booting and heading (GS50 or later) if aphid numbers build up again.

It is recommended to wait until threshold aphid levels are reached before applying insecticide because, in many years, aphid numbers will not reach damaging levels. But it is important to pay close attention to weather forecasts, as very hot or very cold conditions can decimate aphid numbers. Aphids will thrive in mild weather.

Parasitic wasps, ladybeetles, lacewings and hoverflies can provide useful biological control of this pest, mainly by preventing secondary outbreaks.

1 DAFWA MyCrop Diagnostic Tool, 'Aphids', 2017', https://agric.wa.gov.au/n/2157

2 Coutts, B and Micic, S (2016) Aphid Feeding Damage to Cereal Crops, DAFWA, https://agric.wa.gov.au/n/113

MORE INFORMATION

DPIRD MyCrop 'RLEM': https://agric.wa.gov.au/n/2177

TimeRite®: www.timerite.com.au

GRDC 'Back Pocket Guide — Crop Mites': www.grdc.com.au/BPG-CropMites

cesar 'Redlegged Earth Mite': http://www.cesaraustralia.com/sustainable-agriculture/pestnotes/insect/Redlegged-earth-mite

DPIRD 'Diagnosing Redlegged Earth Mite': https://www.agric.wa.gov.au/mycrop/diagnosing-redlegged-earth-mite

GRDC Fact Sheet 'RLEM Resistance Management Strategy — Western': https://grdc.com.au/FS-RLEM-Resistance-strategy-West

GRDC 'Management of Insecticide Resistance in RLEM and Screening New MOA Chemistry': http://projects.grdc.com.au/projects.php?action=view_project&project_id=2020

7.5 Redlegged earth mite (*Halotydeus destructor*)

Figure 2: *Similarly to lupin crops (pictured), RLEM can damage wheat at seedling stage.*

(SOURCE: GRDC)

- Affects wheat growth at seedling stage
- Sap-sucking
- Feeds on all stages of plants
- Typically damage is not severe
- Big numbers commonly found in annual pastures at break of the season.

Redlegged earth mite, or RLEM, is particularly damaging to wheat seedlings during autumn and in years when the season break and sowing is late. In this situation, mite numbers can be well established by the time crop seedlings emerge.

Adult RLEM are about the size of a pinhead (up to 1 mm), have velvety black bodies and eight bright orange-red coloured legs. The mites are often gregarious and can be found clumped together in large numbers.

Mites hatch from over-summering eggs in autumn when there is adequate moisture and low temperatures. Eggs produced through the season are thin-walled and hatch immediately. Several generations can develop during winter and spring.

As pastures begin to senesce, the mites produce thick-walled eggs, which resist drying out over summer and carry the mite through to the next season.

Wheat crops sown after a pasture phase are most at risk of RLEM damage.

Mites rupture cells on the surface of leaves and feed on exuding sap. Affected leaves look 'silvered', but do not have holes (as with lucerne flea attack).

RLEM damage to wheat seedlings is more severe if plant growth is slowed by cold temperatures, waterlogging or low seedling density. Severe damage can kill seedlings.

7.5.1 Control of RLEM

Applying insecticide for RLEM control in cereal crops should only be considered if absolutely necessary, as RLEM populations with resistance to synthetic pyrethroids, or SPs (Group 3A) and tolerance of omethoate (Group 1B) have been recorded in WA.

Registered insecticides for control of RLEM in WA wheat crops include (but are not restricted to) products that contain the actives:

- Alpha-cypermethrin
- Beta-cypermethrin
- Bifenthrin
- Chlorpyrifos
- Cypermethrin
- Dimethoate
- Esfenvalerate
- Gamma-cyhalothrin
- Lambda-cyhalothrin
- Methidathion
- Omethoate
- Phosmet.

Using insecticide seed treatments for crops and new pastures with moderate pest pressure directly targets plant-feeding pests and enables smaller amounts of insecticide to be used.

Seed treatments registered for suppression of RLEM in WA wheat crops include those containing thiamethoxam/lambda-cyhalothrin.

Methidathion (Group 1B) at a rate of 200 ml/ha is registered for bare earth control of RLEM and lucerne flea. Bifenthrin (Group 3A) is also registered as a bare earth treatment for RLEM.

The efficacy of a bare earth insecticide is influenced by the application method.

Best results are typically obtained by application in an unbroken layer over the soil surface just before crop emergence.

To prolong the efficacy of all insecticide groups and minimise resistance risks, it is vital to rotate insecticide products and MOAs within and between seasons and limit 'insurance' or prophylactic spraying.

RLEM often occur in combination with other mites, such as blue oat mites (*Penthaleus major*), bryobia mites (*Bryobia praetiosa*) and balaustium mites (*Balaustium medicagoense*).

It is important to correctly identify the pest, as each of the mite species responds differently to registered insecticides and chemical rates.

The wrong treatment will cost money and act to increase selection pressure for further resistance development.

Maintaining pasture dry matter levels below 2 t/ha has been found to help restrict RLEM numbers to low levels in many parts of WA.[3]

An important biological control agent against RLEM and lucerne flea is the pasture snout mite (*Bdellodes lapidaria*).

Insecticide resistance in RLEM is increasing across WA cropping regions.

3 Micic, S (2016) MyCrop: Diagnosing Redlegged Earth Mite, DPIRD, https://agric.wa.gov.au/n/2177

A population of RLEM on the south coast was confirmed to be tolerant to the widely-used insecticide omethoate in late 2014. This population was also resistant to the SP group of chemicals.[4]

It is recommended RLEM be sprayed only if absolutely necessary. The nominal threshold for control is 50 mites/m^2.[5]

Difficulty in controlling RLEM could indicate resistance to SPs, including bifenthrin and alpha-cypermethrin, and mites surviving any insecticide application should be tested for resistance.

To discuss testing and any suspected resistance issues and to facilitate collection of samples for testing, contact Svetlana Micic at DPIRD at svetlana.micic@agric.wa.gov.au

7.5.2 RLEM and spring pastures

Untreated and under-grazed pastures favour RLEM during spring.

Sustained grazing of pastures at this time to maintain livestock feed on offer (FOO) levels below 2 t/ha dry matter — and ideally about 1.4 t/ha dry matter — tends to restrict mite numbers to low levels.[6] These paddocks will often not require spraying for RLEM.

Applying insecticides to some paddocks — including pastures with FOO of more than 3 t/ha — or legume break crops — during spring to prevent RLEM populations producing diapause (over-summering) eggs will also typically reduce the pest population the following autumn.[7]

But routine spraying of all pasture paddocks in spring will not be sustainable and it is advised to base a decision to treat RLEM during spring based on FOO levels, future grazing management options, seed production requirements and intended paddock use next season.

Timerite® is a free package that provides a predicted date in spring, specific to a locality, for spraying to stop RLEM from producing over-summering eggs. Information can be found at https://www.wool.com/woolgrower-tools/timerite/

CSIRO studies have shown spraying on the optimum Timerite® date, or two weeks earlier, can provide effective RLEM control. Waiting for two weeks after that date can significantly increase the carry-over RLEM population.[8]

4 Micic, S (2015) Update on Redlegged Earth Mite Resistance in WA, DAFWA, http://www.giwa.org.au/pdfs/CR_2015/REVIEWED.20.02.2015/Micic,%20Svetlana_Update%20on%20redlegged%20earth%20mite%20resistance%20in%20WA_FINAL_.pdf

5 Umina, P (2012) GRDC Back Pocket Guide — Crop Mites, GRDC, **cesar**, www.grdc.com.au/BPG-CropMites

6 Micic, S (2016) MyCrop: Diagnosing Redlegged Earth Mite, DPIRD, https://agric.wa.gov.au/n/2177

7 Micic, S (2016) MyCrop: Diagnosing Redlegged Earth Mite, DPIRD, https://agric.wa.gov.au/n/2177

8 Australian Wool Innovation Ltd (2016) Timerite®, AWI, http://www.wool.com/woolgrower-tools/timerite/

MORE INFORMATION

DPIRD MyCrop 'Balaustium Mite': https://agric.wa.gov.au/n/2175

Herbiguide 'Balaustium mite': http://www.herbiguide.com.au/Descriptions/hg_Balaustium_Mite.htm

7.6 Balaustium mite (*Balaustium medicagoense*)

- Affects wheat at seedling stage
- Similar in appearance to RLEM
- Greyish-red body and red legs
- Under magnification, short stout hairs can be seen on body
- Adults almost double the size of RLEM
- Require rainfall before over-summering eggs hatch
- Newly hatched nymphs are orange and have six legs
- Development from egg to adult takes about five to six weeks
- Several generations can occur each year
- No registered insecticides for control in wheat crops in WA.

Balaustium mites are the main species of mites affecting wheat crops and feed on plant leaves by probing into the surface cells with their mouth parts and sucking out sap.

Crops sown into paddocks that were previously in a pasture phase and/or had high burdens of broadleaf weeds (especially capeweed, *Arctotheca calendula L.*) tend to be most at risk from damage.

In most situations in WA conditions, wheat crops will not require insecticide treatment as the mites tend to cause little or no damage.

Early control of summer weeds in paddocks that are to be sown to cereals can help to prevent build-up of mite populations.

MORE INFORMATION

DPIRD MyCrop 'Bryobia Mite': https://agric.wa.gov.au/n/2702

7.7 Bryobia mite (*Bryobia praetiosa*)

- Affects wheat at seedling stage
- Easily confused with RLEM
- Difficult to identify without the use of a hand lens
- Common in early autumn
- Cold temperature requirement before hatching.

Bryobia mites, or clover mites, mainly tend to affect canola and lupin crops. But these pests can cause seedling damage in wheat.

Rates of insecticides commonly used to control RLEM and lucerne flea are not typically effective against bryobia mites.

Registered insecticides for control of bryobia mites in WA wheat crops include (but are not restricted to) products with the actives:

- Bifenthrin
- Chlorpyrifos + bifenthrin.

MORE INFORMATION

DPIRD MyCrop 'Blue Oat Mite': https://agric.wa.gov.au/n/2174

7.8 Blue oat mite (*Penthaleus major*)

Blue oat mites typically affect wheat crop growth at the seedling stage and are frequently found with RLEM.

These pests have a purplish-blue body, with red-orange legs and a red dot on their back.

They tend to be found if the cold temperature requirement for hatching has been met and can cause extensive leaf bleaching.

Registered insecticides for control of this mite in WA wheat crops include (but are not restricted to):

- Alpha-cypermethrin
- Beta-cypermethrin
- Bifenthrin
- Chlorpyrifos
- Cypermethrin
- Dimethoate
- Esfenvalerate
- Methidathion
- Omethoate.

MORE INFORMATION

DPIRD MyCrop 'Webworm': https://agric.wa.gov.au/n/2173

7.9 Pasture webworm (*Hednota* spp.)

- Affects wheat before seeding and at seedling stage
- Caterpillars rarely seen above ground
- Caterpillars live in web-lined tunnels (spring/summer)
- Caterpillars hatch from eggs in autumn and feed through winter
- There is a pupal stage followed by emergence as adult moths
- Moths about 10 mm long
- Moths often seen flying in big numbers at night (autumn)
- Moths hide in dry grass in day time (autumn).

Webworm caterpillars sever leaves and whole plants. Big areas of emerging wheat or barley crops can be destroyed by the continual chewing damage of a heavy webworm infestation.

Severed leaves are pulled into the pest's tunnels.

Eggs are not typically laid in big numbers and do not survive well in bare paddocks or stubble. Grassy weeds and pastures favour survival.

Cultivation that results in weed-free paddocks for three weeks after sowing can reduce survival of larval stages. Reduced tillage tends to favour higher pest survival.

It is recommended to treat wheat crops with insecticide for webworm if about 25 percent of plants are seriously damaged at — or just after — emergence.[9]

Registered insecticide treatments for control of pasture webworm in WA wheat crops include (but are not restricted to) the actives:

- Alpha-cypermethrin
- Bifenthrin
- Chlorpyrifos
- Cypermethrin
- Esfenvalerate
- Gamma-cyhalothrin
- Lambda-cyhalothrin
- Permethrin.

9 Micic, S (2016) MyCrop: Diagnosing Webworm, DPIRD, https://agric.wa.gov.au/n/2173

7.10 Lucerne flea (*Sminthurus viridis*)

- Affect wheat at seedling stage
- Appear early in the season
- Chew young wheat leaves
- Particularly problematic on heavier-textured soils
- Can cause seedling death when in big numbers.

Lucerne fleas are small jumping bugs also commonly known as springtails.

These pests eat leaf tissue and leave the leaf surface covered in a whitish film.

From a distance, severely affected crop and pasture areas appear bleached.

Heavy soils and moisture favour the lucerne flea and it cannot live in very sandy situations.

Systemic or contact insecticides can control lucerne flea in crops and pastures, but SP treatments tend to be ineffective against the pest.

The pasture snout mite is a predator of lucerne fleas and can be found across most WA grainbelt areas where lucerne flea is found. This exerts a useful level of control.

Registered insecticides for control of lucerne flea in WA wheat crops include (but are not restricted to) products containing the actives:

- Chlorpyrifos
- Dimethoate
- Methidathion
- Omethoate.

Seed treatment for suppression of lucerne flea in WA wheat crops contains the actives thiamethoxam/lambda-cyhalothrin.

MORE INFORMATION

DPIRD MyCrop 'Lucerne Flea': https://agric.wa.gov.au/n/2164

IPM 'Guidelines for Lucerne Flea': http://ipmguidelinesforgrains.com.au/pests/lucerne-flea-in-winter-seedling-crops/

cesar Australia 'Lucerne Flea': http://www.cesaraustralia.com/sustainable-agriculture/pestnotes/insect/Lucerne-flea

7.11 Cutworms (*Agrotis munda, A. infusa, A. Rictonis* and *A. Omphaletis*)

- Affect wheat at seedling stage
- Not a regular pest in wheat crops
- Chew through leaves or stems
- Most damage occurs in autumn
- Larvae hide in the soil during the day
- Two large caterpillars per 0.5 m of cereal row can cause extensive damage.

Several species of cutworms can be problematic in WA wheat crops, particularly those sown after a pasture phase.

Weather and food supply are the most important factors in determining populations.

Occasionally, autumn attack by armyworm (*Leucania convecta*) in cereals resembles damage from cutworms. This is significant, because armyworm tends to be more difficult to control with insecticides than cutworms — making correct pest identification vital.

Biological control of cutworms by fungal diseases can be successful and wasp and fly parasites can also actively prevent more frequent and serious outbreaks.

Cutworms can be controlled in WA wheat crops with registered rates of insecticides including (but not restricted to) the actives:

- Alpha-cypermethrin
- Beta-cypermethrin
- Chlorpyrifos
- Cypermethrin
- Esfenvalerate

MORE INFORMATION

DPIRD MyCrop 'Cutworm': https://agric.wa.gov.au/n/2161

DPIRD hub 'Cutworm: Pests of Crops and Pastures': https://www.agric.wa.gov.au/pest-insects/cutworm-pests-crops-and-pastures

IPM guidelines 'Cutworms': http://ipmguidelinesforgrains.com.au/pests/soil-insects/cutworms/

cesar 'Cutworms': http://www.cesaraustralia.com/sustainable-agriculture/pestfacts-south-eastern/past-issues/2014/pestfacts-issue-no-4-5th-june-2014/cutworms/

- Gamma-cyhalothrin
- Lambda-cyhalothrin
- Permethrin.

7.12 Armyworm (*Leucania convecta*)

MORE INFORMATION

DPIRD MyCrop 'Armyworm': https://agric.wa.gov.au/n/2159

- Affects wheat at harvest
- Caterpillars are plump and smooth (hairless)
- Characterised by three parallel white stripes on the collar behind a big head
- Check for green to straw-coloured droppings
- Droppings are the size of a match head
- Droppings found between cereal rows
- Damage to weeds can indicate presence
- Wheat crops less frequently attacked than barley
- Wheat tends to suffer only minor damage.

Assessing the number of armyworms in a cereal crop can be difficult, as the location of this pest tends to vary according to weather conditions and feeding preference.

Sometimes armyworms are found sheltering on the ground and under leaf litter. At other times the pest can be seen high up on plants and easily picked up using sweep nets.

Armyworm caterpillars are most damaging to wheat crops close to harvest, when grubs chew through grain head stems and cause the heads to fall to the ground. The economic trigger for spraying in wheat is typically 10 grubs/m^2.[10]

Registered insecticides for control of armyworm in WA wheat crops include (but are not restricted to) the actives:

- Alpha-cypermethrin
- Beta-cypermethrin
- Chlorpyrifos
- Cypermethrin
- Methidathion
- Methomyl
- Permethrin
- Esfenvalerate (suppression only).

7.13 Spotted vegetable weevil, or Desiantha weevil (*Steriphus diversipes*)

MORE INFORMATION

DPIRD 'Desiantha Weevil in Cereals': https://agric.wa.gov.au/n/2162

- Affects wheat at seedling stage
- Sporadic pest of cereal seedlings
- Mostly found on the south coast
- Late sown crops most at risk
- Favours sand over gravel and sandy duplex soils
- No registered insecticide for control in wheat in WA.

The larval stage of the Spotted vegetable weevil, or Desiantha weevil, can destroy big tracts of young crops when heavily infested.

Larvae chew the swollen seed or bore into the underground stem of seedlings, causing these to be stunted, wither or die. The pest can also bore into tillers at tillering, causing these to die.

Desiantha weevil larvae are white and legless, with orange-brown heads and grow up to 6 mm in length. Larvae remain under the soil and are difficult to find.

10 Micic, S (2016) MyCrop: Diagnosing Armyworm, DPIRD, https://agric.wa.gov.au/n/2159

MORE INFORMATION

DPIRD MyCrop 'African Black Beetle': https://agric.wa.gov.au/n/2156

7.14 African black beetle (*Heteronychus arator*)

- Affects wheat at seedling stage
- Can cause economic damage to cereals (autumn/winter)
- South coast particularly affected
- Crops susceptible close to/following kikuyu pastures
- Adults are shiny black (brown when newly emerged)
- Adults grow to 12 mm long
- Soil-dwelling larval stage mostly in late spring/summer/early autumn
- Larvae are C-shaped and up to 25 mm long
- No registered insecticides for use in WA wheat crops.

If present in crops, African black beetles are likely to be seen walking on the soil surface at night.

A density of 2-6 beetles/m^2 can cause problems, especially in some pastures.[11]

There are no insecticide actives specifically registered for control of African black beetle in pasture or cereal crops in WA.

But pasture seed treated with imidacloprid for RLEM has shown some efficacy against this pest.

Increasing crop seeding rate and avoiding the use of drill rows can help manage African black beetle in wheat.

MORE INFORMATION

DPIRD MyCrop 'Snails': https://agric.wa.gov.au/n/2172

GRDC Fact Sheet 'Snail Management': https://grdc.com.au/Resources/Factsheets/2012/09/Snail-Management

GRDC Hot Topic 'New Insights to Give Snails and Slugs the Slip': https://grdc.com.au/Media-Centre/Hot-Topics/New-insights-to-give-snails-and-slugs-the-slip

7.15 Snails and slugs

Figure 3: *Snails are not a significant pest of wheat crops across much of the WA grainbelt, but can cause damage in some areas and seasons.*

(SOURCE: GRDC)

- Affect wheat at seedling stage and harvest
- Snail damage to WA crops is increasing in some areas, but is not a widespread issue across the grainbelt
- Slugs are particularly problematic in higher rainfall areas
- Registered molluscicides for WA wheat are metaldehyde and methiocarb.

11 DAFWA MyCrop Diagnostic Tool, 'African Black Beetle', 2017, https://agric.wa.gov.au/n/2156

WA wheat crops can be affected in some areas (mostly in the southern and south eastern grainbelt) by three main species of snails and two main species of slugs, as outlined below.

The small pointed snail (*Prietocella barbara*)

- Has a conical shell with brown bands of varying width
- Typically less than 10 mm in length and diameter
- Occurs on all soil types in the high rainfall area.

The white Italian snail (*Theba pisana*)

- Grows up to 30 mm in diameter
- White with broken brown bands
- Prefers alkaline sandy soils.

The vineyard snail (*Cernuella virgate*)

- Grows up to 20 mm in diameter
- Has almost continuous brown bands
- Prefer alkaline sandy soils.

The black-keeled slug (*Milax gagates*) and reticulated slug (*Deroceras reticulatum*)

- Typically found on WA's heavy clay soils
- Prefer wet areas
- Common in high rainfall zones.

Conservation farming practices have resulted in significant increases in slug and snail populations in some WA cropping regions in recent years.

Snail species can impact on wheat grower returns on the back of yield losses and grain contamination at harvest.

It is recommended to monitor snail numbers during and after harvest to determine whether control pre-sowing is necessary.

A combination of measures is required for effective control of snails and slugs, including stubble management, summer weed control and baiting.

While all bait formulations can kill snails and slugs, experience indicates none will result in 100 percent mortality.

7.15.1 Snail damage and cost

Snails are primarily limited to the south coast region, from Albany to Esperance. Some are found (along with slugs) in the wetter parts of the western great southern area and in pockets along the coastal strip near Geraldton.

Small pointed snails can cause economic crop damage in high rainfall areas. The vineyard and white Italian snails commonly cause crop damage in the Geraldton region and on the Greenough flats — the area between Dongara and Geraldton.

Economic losses result from reduced crop yields and/or grain contamination.

Some growers first discover snails are a problem in their crops when their grain is rejected from grain handlers.

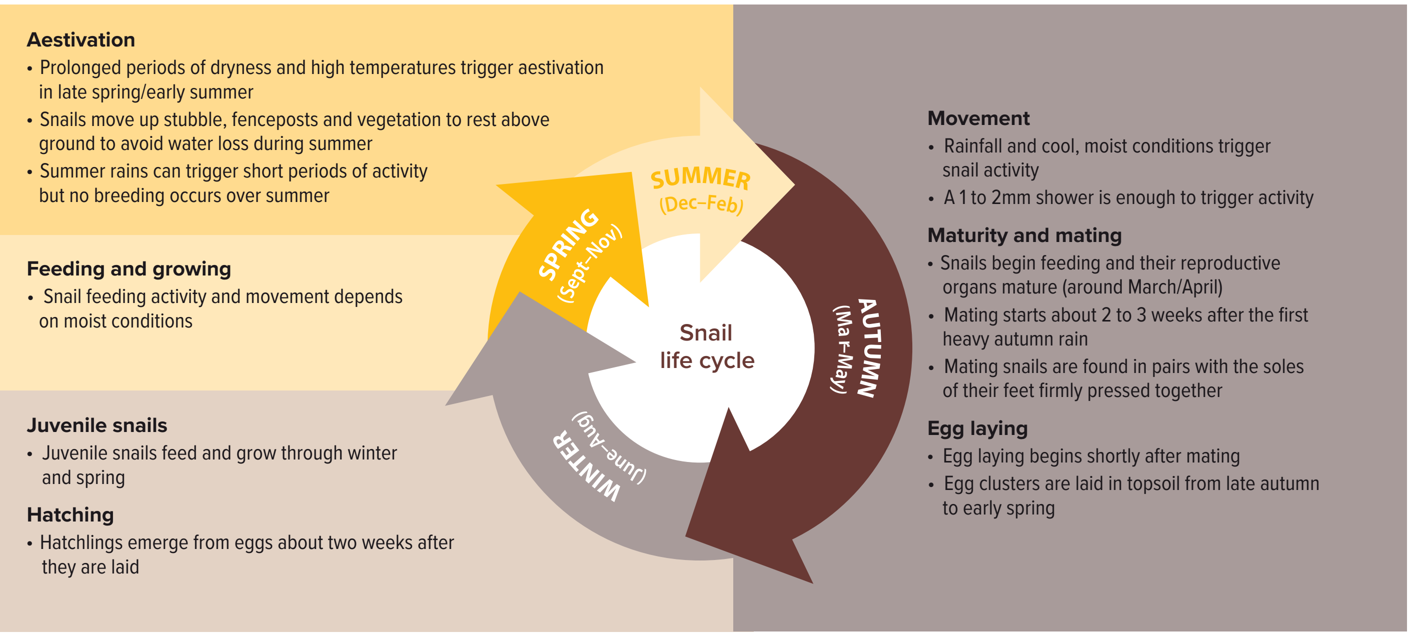
Rejection occurs if more than half of a dead — or one live — snail is found in a 0.5 L wheat grain sample (but standards should always be confirmed with the grain buyer).

Identifying the snail species and sizes in a paddock underpins management options.

During summer, snails are dormant (aestivation). Egg laying starts after snails are activated by autumn rain and continues while soil is moist.

The most effective control program will be an integrated program that uses the most appropriate option for each of the seven stages of the snail life cycle, as shown in Figure 4.

Figure 4: *The snail life cycle.*[12]



12 GRDC Fact Sheet 'Snail Management': https://grdc.com.au/Resources/Factsheets/2012/09/Snail-Management

MORE INFORMATION

GRDC Back Paddock Guide 'Snail Identification and Control': www.grdc.com.au/Resources/Publications/2011/03/Snail-Identification-and-Control-The-Back-Pocket-Guide

DPIRD 'Identification and Control of Pest Slugs and Snails for Broadacre Crops in WA': www.agric.wa.gov.au/grains/identification-and-control-pest-slugs-and-snails-broadacre-crops-western-australia

MORE INFORMATION

IPM Guidelines 'Slugs and Snails': http://ipmguidelinesforgrains.com.au/pests/slugs-and-snails/

SARDI 'Bash'em, Burn'em, Bait'em': https://grdc.com.au/resources-and-publications/all-publications/factsheets/2012/09/grdc-fs-snailmanagement

7.15.2 Monitor and manage snails

It is advised to monitor snails regularly to establish numbers, types, activity and success of control measures.

It is best to check for snails in the early morning, or evening, when conditions are cooler and snails are more active.

It is recommended to look closely in the crowns of last year's stubble, as snails can be easily missed on a casual inspection.

Thresholds for control of snails in various crops and pastures are outlined in Table 1.

Table 1: Thresholds for snail control.[13]

	Crops			
Snail species	Cereals (wheat)	Oilseeds (canola)	Pulses (lupins)	Pastures
Small pointed snail	40/m^2	20/m^2	5/seedling	100/m^2
White Italian snail	20/m^2	5/m^2	5/m^2	80/m^2

When estimating snail numbers, it is advised to sample 10 cm by 10 cm quadrants at 50 locations across a suspect paddock and around the paddock boundary.

Simple sieve boxes can be used to separate snails by size and it is advised that snails larger than 7 mm are more likely to take bait.[14]

Effective snail control requires a targeted and integrated approach across the whole year.

Pre-sowing options for snails include a combination of effective summer weed control and stubble management tactics, such as bashing, burning or grazing.

Baiting is the only control option after crops have been sown. Research and experience indicates mortality rates from baiting are typically between 60 to 90 percent for mature round snails and 50 to 70 percent for mature pointed snails.[15]

Baiting is an effective control measure when snails are mobile and actively seeking food. It is advised to lay pellets along fence lines and paddock boundaries, as well as in the paddock.

Whole paddock, border and fenceline baiting is most effective when rain or moisture triggers snail activity in autumn and before significant egg laying starts (during early autumn). This can reduce potential population build up for that season.

Bait degrades in UV light and degradation rates are reduced as day length shortens. In trials, the concentration of metaldehyde fell from 15 to 4.9 percent in four weeks when bait was spread in February, but to 7.5 percent when spread a month later.[16]

It is advised to target mature snails — round snails larger than 7 mm in diameter and conical snails larger than 7 mm in length — as baits are largely ineffective against juvenile snails.

The best time to apply snail pellets is early in the season when morning temperatures are low and dew forms and after the first germinating rains when snails start to emerge and look for food.

13 GRDC Back Paddock Guide 'Snail Identification and Control': www.grdc.com.au/Resources/Publications/2011/03/Snail-Identification-and-Control-The-Back-Pocket-Guide

14 GRDC Back Paddock Guide 'Snail Identification and Control': www.grdc.com.au/Resources/Publications/2011/03/Snail-Identification-and-Control-The-Back-Pocket-Guide

15 GRDC (2012) Fact Sheet — Snail Management, Southern and Western Regions, GRDC, www.grdc.com.au/GRDC-FS-SnailManagement

16 GRDC (2012) Fact Sheet — Snail Management, Southern and Western Regions, GRDC, www.grdc.com.au/GRDC-FS-SnailManagement

Recent trials in WA found growers can spend between $15 and $85/ha on baits, but may not be applying them effectively.[17] Spreaders not calibrated correctly can result in an uneven distribution of baits.

The more even the bait distribution, the more likely that snails will come into contact with the bait, resulting in better control.

Stubble burning is still the most effective pre-sowing method for controlling snails in WA — if an even burn is achieved and taking into account erosion risks.

It is advised to only burn stubbles in paddocks with the highest number of snails to reduce negative impacts on soil properties and the risk of erosion.

A complete, even, burn can achieve a 100 percent kill, while a patchy burn results in a 50 to 80 percent kill.[18]

7.16 Mice

Figure 5: *Mice can cause significant crop losses in some seasons and in some regions.*

(SOURCE: GRDC)

- Frequency of plagues in WA have increased in past 20 years
- All crop types, crop stages and cropping regions affected
- Damage at sowing can devastate emerging wheat crops
- Critical periods are autumn and spring.

Strategies to control and reduce mouse populations in WA include:

- » Limiting available food sources
- » Monitoring incidence throughout the year
- » Bait as necessary
- » Registered bait active is zinc phosphide
- » Bait cannot be applied to bare ground
- » Manage at flowering and seed set to protect grain yields
- » Manage grain and weed seed residues all year.

MORE INFORMATION

GRDC Fact Sheet 'Mouse Management': www.grdc.com.au/GRDC-FS-MouseManagement2012/

Invasive Animals CRC 'MouseAlert': http://www.feralscan.org.au/mousealert/

GRDC Hot Topic 'Mice': http://grdc.com.au/Media-Centre/Hot-Topics/Mice

PestSmart 'Connect Toolkit': www.pestsmart.org.au.

17 GRDC (2012) Fact Sheet — Snail Management, Southern and Western Regions, GRDC, www.grdc.com.au/GRDC-FS-SnailManagement

18 GRDC (2012) Fact Sheet — Snail Management, Southern and Western Regions, GRDC, www.grdc.com.au/GRDC-FS-SnailManagement

Intensive cropping rotations, minimum tillage and stubble retention, more diverse crops, higher grain yields and fewer livestock are all contributing factors to higher mouse impact on wheat crops in WA.

These conditions provide mice with abundant food and cover, as well as a favourable habitat for breeding.

Hygiene in and around paddocks, grain storage facilities and fodder storage facilities — combined with tactical baiting programs — remain the key control options. It is recommended to clean-up grain spills in the paddock and around yards at sowing and harvest and remove rubbish and nesting material from sheds.

Mouse numbers increase and decline rapidly depending on seasonal conditions and feed availability. Mice can move up to 300 m each day, so it is advised to regularly monitor activity on a paddock-by-paddock basis, rather than a single site on the farm.

Mice typically damage cereal crops at sowing by digging into the soil and eating the seed, or just after emergence when they feed on the seedling.

Wheat is most vulnerable during the first two to three weeks following crop emergence (when every seed removed is equal to one less plant to provide yield).

Although there is generally less crop damage during the vegetative stages, mice can chew crops to supplement their diet.

In the worst cases, this pest can reduce yields by 50 percent during flowering.[19] After grain fill, the risk of damage slows as the mice can obtain more nutrients from less feed.

Trapping with 'snap traps' throughout the year can indicate mouse population levels and breeding status.

A trapping rate of 10 percent indicates an emerging issue. A trapping rate of 20 percent or more in an early maturing crop indicates a problem.[20]

Recommendations for laying traps include to set out a straight line of 20 to 25 traps, spaced 10 m between each trap, for three consecutive nights.

Baiting is the only option available for in-crop control for mice.

Registration details for baits tend to change frequently and not all products are registered for use in-crop.

Check with your agronomist, adviser, retailer or the Australian Pesticides and Veterinary Medicines Authority (APVMA) for current control options.

Tips for effective baiting include:

- Application by Chemcert registered landholders or commercial operators
- Consult the label for use instructions
- Wherever possible, apply within 24 hours of sowing
- Lay during late afternoon and early evening (after birds have fed)
- Maintain a buffer of more than 50 m from areas of remnant native vegetation
- Advise any beekeepers with hives near the paddock well in advance of baiting
- Always wear personal protection equipment (PPE) when handling baits
- Wear gloves
- Check paddocks and surrounding areas for non-target animal mortalities
- Only use registered baits
- Continue to monitor mouse activity after baiting.[21]

19 GRDC (2012) Fact Sheet, Mouse Management, Western Region, GRDC, www.grdc.com.au/GRDC-FS-MouseManagement2012

20 GRDC (2012) Fact Sheet, Mouse Management, Western Region, GRDC, www.grdc.com.au/GRDC-FS-MouseManagement2012

21 GRDC (2012) Fact Sheet, Mouse Management, Western Region, GRDC, www.grdc.com.au/GRDC-FS-MouseManagement2012

Frost and heat stress

8.1 Frost Overview

On nights when still and cold air, clear skies and low humidity combine, temperatures can drop rapidly and result in radiant frost that can affect Western Australian crops.

Damage can be significant when frost is severe, prolonged and/or occurs at susceptible stages of plant development.

The temperatures experienced and recorded in the crop during a frost can vary widely due to differences in topography, microenvironment and recording method.

Widespread spring frosts were reported across many eastern, central and southern grainbelt areas in 2016, when WA experienced its coldest September average minimum temperatures on record. It is estimated (conservatively) that two million tonnes of total grain was shaved off WA deliveries – worth about $600 million in losses to growers. In 2005, WA grain growers lost about 700,000 tonnes of grain due to frost, worth an estimated $90 million.

The risk, incidence and severity of frost varies between and within years and across landscapes, so growers are advised to assess their individual situation regularly.

The occurrence of frost and subsequent frost damage to grain crops is determined by a combination of factors, including:

- Temperature
- Humidity
- Wind
- Topography
- Soil type, texture and colour
- Crop species and variety
- Crop management.

Highest cereal crop losses (in terms of grain yield and quality) tend to occur when there are frosts between the booting and grain ripening stages of growth.

Frost damage is not always obvious and crops should be inspected for five to seven days after a suspected event.

Strategies to deal with the financial and personal impact of frost also need to be considered as part of whole farm and full year risk management plans.

MORE INFORMATION

GRDC 'Frost – Frequently asked questions': www.grdc.com.au/frost-faq

GRDC Western Wheat, Western Canola, Western Oat and Northern Durum wheat GrowNotes™: www.grdc.com.au/GrowNotes

GRDC Tips and Tactics 'Managing Frost Risk': www.grdc.com.au/ManagingFrostRisk

GRDC 'National Frost Initiative': www.grdc.com.au/GRDC-Video-NationalFrostInitiativePlaylist

DPIRD 'Frost and Cropping': www.agric.wa.gov.au/frost/frost-and-cropping

GRDC Ground Cover 'Frost Supplement': www.grdc.com.au/GCS109

GRDC Back Pocket Guides 'Frost': https://grdc.com.au/resources-and-publications/all-publications/bookshop/2012/01/cereals-frost-identification-the-back-pocket-guide-grdc416 and www.grdc.com.au/GRDC-BPG-FrostPulses

GRDC Hot Topic 'What to do with a Frosted Crop': www.grdc.com.au/FrostedCrop

GRDC Hot Topic 'Pre-seeding Planning to Manage Frost Risk in WA': www.grdc.com.au/HT-PreseedingForFrostManagement

MORE INFORMATION

DPIRD 'Frost - diagnosing the problem' https://www.agric.wa.gov.au/frost/frost-diagnosing-problem

GRDC Frost videos https://www.youtube.com/watch?v=GC2P2Tha5Es&list=PL2PndQdkNRHGLPDeHqGVmEcUP-4B2Ka93

8.1.1 The changing nature of frost

The length of the frost season has increased across much of the Australian grainbelt — by 10-55 days between 1960 and 2011.[1]

CSIRO analysis of climate data for this period suggests increasing frost incidence was due to the southerly displacement and intensification of high-pressure systems (sub-tropical ridges) and heightened dry atmospheric conditions associated with more frequent El Niño conditions. The southern shifting highs brought air masses from farther south than in the past. This air was very cold and contributed to frost conditions.

In the WA grainbelt, the data showed there were fewer earlier frosts and a shift to frosts later into the season in the period 1960-2011, but the frost window remained the same length.

The frost window lengthened by three weeks in the Victorian grainbelt and by two weeks in the New South Wales grainbelt.[2]

8.1.2 Frost identification

It is recommended to use accurate paddock-based weather stations or temperature data loggers (such as Tiny Tags and iButtons) to identify if a frost has occurred.

For best results, at least two or three field thermometers are required to give representative temperatures across a crop.

In undulating country, it is advised to use thermometers at various heights in the landscape.

Even if Bureau of Meteorology (BoM) data says the conditions for a frost were not quite reached, it is still worth checking crops.

Minimum air temperatures measured at crop canopy height can sometimes differ by as much as 2-4˚C or more from temperatures recorded at the weather station.[3] Temperatures and other weather conditions typically leading up to a frost are shown in Table 1.

Table 1: Atmospheric conditions leading up to a frost event.[4]

Measurement	3pm -6pm	6pm-9pm	Frost
Temperature at Screen height	16 → 8°C	12 → 6°C	<2°C
Cloud Cover	V low	Low	Nil
Wind Speed	<3 m/s	<1 m/s	0 m/s
Barometric Pressure	1008-1009	1008 — 1009	1004 — 1008

Some crop symptoms will appear in the first 24 hours after a frost event, but most damage will take at least a few days to become apparent.

The more time that passes after the frost event, the easier it will be to observe plant and grain symptoms. But fewer management options may be available.

In frost-prone areas of a farm, particularly low-lying areas, it is advised to inspect cereal heads regularly during the later growing stages to ensure yield losses due to frost are identified well before harvest.

1 GRDC (2016) Tips and Tactics, Managing Frost Risk, GRDC, www.grdc.com.au/ManagingFrostRisk

2 GRDC (2016) Tips and Tactics, Managing Frost Risk, GRDC, www.grdc.com.au/ManagingFrostRisk

3 GRDC (2016) Tips and Tactics, Managing Frost Risk, GRDC, www.grdc.com.au/ManagingFrostRisk

4 GRDC (2016) Tips and Tactics, Managing Frost Risk, GRDC, www.grdc.com.au/ManagingFrostRisk

8.1.3 Tips for measuring temperature

Plant surfaces cool more quickly than the surrounding air, so measuring air temperature is not entirely accurate in determining plant temperature.

Temperature increases above the canopy of a crop and, if the canopy is reasonably developed, it can also rise below the canopy.

Measuring temperature in-crop at weather station height, such as when a Stevenson Screen is installed at 1.4 metres, will not be the same as measuring temperatures at the canopy height or ground level.

Overnight temperatures at ground level (where heat is being lost) can be as much as 4°C lower than those measured in a Stevenson Screen. Differences of 10°C have been recorded.[5]

A typical rule-of-thumb is the canopy temperature will be about 1.5 to 2.5°C lower than the Stevenson Screen temperature during a frost.

Several live weather stations are set up across WA by the Department of Primary Industries and Regional Development (DPIRD) and BoM. These record up-to-the-minute information about climatic conditions and can be readily accessed by growers through the DPIRD website at this link: www.agric.wa.gov.au[6]

Major frost events are recorded by satellites, which provide land surface temperatures. Frost maps (current and historical) are then generated by the Department of Land Information (DLI) and can be viewed at its website at this link www.rss.dola.wa.gov.au.

8.1.4 Frost effects on crops

Figure 1: *variability in the incidence and severity of frost means WA growers are advised to adopt a range of pre-season, in-season, and post-frost event tactics as part of whole-farm management plans.*

(SOURCE: DPIRD)

Wheat plants are most susceptible to frost damage during and after flowering and are also vulnerable at the earlier stages of booting (from Zadoks Growth Scale stage GS39 to GS71).

Losses in wheat grain yield and quality due to frost primarily occur between stem elongation and late grain filling.

5 GRDC (2016) Tips and Tactics, Managing Frost Risk, GRDC, www.grdc.com.au/ManagingFrostRisk

6 Rebbeck, M and Knell, G (2007) Managing Frost Risk: A Guide for Southern Australian Grains, GRDC, https://grdc.com.au/Resources/Bookshop/2007/06/Managing-Frost-Risk-a-guide-for-southern-Australian-grains

Frost damage may be sporadic across a paddock. Not all plants will show obvious symptoms and damage may not be evident until five to seven days after the frost event has occurred.

Frost can affect crops in several complex ways, from cold or chilling to desiccation and — finally — freezing.

This tends to be a 'stepped' response, in that desiccation will not occur without cold damage first and freezing damage will only occur after first experiencing cold and desiccation damage.

Freezing damage tends to be random throughout the crop canopy and tissues, due to the random nature of the ice nucleation and formation.

8.2 Stages of frost damage

Cold

Cold, or chilling, damage occurs when wheat plants are exposed to temperatures less than 10°C and down to –2°C.[7]

If the changes in temperature are sudden, the plant is typically unable to increase the fluidity of membranes (largely made of fats) at the lower temperature and this compromises cellular and plant energy balances.

If this occurs at critical stages in reproductive development, it can cause a few or all florets to abort during pollen development.

The damage is not related to the formation of ice within plant tissue, although it may appear to be.

Desiccation

Desiccation from ice formation occurs at temperatures from 0°C to –2°C.[8]

When plants are exposed to freezing temperatures during a white frost, the dew initially freezes on the outside of the plant, but then the ice nucleation can move in the leaf through cracks in the leaf cuticle and stomata.

The water inside the leaf then starts to freeze. Initially the water around the cells freezes but it then draws out the water from inside the cells and dehydrates them.

The cells may not always freeze or have ice form inside them. This process will not necessarily kill the cells if the dehydration and desiccation do not go too far.

When the ice thaws, these cells can rehydrate and recover — but can still suffer from desiccation.

Freezing

Freezing damage is the final stage of frost damage and occurs when there is rapid ice nucleation and ice crystals form. The ice crystals physically rupture cell walls and membranes.

Freezing damage typically is not reversible, but can be limited to specific tissues in the plants — for example, stem nodes, individual florets and individual tillers.

7 Rebbeck, M and Knell, G (2007) Managing Frost Risk: A Guide for Southern Australian Grains, GRDC, https://grdc.com.au/Resources/Bookshop/2007/06/Managing-Frost-Risk-a-guide-for-southern-Australian-grains

8 Rebbeck, M and Knell, G (2007) Managing Frost Risk: A Guide for Southern Australian Grains, GRDC, https://grdc.com.au/Resources/Bookshop/2007/06/Managing-Frost-Risk-a-guide-for-southern-Australian-grains

8.3 Managing sowing times and the season for frost risk

Sowing time remains a big driver of yield in all crops, with the primary objective in WA conditions being to achieve a balance between the plant flowering after the risk of frost has passed — but before the onset of heat stress.

The potential loss of yield from late sowing to avoid frost risk is often outweighed by the potential gains from sowing on time to reduce heat and moisture stress in spring.

To minimise frost risk, it is advised to use a mix of sowing dates, crop types and maturity types to allow incorporation of 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.

Research trials have found blending a short season wheat variety with a long season variety could be an effective strategy.

But the same effect may be achieved by sowing one paddock with one variety and other paddocks with other varieties to spread risks.

No wheat or barley varieties are tolerant to frost.

It is advised to consider using wheat and barley varieties that have lower susceptibility to frost during flowering to manage frost risk of the cropping program, while maximising yield potential.

Preliminary ranking information for current wheat and barley varieties for susceptibility to reproductive frost, developed through GRDC-funded research, is now available on the National Variety Trials (NVT) website at this link: www.nvtonline.com.au

A new variety is best managed based on how known varieties of similar ranking are currently managed.

MORE INFORMATION

GRDC RCSN Case Study Booklet 'Managing Frost Risk': https://grdc.com.au/ManagingFrostRiskWA

8.4 Risk management tactics for frost

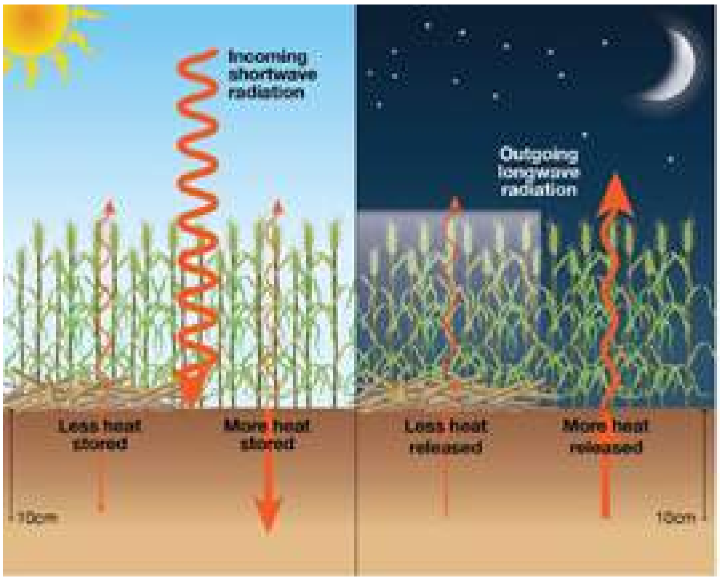
The variability in the incidence and severity of frost means WA growers are advised to adopt a range of pre-season, in-season and post-frost event tactics as part of whole farm management plans and plans for particularly frost-prone areas of farms.

Tactics that may be worth consideration are outlined in Tables 2-5.

Table 2: Pre-season frost risk management strategies.[9]

Assess personal approach to risk
Individuals will each have a different approach
Identify and measure extent of risk
Evaluate risk management alternatives
Tailor risk advice to risk attitude
Review conservative farming practices in light of latest research.
Assess frost risk of property
Consider frost risk for location
Use historic seasonal records and forecasts
Consider spatial variability (topography and soil type) across the landscape
Consider using temperature monitoring equipment (e.g. Tinytags, iButtons and weather stations).
Diversify the business
Consider enterprise options to spread financial risk
Take into account business location and manager skills
Intensive cropping systems can be more at risk of frost.
Zone property/paddock
Identify frost-prone paddocks or areas in paddocks
Precision tools, such as topographic, electromagnetic and yield maps and temperature monitors can locate frost-prone zones
Frost-prone paddocks can be high yielding areas when frosts do not occur
Options for frost-prone zones can be crop grazing, hay or oat production
It may be best to avoid expensive or highly susceptible crops.

Figure 2: *The soil heat bank has an important role in frost risk and damage to cereal crops in WA.*[10]



9 GRDC (2016) Tips and Tactics, Managing Frost Risk, GRDC, www.grdc.com.au/ManagingFrostRisk

10 GRDC (2016) Tips and Tactics, Managing Frost Risk, GRDC, www.grdc.com.au/ManagingFrostRisk

Table 3: In-season frost risk management strategies.[11]

Review nutrient management
Assess nutrient levels using soil and plant tissue testing
Target fertilisers, including nitrogen (N), phosphorus (P), potassium (K), on high-risk paddocks
Consider re-allocating nutrients to lower-risk areas
High levels of N can increase biomass and risk of frost damage
Manage N to frost risk and yield potential
Avoid deficiencies in K or copper (Cu) if possible.
Modify the soil heat bank
This is important in reducing frost risk, as illustrated in Figure 2
Storage and release of heat from the soil heat bank into the crop canopy at night can be manipulated
Practices include clay delving, mouldboard ploughing or spading (primarily used to alleviate water repellency)
Rolling sandy soil and loamy clay soil may reduce frost risk
Lower stubble loads — more than 1.5 tonnes per hectare in low production environments (with average wheat yields of 2-3t/ha) and 3 t/ha in high production environments (with average wheat yields of 3-5 t/ha) can increase frost severity and duration
Cross-sowing/seeding may work in some areas.
Select appropriate crops
Crop type and variety selection is key to managing frost-prone paddocks and zones
Crops grown for hay are harvested for biomass and can reduce grain loss from frost
Pasture rotations are a lower-risk enterprise
Oats are the most frost tolerant crop during the reproductive stage
Barley is more tolerant than wheat at flowering (not necessarily during grain fill)
Decision support tools include: Flower Power (DAFWA) https://www.agric.wa.gov.au/frost/flower-power and Yield Prophet® www.yieldprophet.com.au.
Manipulate flowering times
Ensure flowering windows for wheat are spread widely
Use more than one variety with a range of phenology
Manipulating sowing dates to spread the flowering window
Consider impact of hot, dry finishes due to heat and moisture stress
If sowing more than one variety, sow winter wheat first, then a long season spring wheat (or a day-length-sensitive wheat), then an early maturing wheat
Sowing at the start of a variety's preferred window typically achieves higher yields.
Crop grazing
Key to success is grazing early — start at crop four-five leaf stage or earlier
Graze hard for a short period — may need high stock numbers
Fourteen days of grazing typically delays crop flowering by about seven days
Grazing after first node (GS31) can significantly delay flowering and reduce crop yield so it is best to remove stock before the crop reaches GS31
Crops provide extra fodder for livestock and livestock reduce crop biomass.

11 GRDC (2016) Tips and Tactics, Managing Frost Risk, GRDC, www.grdc.com.au/ManagingFrostRisk

Table 4: Post-frost event frost risk management strategies.[12]

Inspection
Inspect crops after a suspected frost event/s — especially at/after flowering
Collect a (random) sample of heads to estimate yield loss
Monitor for up to two weeks after the event
When damage is estimated, closely analyse options for the affected crop.
Take through to harvest
If frost is prior to/around GS31-GS32, cereals can produce new tillers to compensate for damaged plants (if spring rainfall is adequate)
These may contribute to grain yield
Later frost allows less time for compensatory growth
Undertake gross margin analysis to determine the required grain yield to recover harvesting costs.
Cut and bale
An option when frosts occur at flowering and through grain fill
Assess crops for hay quality within a few days of a frost event
Be prepared to cut a bigger area than originally intended
Can reduce stubble, weed seedbanks and disease loads for the next season
Potential for more rotation options in the following season
Hay production can be expensive — have a path to market or plan for on-farm use.
Grazing, manuring and crop-topping
Grazing frosted crops is an option after a late frost (where chance of plant recovery is low or hay is not an option)
Crop-topping for weed seed control may be incorporated
Ploughing-in/manuring the green crop can return organic matter and nutrients to the soil
Manuring can help manage crop residues, weeds and improve soil fertility
Economics need to be considered carefully.
Harvesting and marketing frosted grain
At flowering — wheat grain is typically aborted and yield reduced, but quality can be high
At watery stage — grain does not develop any solids, frosted grains do not appear in the sample and unfrosted grains can be bigger with high test weight
At milk stage — grains may continue development but be light and shrivelled with low hectolitre weight and high screenings
At late dough stage — grain can be wrinkly/scalloped, have low hectolitre weight and higher screenings and further cleaning may be required
Adjust header settings to maximise quality of grain harvested
Frosted grain in the category 'Dry Green, Sappy and Frost Distorted' has maximum limit of 1 percent in the sample
Samples with 1-10 percent frosted grain is classified as Australian General Purpose (AGP)
Grain exceeding this level will be classified as and suitable for stock feed
Cleaning grain may lead to higher classification — consider economics.

12 GRDC (2016) Tips and Tactics, Managing Frost Risk, GRDC, www.grdc.com.au/ManagingFrostRisk

Retaining seed from frosted crops
Frost at flowering — grain is often plump and makes good quality seed
Frost during grain fill — can lead to poorer seed germination and establishment
If graded, frosted grain can still lead to 20-50 percent lower crop establishment
It may be necessary to retain more seed than usual
Sow into an optimum seed bed and increase seeding rates.

Table 5: Strategies for recovering from frost.[13]

Strategies for recovering from frost
Act early if frost damage has had a serious financial impact.
Prepare a future business plan
Where necessary, seek advice about tactics from advisers and rural counsellors
Communicate and discuss likely impact of frost with financiers
Consider how finances can be adjusted
Assess factually physical, financial and manager/staff implications
Develop alternate strategies for dealing with frosted crops in future
Prepare a draft budget and physical plans for next year
Provide this information to business partners and financiers
Review budgets and plans as information and circumstances change
Be conscious frost can be an emotional rollercoaster and trigger feelings of depression, grief and loss
Maintain contact with family, friends and colleagues
Seek professional advice if necessary
Be aware of the impact on neighbours and the community
Frost can be easily forgotten from one year to the next — don't let early rain distract from having plans in place.

8.5 Research and the GRDC National Frost Initiative (NFI)

In some cases, frost is costing WA growers average yield losses of up to 10-20 percent per year across their total cropping programs in a 10-year period.

The National Frost Initiative (NFI) is a GRDC-funded project tackling frost from several angles to deliver growers a combination of genetic, management and environmental solutions to help mitigate risk.

Projects that come under the multi-disciplinary approach of the NFI include:

1. Genetics

- Developing more frost-tolerant wheat and barley germplasm
- Ranking current wheat and barley varieties for susceptibility to frost.

2. Management

- Developing best practise crop canopy, stubble, nutrition and agronomic management strategies
- Searching for innovative products.

13 GRDC (2016) Tips and Tactics, Managing Frost Risk, GRDC, www.grdc.com.au/ManagingFrostRisk

3. Environment

- Predicting the occurrence, severity and impact of frost events on crop yields and frost events at the farm scale
- Enabling better risk management.

Supported by the NFI, new tools to spatially assess frost risk and pinpoint crop damage rapidly and accurately are being tested by researchers nationally in efforts to improve understanding of frost and effective farm-scale responses.

At sites in WA, South Australia and Victoria, researchers are trialling:

- Satellite and other spatial information to develop high-resolution frost risk maps
- Remote sensing approaches and temperature data loggers to assess and map frost damage in wheat
- A range of platforms for the sensors, including satellite, unmanned aerial vehicles (UAVs), hand-held and static mounted.

There is potential to use the data generated from these sources in paddock zoning and planning, along with other precision agricultural data such as topographic, electro-magnetic and yield maps, temperature monitors and the grower's own experiences in previous seasons.

8.6 Heat stress

Heat and/or drought stress has potential to affect the processing quality of durum wheat.

Nationally, researchers are investigating how to boost wheat plant ability to withstand higher temperatures at development stages that are critical for yield.

This is typically from booting, around August, through anthesis to grain filling, around the end of October.

The optimum ambient temperature for wheat anthesis and grain filling ranges from 12°C to 22°C and exposure to temperatures above this has potential to significantly reduce grain yield.

Heat stress (defined as four consecutive days with maximum daily temperatures above 22°C) is increasingly affecting wheat yield potential in WA — particularly in parts of the northern grainbelt — and 2014 crop losses in this area were severe.[14]

A marked increase in heat stress events during spring since 1975 has been identified in WA's northern agricultural region.[15]

Globally, temperatures are predicted to rise by 2°C by the year 2050 and researchers say growers in some areas will need to adapt to warmer spring temperatures and expected less rainfall.[16]

New adaptations will be required for crop growth, potentially including tolerant varieties, changes of species, shifting planting seasons and a change in management tactics.

8.6.1 Effects of heat stress

Heat stress typically causes a significant reduction in grain number and grain size, the two key wheat yield components.

14 GRDC Ground Cover (2015) Issue 118: Researchers Hope to Take the Heat Off Warm Springs, GRDC, https://grdc.com.au/Media-Centre/Ground-Cover/Ground-Cover-Issue-118-Sep-Oct-2015/Researchers-hope-to-take-the-heat-off-warm-springs

15 GRDC Ground Cover (2015) Issue 118: Researchers Hope to Take the Heat Off Warm Springs, GRDC, https://grdc.com.au/Media-Centre/Ground-Cover/Ground-Cover-Issue-118-Sep-Oct-2015/Researchers-hope-to-take-the-heat-off-warm-springs

16 GRDC Ground Cover (2015) Issue 118: Researchers Hope to Take the Heat Off Warm Springs, GRDC, https://grdc.com.au/Media-Centre/Ground-Cover/Ground-Cover-Issue-118-Sep-Oct-2015/Researchers-hope-to-take-the-heat-off-warm-springs

Some wheat varieties are able to retain grain number and others can retain grain size after heat stress, offering the potential to combine the positive effects of both grain number and grain size to improve heat stress tolerance in future varieties.

National research is being carried out to assess international wheat introductions from regions that experience heat stress.

Screening of this exotic material to date has uncovered promising genetic variation in grain number and size. Crosses have been made and evaluation of gene mapping populations from contrasting lines is being conducted.

8.6.2 Developing heat tolerant wheat

Research is studying wheat traits that are important to heat stress tolerance, undertaking genetic mapping of genomic regions affecting heat tolerance and characterising parents to select for this trait.[17]

Effects of heat on wheat quality traits relating to baking and pasta are also being investigated, along with varieties that have stable quality under heat stress conditions.

The aim is to help wheat breeders develop varieties that are better able to handle the harsh, and generally warming, growing conditions across southern Australia.

Trials have found a 3-5 percent reduction in wheat yield — about 190 kg/ha — for every 1°C increase in temperature above 15°C during flowering and grain filling.[18] This can be day or night-time temperatures.

Studies in 2010-11 showed that, at critical stages, increases in daily minimum temperatures above 20°C could reduce wheat yield more than increases in daily maximum temperatures above 22°C.[19]

The researchers found heat stress increased pollen sterility and reduced grain numbers and size. Therefore, breeders could potentially select for heat tolerance using traits for grain number, size and rate of filling under heat stress.

Research using controlled heat chambers and field trials in SA found significant variation in wheat variety tolerance to heat stress.[20]

Growing locally adapted varieties and ensuring timely sowing suited to their maturity are the best ways growers can reduce the risks of crops being damaged by heat stress in spring.

Later sown crops tend to have more likelihood of being exposed to heat stress at more sensitive growing stages, particularly during flowering and grain filling, and a higher risk of losing yield potential.

Researchers are quantifying the level of heat stress tolerance in current wheat varieties, advanced breeding lines and exotic lines, as well as using 'gene mapping' to understand the genetics of heat tolerance sources identified to date.[21]

The goal is to develop molecular markers allowing plant breeders to easily select for heat tolerance on a large scale.

A wide range of variation for heat stress tolerance has been found in the material screened to date.

17 Telfer, P, Edwards, J, Bennett, D and Kuchel, H (2015) Heat Stress Tolerance of Wheat, GRDC Update Papers, https://grdc.com.au/Research-and-Development/GRDC-Update-Papers/2015/02/Heat-stress-tolerance-of-wheat

18 Telfer, P, Edwards, J, Bennett, D and Kuchel, H (2015) Heat Stress Tolerance of Wheat, GRDC Update Papers, https://grdc.com.au/Research-and-Development/GRDC-Update-Papers/2015/02/Heat-stress-tolerance-of-wheat

19 Telfer, P, Edwards, J, Bennett, D and Kuchel, H (2015) Heat Stress Tolerance of Wheat, GRDC Update Papers, https://grdc.com.au/Research-and-Development/GRDC-Update-Papers/2015/02/Heat-stress-tolerance-of-wheat

20 Telfer, P, Edwards, J, Bennett, D and Kuchel, H (2015) Heat Stress Tolerance of Wheat, GRDC Update Papers, https://grdc.com.au/Research-and-Development/GRDC-Update-Papers/2015/02/Heat-stress-tolerance-of-wheat

21 Telfer, P, Edwards, J, Bennett, D and Kuchel, H (2015) Heat Stress Tolerance of Wheat, GRDC Update Papers, https://grdc.com.au/Research-and-Development/GRDC-Update-Papers/2015/02/Heat-stress-tolerance-of-wheat

Harvest

9.1 Overview

Figure 1: *Durum wheat is a premium product and it is recommended the crop is harvested as soon as the grain reaches 'dead ripe' maturity stage.*

(SOURCE: GRDC)

Durum wheat is a premium product, trading into a high quality food market, and attention to detail at harvest is critical.

It is recommended the crop is harvested as soon as the grain reaches 'dead ripe' maturity stage.

Buyers of durum wheat typically consider grain appearance important and pay premiums for large, well-filled, hard, vitreous grain with a low percentage of mottled and bleached seeds.

Optimising grain quality requires close attention to harvester machine settings, careful segregation and clean, insect-free grain storage. Damaged, contaminated or insect-infested grain will typically be downgraded.[1]

Some durum wheat varieties are marginally more difficult to thresh than others and concave adjustments to the harvester may be necessary.

Durum wheat varieties are not prone to shedding, which can be a significant issue for bread wheats when wind and rain prevail at harvest, but their very hard grain has more tendency to fracture than the grain of bread wheats.[2]

MORE INFORMATION

Grain Trade Australia Wheat Trading Standards, 2016/17 season: http://www.graintrade.org.au/sites/default/files/Section_02-Wheat_Trading_Standards_2016-2017.pdf

GRDC 'Stored Grain' hub: www.storedgrain.com.au

GRDC Fact Sheet 'Grain Marketing and Pesticide Residues': www.grdc.com.au/GRDC-FS-ManagingMRLs

1 Hare, R (2006) Agronomy of the Durum Wheats Kamilaroi, Yallaroi, Wollaroi and EGA Bellaroi, Primefacts 140, NSW Department of Primary Industries, http://www.dpi.nsw.gov.au/__data/assets/pdf_file/0007/63646/Agronomy-of-the-durum-wheats---Primefact-140-final.pdf

2 Hare, R (2006) Agronomy of the Durum Wheats Kamilaroi, Yallaroi, Wollaroi and EGA Bellaroi, Primefacts 140, NSW Department of Primary Industries, http://www.dpi.nsw.gov.au/__data/assets/pdf_file/0007/63646/Agronomy-of-the-durum-wheats---Primefact-140-final.pdf

MORE INFORMATION

DPIRD 'Wheat Grain Quality — Falling Number and Sprouting Tolerance': https://agric.wa.gov.au/n/3124

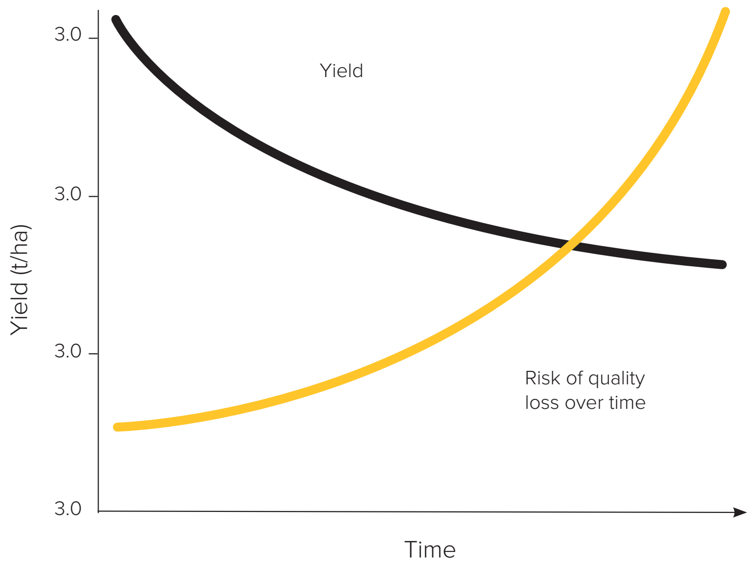
9.2 Managing a wet harvest

To optimise grain quality, harvest of durum wheat ideally needs to start as soon as the crop is mature.

Harvest can (in theory) start as soon as grain moisture content falls below about 20 percent, although receival standards dictate a grain moisture content of 12.5 percent on delivery.

For each day a mature wheat crop remains in the paddock, it is exposed to ongoing yield and quality loss. This, in turn, impacts on returns, as illustrated in Figure 2.

Figure 2: *Impact of a delayed harvest on wheat yield and quality.*[3]



Rain during the harvest period impacts on grain quality through the development of mould and fungi, darkening of the grain and/or stimulation of germination (sprouting).

Sprouting uses the grain's energy stores and reduces bulk density, weight and ultimately yield. Yield losses of 10-50 percent have been recorded in years with exceptional sprouting events.[4]

Although durum wheat varieties have slightly better resistance to pre-harvest sprouting than current bread wheat lines, they can be downgraded to feed due to bleaching and softening of the grain in prolonged wet harvest conditions.

Weather-affected grain that is soft reduces the semolina extraction in the mill and results in low pasta dough strength due to the partial enzymatic breakdown of starches and proteins.

It is not advisable to leave durum wheat crop harvest until last in the program, relying on the crop's weathering resistance. This resistance is only relative to other varieties and can eventually fail. Weathered durum wheat grain is not as valuable as premium durum wheat grain and may be received as feed grain.

Weather-damaged grain can be retained and dried for planting the following year, provided there is no sign of embryo development (in the form of shoots and/or roots).

There are several methods to deal with high moisture grain at harvest, as outlined below, and the key is to act quickly and effectively.

3 DPIRD 'Wheat Grain Quality — Falling Number and Sprouting Tolerance': https://agric.wa.gov.au/n/3124

4 Metz, N (2006) The WA Guide to High Moisture Harvest Management, Grain Storage and Handling, CBH Group and The South East Premium Wheat Growers Association, http://catalogue.nla.gov.au/Record/4227397

Blending

- High-moisture grain is mixed with lower-moisture grain
- This creates a sample with acceptable moisture content
- Cost-effectively manages grain batches slightly above 12.5 percent moisture.

Aeration cooling

- For grain with moderate moisture content (up to 15 percent)
- Allows holding for a short time until drying equipment is available.

Aeration drying

- Big volumes of air force a drying front through the stored grain
- This slowly removes moisture
- Supplementary heating can be added
- Can be combined with blending and aeration cooling
- Can handle grain up to 18 percent moisture content
- Requires significant capital investment.

Continuous flow drying

- Grain is transferred through a dryer
- Uses a high volume of heated air to pass through the grain.

Batch drying

- Typically uses a transportable trailer
- Can dry 10-20 tonnes of grain at a time
- Uses a high volume of heated air
- Air passes through the grain and out of perforated walls.

Capital invested in managing high-moisture grain (such as for a grain dryer) is best considered on a per hectare basis in the context of the whole harvest program.

Analysis of costs per tonne in isolation can be misleading.

9.2.1 Harvesting high moisture grain

Harvesting crops with high moisture content requires careful machinery set-up and operation. High-moisture crops are heavier and more pliable in cool, damp conditions and typically do not break up as easily during threshing.

High-moisture crops tend to require slightly harder threshing and the grain sieves of harvesting machines can experience heavier loads. This can slow harvesting capacity and increase fuel consumption.

Green or damp straw puts an additional load on harvester knives and dry matter can build up under the knife fingers. Slowing the ground speed or lowering the cutter height can help. This allows the crop to receive more threshing attention and the grain cleaning sieves are not placed under as much load.

Stripper fronts (purpose-built header fronts which strip the crop head from the stalk rather than cutting it) can prove more effective in consistently damp conditions in some areas.

9.2.2 Pre-sprouting

Figure 3: *Durum wheat can be susceptible to sprouting damage if harvest conditions are conducive.*

(SOURCE: GRDC)

The susceptibility of durum wheat varieties to sprouting damage is due to a combination of several traits. Grain dormancy — the ability to resist germinating when water is absorbed — is the most important of these.[5]

Other traits impacting on sprouting damage include:

- Seed coat dormancy
- Dormancy inhibitors released from the glumes when wet
- Rate of water absorption
- Attributes that relate to the structure of the wheat head.

Historically, the term 'sprouting tolerance' has been associated with germination index (GI) because this has been regarded as the most important and easily measured trait. Unfortunately, experience shows that GI does not always provide an accurate indication of what will happen in the field after a rainfall event.

9.2.3 Falling number index

The response of durum wheat varieties to wet harvest conditions is measured by falling numbers (FN) at grain delivery. The falling number test provides an indication of the amount of sprouting damage that has occurred in a wheat sample.

Wheat varieties are rated for ability to maintain FN after rainfall events leading up to harvest.

The falling number index (FNI) encompasses GI and other attributes, such as head structure.[6]

On a scale of one to nine, the higher the FNI, the more likely a variety is to maintain FN (and the lower the susceptibility to sprouting leading up to harvest).

The highest FNI of currently available for WA wheat varieties (as at 2016) is seven.[7]

MORE INFORMATION

DPIRD 'Wheat Grain Quality: Falling Number and Sprouting Tolerance'
https://agric.wa.gov.au/n/3124

5 Hare, R (2006) Agronomy of the Durum Wheats Kamilaroi, Yallaroi, Wollaroi and EGA Bellaroi, Primefacts 140, NSW Department of Primary Industries, http://www.dpi.nsw.gov.au/__data/assets/pdf_file/0007/63646/Agronomy-of-the-durum-wheats---Primefact-140-final.pdf

6 Grain Trade Australia (2016-17), Guide to the GTA Grain Trading Standards, GTA, http://www.graintrade.org.au/commodity_standards

7 DPIRD, Wheat grain quality — falling number and sprouting tolerance, 2017, https://www.agric.wa.gov.au/wheat/wheat-grain-quality-falling-number-and-sprouting-tolerance?page=0%2C1

9.2.4 Protein content

Protein content is an important factor in grain classification of durum wheat at receival and can be affected by weather at harvest.

Classifications and premiums are:

- Australian durum 1 (ADR1) attracts a premium similar to Australian Prime Hard (APH), or better
- Australian durum 2 (ADR2) attracts a premium similar to Australian Hard (AH), or better.[8]

Grain from durum wheat varieties with adequate protein is very hard, vitreous and free from mottling. A shortage of protein will give a mottled, softer grain.

For milling, a small percentage of mottled grains can be tolerated in top grades. But a higher proportion will result in downgrading to a 'flour' or 'fines' formation, which has a lower economic value than that of semolina.

9.2.5 Black point

Black point is a dark discoloration at the germ end of otherwise healthy grain.

Research suggests it is not a disease caused by fungi, but a physiological character resulting from the formation of dark compounds in the outer layers of the grain. Some varieties are more prone to develop these dark compounds in warm and moist conditions.

In wheat, the discoloration occurs in the outer portions of the seed and — in some severe cases — may extend along the groove on the underside of the grain.

While durum wheat varieties vary in their tolerance to black point, they are more resistant to black point than bread wheat. But this may not offer sufficient protection in prolonged wet seasons.

It is advised to ensure all grain handling equipment, such as headers, bins, augers and silos, are free from contaminant grain.

The presence of foreign seeds (such as a maximum 3 percent bread wheat seed) can downgrade durum wheat grain.

A small percentage of discoloured seeds can be present after a wet pre-harvest period, when black point is most active. This level of incidence is typically below the minimum dockage limits in most seasons.

Black point tolerance is 3 percent for ADR1 and 3-5 percent for ADR2 and ADR3.[9] Because small fragments of bran are included in semolina, discoloured grain can leave small black specks that can be seen in the pasta.[10]

However, if retained for seed, grain with black point will typically germinate satisfactorily the following year.

9.2.6 Retaining seed

Durum wheat seed is, on average, about 20 percent bigger than bread wheat seed. The sowing rate for durum wheat varieties should be adjusted based on 1000 grain weight data to sow 100 seeds per square metre (in low rainfall zones) or 120-150 seeds/m^2 (in medium-high rainfall zones).[11]

A higher planting rate may be beneficial in some situations, such as when using seed with a low germination or when early or late sowing.

MORE INFORMATION

GRDC Fact Sheet 'Retaining Seed': www.grdc.com.au/GRDC-FS-RetainingSeed

8 Hare, R (2006) Agronomy of the Durum Wheats Kamilaroi, Yallaroi, Wollaroi and EGA Bellaroi, Primefacts 140, NSW Department of Primary Industries, http://www.dpi.nsw.gov.au/__data/assets/pdf_file/0007/63646/Agronomy-of-the-durum-wheats---Primefact-140-final.pdf

9 Hare, R (2006) Agronomy of the Durum Wheats Kamilaroi, Yallaroi, Wollaroi and EGA Bellaroi, Primefacts 140, NSW Department of Primary Industries, http://www.dpi.nsw.gov.au/__data/assets/pdf_file/0007/63646/Agronomy-of-the-durum-wheats---Primefact-140-final.pdf

10 Hare, R (2006) Agronomy of the Durum Wheats Kamilaroi, Yallaroi, Wollaroi and EGA Bellaroi, Primefacts 140, NSW Department of Primary Industries, http://www.dpi.nsw.gov.au/__data/assets/pdf_file/0007/63646/Agronomy-of-the-durum-wheats---Primefact-140-final.pdf

11 Hare, R (2006) Agronomy of the Durum Wheats Kamilaroi, Yallaroi, Wollaroi and EGA Bellaroi, Primefacts 140, NSW Department of Primary Industries, http://www.dpi.nsw.gov.au/__data/assets/pdf_file/0007/63646/Agronomy-of-the-durum-wheats---Primefact-140-final.pdf

Conventional sowing equipment can be used for durum wheats, but the bigger seed size may necessitate machinery adjustments.

To optimise seed germination and vigour, it is advised to use seed that is:

- True to type (varietal purity)
- Free of diseased seed and weed seeds
- Not cracked or containing small grains
- Not contaminated with barley and bread wheat grain
- High quality, preferably from certified seed stocks
- Has a germination percentage more than 80 percent.

When harvesting durum wheat paddocks for retained seed to use the following season, it is best to avoid paddocks with rogue off-types, contaminant crops or high weed burdens.

Seed grain for sowing in subsequent seasons is ideally stored in clean silos that can be aerated, are sealed for insect control and keep grain as dry and as cool as possible.

Such storage conditions will assist in the maintenance of high-viability seed for the following season.

It is advised to treat seed with an appropriately registered product just prior to sowing to control smut and bunt. Seed treatments can also offer protection to establishing seedlings from damping-off diseases.

It is worth noting that some chemical constituents have potential to reduce seed viability and seedling vigour if in contact with the seed for any length of time.

If durum wheat crops are weather damaged, some grain may still be viable as seed for the subsequent cropping season — provided any damaged seed dries out before the embryo starts to grow.[12]

Mild damage often appears as a loose and wrinkled seed coat. Severe damage can be identified through stained seed or signs of germination.

It is essential to determine whether the damage is cosmetic, or the symptom of a seed-borne disease, and whether it will impact on germination.

It is advisable to test and grade any retained seed for germination, vigour and disease pathogens.

Knowing the germination percentage of grain at harvest will help determine how much extra seed may be required at sowing. A germination test before sowing can enable sowing rates to be adjusted accordingly.

Achieving and maintaining low temperature, humidity and grain moisture levels for stored grain is important.

Damaged grain and grain retained for seed is best used within 12 months.[13]

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12 GRDC (2011) Fact Sheet — Retaining Seed, GRDC, www.grdc.com.au/GRDC-FS-RetainingSeed

13 GRDC (2011) Fact Sheet — Retaining Seed, GRDC, www.grdc.com.au/GRDC-FS-RetainingSeed

MORE INFORMATION

GRDC 'Stored Grain' hub: http://storedgrain.com.au/

GRDC 'Grain Storage Workshops': http://storedgrain.com.au/events/category/western-region/

GRDC Back Pocket Guide 'Stored Grain Pests Identification': http://storedgrain.com.au/stored-grain-pests-identification-the-back-pocket-guide-2011/

9.3 Grain storage

Figure 4: *An on-farm storage system designed to promote good grain hygiene, including aeration and sealable silos for fumigation, is a valuable tool to maximise returns from durum wheat.*

(SOURCE: GRDC)

An on-farm storage system designed to promote good grain hygiene, including aeration and sealable silos for fumigation, is valuable to maximise returns from growing durum wheat.

Increasingly, WA growers are storing grain for up to 12 months to expand their marketing options. To do this effectively, the storage system needs to be set up to allow effective control of stored grain insect pests and maintain grain quality. Gas-tight, sealed and aerated storage is the best way to achieve this. Fumigating the grain (if necessary) kills any insects present and the aeration maintains grain quality. In a gas-tight sealed silo, grain can be fumigated effectively providing quick, inexpensive and long-lasting insect control.[14]

Actives that can be used in grain storage systems for pest control include (but are not restricted to):

- Chloropicrin
- Chlorpyrifos
- Deltamethrin
- Dichlorvos
- Ethyl formate
- Fenitrothion
- Maldison
- Methoprene
- Methyl bromide
- Phosphine
- Pirimiphos-methyl
- Spinosad
- Sulfuryl fluoride
- Triflumuron.

14 GRDC (2014) Fact Sheet — Grain Storage: Grain Fumigation Guide, GRDC, www.grdc.com.au/GRDC-FS-GrainFumigationGuide

Other registered treatments for grain storage include inert dusts, such as Amorphous silica and Diatomaceous earth (DE).

Although not fumigants, there are several seed treatments registered for control of grain storage pests, including:

- Imidacloprid (+fungicide active)
- Cypermethrin (+fungicide active)
- Triflumuron (+fungicide active).

Similarly to any piece of farm equipment, gas-tight sealed silos need to be well maintained to work efficiently.

It is recommended to check seals before each filling and replace these if worn or damaged. Always pressure test the silo to ensure it is sealed.

In conjunction with sound management practices, including checking grain temperatures and regular monitoring for insect infestations, an on-farm storage system that is well designed and maintained and correctly operated provides the best insurance for production of quality grain.

9.3.1 Types of on-farm storage

It is advised to conduct a cost:benefit analysis before investing in on-farm grain storage infrastructure.

Post-harvest can be a good time to plan future requirements, as grain storage issues and opportunities can be most easily identified at this stage of the season.[15]

The advantages and disadvantages of the main types of on-farm grain storage options are outlined in Table 1.

15 White, B (2012) Grain Storage Facilities — Planning for Efficiency and Quality, GRDC, www.grdc.com.au/GRDC-Booklet-GrainStorageFacilities

Table 1: Advantages and disadvantages of grain storage options.[16]

Storage type	Advantages	Disadvantages	More information
Gas-tight sealable silo	Gas-tight sealable status allows phosphine and controlled atmosphere options to control insects. Easily aerated with fans. Fabricated on-site or off-site and transported. Capacity from 15 tonnes up to 3000 tonnes. Up to 25 year plus service life. Simple in-loading and out-loading. Easily administered hygiene (cone base particularly). Can be used multiple times inseason.	Requires foundation to be constructed. Relatively high initial investment required. Seals must be regularly maintained. Access requires safety equipment and infrastructure. Requires an annual test to check gas-tight sealing.	http://storedgrain.com.au/managing-sealed-unsealed-storage/ http://storedgrain.com.au/stored-grain-silos-fumigation/ http://storedgrain.com.au/pressure-testing/ http://storedgrain.com.au/silo-pressure-test-demonstration/ http://storedgrain.com.au/national-standard-sealed-silos/
Non-sealed silo	Easily aerated with fans. 7–10% cheaper than sealed silos. Capacity from 15 tonnes up to 3000 tonnes. Up to 25 year plus service life. Can be used multiple times inseason.	Requires foundation to be constructed. Silo cannot be used for fumigation. Insect control options limited . Access requires safety equipment and infrastructure.	http://storedgrain.com.au/managing-sealed-unsealed-storage/
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 all ground operated. Can accommodate high-yielding seasons.	Requires loader and unloader. Increased risk of damage beyond short-term storage (typically three months). Limited insect control options, fumigation only possible under specific protocols. Requires regular inspection and maintenance which needs to be budgeted for. Aeration of grain in bags currently limited to research trials only. Must be fenced off from livestock. Prone to attack by mice, birds, foxes etc. Limited wet weather access if stored in paddock. Single use only — need to dispose of bag after use.	http://storedgrain.com.au/successful-storage-in-grain-bags/ http://storedgrain.com.au/wp-content/uploads/2013/06/Insects-apest-in-harvest-bags.pdf
Grain storage sheds	Multi-purpose infrastructure. 30 year plus service life. Low cost per stored tonne. Aeration systems require specific design.	Risk of contamination from alternative purpose use. Difficult to seal for fumigation. Vermin control is difficult. Limited insect control options. Difficult to unload	http://storedgrain.com.au/managing-sealed-unsealed-storage/
Underground storage	Inexpensive and simple. Provides ideal insect control by excluding air. Can maintain grain quality during long-term storage.	Poor site selection and management can affect grain quality.	https://www.agric.wa.gov.au/barley/underground-storage-grain

16 White, B (2012) Grain Storage Facilities — Planning for Efficiency and Quality, GRDC, www.grdc.com.au/GRDC-Booklet-GrainStorageFacilities

Silos are the most common method of storing grain on-farm in Australia. These come in a variety of configurations, including flat-bottom or cone base, and are available as gas-tight sealable or non-sealed and aerated or non-aerated.

Other options include grain storage bags, bunkers and sheds.

Grain storage bags are increasing in popularity as a short-term storage solution to assist with harvest logistics. With careful management, growers can also use storage bags to provide short-term marketing opportunities.

Where options are limited, well-prepared sheds can be used to store grain during harvest, offering a similar storage time to grain storage bags.

MORE INFORMATION

GRDC Stored Grain 'Economics of On-Farm Grain Storage, Cost Benefit Analysis': http://storedgrain.com.au/economics-booklet/

9.3.2 Economics of grain storage

When making decisions about storage infrastructure, it is important to compare the expected returns from grain storage versus expected returns from other farm business investments, such as more land, a chaser bin, a wider boomspray, a second truck or paying-off debt.

Calculating the costs and benefits of on-farm storage will deliver a return-on-investment (ROI) value that can be compared with other investment choices.

To make a viable decision, it is necessary to realistically determine costs and benefits on a dollars per tonne ($/t) basis. For example, grain market projections are fraught with difficulty and are best kept conservative.

A more realistic approach is to use averages based on medium to long-term trends. Many growers who invest in on-farm grain storage have paid for the infrastructure in one or two years because they can sell into the market at its peak.

MORE INFORMATION

GRDC Stored Grain 'Insect Control': http://storedgrain.com.au/category/information-hub/insect-control/

GRDC Fact Sheet 'Grain Storage — Stored Grain Pests — Identification, Western': www.grdc.com.au/GRDC-FS-StoredGrainPestID

Plant Biosecurity CRC: 'An Integrated Approach to Manage Pests and Resistance to Phosphine in Stored Grain': http://www.pbcrc.com.au/research/project/3150

9.3.3 Grain storage pests

Grain for human consumption (especially export grain) must not contain live insects. If stored grain is not properly managed, it can become infested with stored grain insect pests.

Grain Trade Australia (GTA) has nil tolerance to live, stored grain insects for all grades of wheat — from premium milling grades to feed. GTA also stipulates standards for heat-damaged, bin-burnt, storage mould-affected or rotten wheat, all of which can result in the discounting or rejection of grain.[17]

Effective management of stored grain can help to eliminate these risks to wheat quality.

Hygiene, aeration and cooling are the three critical management tools for successful insect control in on-farm grain storage. Regular inspection of storage facilities will provide an early warning of any insect infestation.[18]

Protecting any stored grain from insect attack makes economic sense because even feed grain can lose value though loss of protein or palatability which can affect livestock growth rates.

Retained seed is next year's investment and if insects are present they can destroy the germ of the grain.

The most common insect pests of stored cereal grains in Australia include:

- Weevils (*Sitophilus spp.*) — Rice weevil is most common in wheat
- Lesser grain borer (*Rhyzopertha dominica*)
- Rust-red flour beetle (*Tribolium spp.*)
- Saw-toothed grain beetle (*Oryzaephilus spp.*)
- Flat grain beetle (*Cryptolestes spp.*)
- Indian meal moth (*Plodia interpunctella*)
- Angoumois grain moth (*Sitotroga cerealella*).

17 Grain Trade Australia (2016-17), Guide to the GTA Grain Trading Standards, GTA, http://www.graintrade.org.au/commodity_standards

18 GRDC (2013) Fact Sheet — Grain Storage Pest Control Guide, Western Region, GRDC, www.grdc.com.au/GRDC-FS-GrainStoragePestControl

9.3.4 Managing stored grain pests — hygiene

A combination of meticulous grain hygiene, well managed aeration cooling and correct fumigation (if necessary) typically overcomes 85 percent of grain storage pest problems and helps to maintain grain quality.[19]

The first grain harvested is often at the highest risk of early insect infestation due to contamination of equipment.

It is advised to remove grain residues from empty storages and grain handling equipment, such as harvesters, field bins, augers and silos, to facilitate an uncontaminated start for new season grain.

Equipment can be cleaned by blowing or hosing out residues and dust and then using a structural treatment if needed.

Inert dusts, such as Dryacide®, Absorba-Cide®, Cut 'N Dry™ and Perma-Guard®, can be used to treat the header, storage and handling equipment for residual control. Always read and follow label directions.[20]

It is also recommended to remove and discard any grain left in hoppers and bags from the grain storage site so this material does not provide a habitat for pests during the off-season.

9.3.5 Managing stored grain pests — aeration cooling

Freshly harvested grain typically has a temperature of about 30°C, which is ideal for breeding of storage pests — as shown in Table 2 — and can reduce germination of retained seed.

Table 2: The effect of grain temperature and moisture on stored grain insect and mould development.[21]

Grain temperature (°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 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

Research has shown rust-red flour beetles typically stop breeding at storage temperatures of about 20°C, lesser grain borers at about 18°C and other storage pests at about 15°C or lower.[22]

It is advised to aim for stored grain temperatures of less than 23°C during summer months and less than 15°C during winter using aeration fans in storage systems. Research has found grain temperatures below 20°C can significantly reduce mould growth and insect development.[23]

19 Botta, P (2016) On Farm Grain Storage Creating Value for the Business, GRDC Update Papers, https://grdc.com.au/Research-and-Development/GRDC-Update-Papers/2016/07/On-farm-grain-storage-creating-value-for-the-business

20 Botta, P (2016) On Farm Grain Storage Creating Value for the Business, GRDC Update Papers, https://grdc.com.au/Research-and-Development/GRDC-Update-Papers/2016/07/On-farm-grain-storage-creating-value-for-the-business

21 GRDC (2013) Fact Sheet — Grain Storage Pest Control Guide, Western Region, GRDC, www.grdc.com.au/GRDC-FS-GrainStoragePestControl

22 Botta, P (2016) On Farm Grain Storage Creating Value for the Business, GRDC Update Papers, https://grdc.com.au/Research-and-Development/GRDC-Update-Papers/2016/07/On-farm-grain-storage-creating-value-for-the-business

23 Botta, P (2016) On Farm Grain Storage Creating Value for the Business, GRDC Update Papers, https://grdc.com.au/Research-and-Development/GRDC-Update-Papers/2016/07/On-farm-grain-storage-creating-value-for-the-business

9.3.6 Managing stored grain pests — insect control

Phosphine — sold in solid formulation of aluminium phosphide (AlP), under trade names such as Phostoxin® or Fumitoxin® — is the most common disinfestation treatment for insect pests in stored grain.[24]

Fumigating storage facilities with phosphine is a common component of many integrated pest control strategies.

But phosphine resistance in grain storage pests is widespread and phosphine should only be used in a pressure-tested, sealed silo.

Effective phosphine fumigation typically requires seven days when storage temperatures are above 25°C and 10 days when temperatures are 15-25°C. But always check the product label.[25]

Grain protectants Conserve Plus and K-Obiol®Combi are registered for use in WA — but by bulk handlers only. These products have strict application requirements that must be adhered to.

Insect infestations tend to be unevenly distributed in a silo but these pests seek out the most favourable places, such as the grain peak and around hatches where moisture can get in. If insects are found, or damage is detected, it is advised to treat the infestation. If grain is infested, the only way to eradicate insects is by fumigation.

Any grain found with holes is an indication that primary pests, such as the lesser grain borer or the rice weevil, have infested the grain. Correct insect identification is important to determine a suitable control tactic.

It is imperative any system that has some gas-tight sealed storage meets a standard pressure test. New grain storage facilities must meet Australian Standard AS 2628-2010 (Sealing requirements for storage control) to provide confidence that they are gas-tight.[26]

Research shows fumigation of grain storage that is not pressure sealed does not achieve a high enough concentration of fumigant for long enough to kill pests at all life cycle stages.[27]

In a gas-tight sealed silo, grain can be fumigated effectively and provide quick, inexpensive and long-lasting insect control. Market flexibility is enhanced because grain is stored residue-free.

24 Botta, P (2016) On Farm Grain Storage Creating Value for the Business, GRDC Update Papers, https://grdc.com.au/Research-and-Development/GRDC-Update-Papers/2016/07/On-farm-grain-storage-creating-value-for-the-business

25 Botta, P (2016) On Farm Grain Storage Creating Value for the Business, GRDC Update Papers, https://grdc.com.au/Research-and-Development/GRDC-Update-Papers/2016/07/On-farm-grain-storage-creating-value-for-the-business

26 Botta, P (2016) On Farm Grain Storage Creating Value for the Business, GRDC Update Papers, https://grdc.com.au/Research-and-Development/GRDC-Update-Papers/2016/07/On-farm-grain-storage-creating-value-for-the-business

27 Botta, P (2016) On Farm Grain Storage Creating Value for the Business, GRDC Update Papers, https://grdc.com.au/Research-and-Development/GRDC-Update-Papers/2016/07/On-farm-grain-storage-creating-value-for-the-business

9.3.7 Managing stored grain pests — phosphine resistance

An almost total reliance on phosphine through the value chain puts WA at risk of the evolution of pest resistance.

Since 1982, an extensive phosphine resistance monitoring and management program has been in place.

This program involves grain insect samples from across WA being submitted by CBH Group, or collected by a network of DPIRD field staff, for resistance testing.

Insects are initially screened for phosphine resistance with a 30-minute 'Reichmuth' test, followed by tests designed to detect high resistance (if necessary).

During 2013-14, sampling found 60 percent of the 251 strains received for high resistance testing showed positive results (compared with 58 percent and 252 strains during 2013).[28]

Eradication involves regular insect trapping, sampling and resistance monitoring on an ongoing basis to ensure strongly resistant strains are completely controlled.

Many WA growers are now investing in large capacity (often up to 1500 t), flat bottom silos for storing grain on-farm.

Researchers are investigating if label directions for phosphine are appropriate for these bigger storage facilities, as these were first compiled in the 1970s (based on smaller storage facilities).

Key findings from fumigations in 1400 t silos carried out through this project include:

- Recirculation facilitates gas distribution in large silos
- Fumigation in large silos without recirculation leads to lower concentrations in the silo base — reducing effectiveness
- Peak concentration of phosphine typically occurs between day four and six and then drops
- The current pressure half-life standard (AS2628) of five minutes is appropriate for large silos and vital for effectiveness
- Fumigations are likely to fail where there are points of gas or fresh air leaks in a silo
- Pressure testing prior to fumigation is a vital step to identify and locate gas leaks.[29]

28 DPIRD (2016) Stored Grain Insect Resistance Monitoring and Management, DAFWA, https://www.agric.wa.gov.au/exporting-western-australia/stored-grain-insect-resistance-monitoring-and-management

29 Ridley, A, Burrill, P and Collins, P (2016) Killing Storage Pests Without Mercy, Queensland Department of Agriculture and Fisheries, GRDC Update Papers, https://grdc.com.au/Research-and-Development/GRDC-Update-Papers/2016/06/Killing-storage-pests-without-mercy

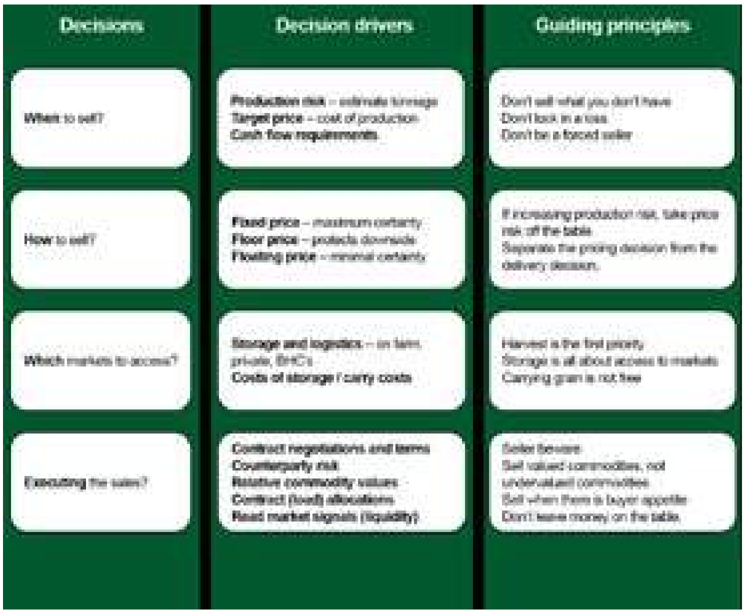
Grain Marketing

Information and tables for this chapter were produced and supplied by Profarmer Australia

10.1 Overview

The final step in generating farm income is converting tonnes of grain produced into dollars at the farm gate. This chapter provides best-in-class marketing guidelines for managing price variability to protect income and cash-flow. It outlines the decisions to be made, the drivers behind the decisions and the guiding principles for each decision point, as illustrated in Figure 1.

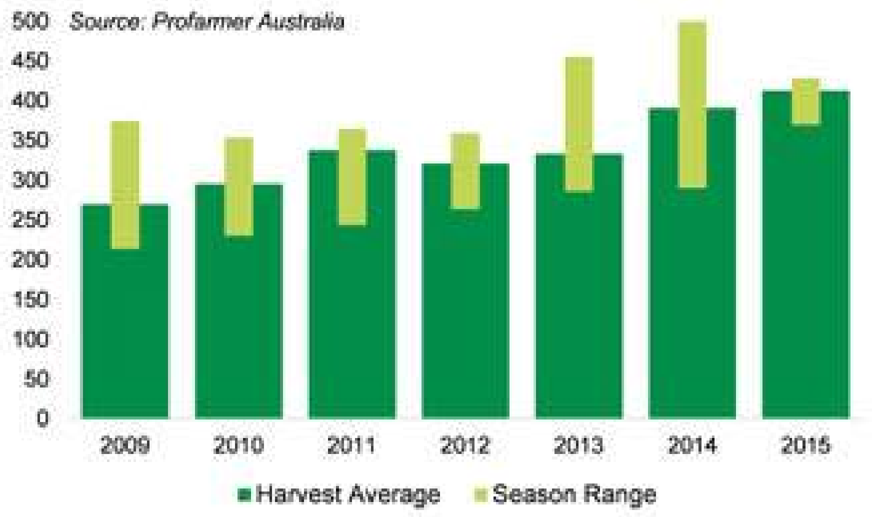
Figure 1: *Grain Selling – best practice in conversion of tonnes to dollars.*



Note to figure: References are made to the section of the GrowNotes™ you will find the detail.

As shown in Figure 2, Port Adelaide durum wheat values have varied by $100 to $310 per tonne during the past seven years (representing a variability of 35-80 percent). For a property producing 500 tonnes of durum wheat, this means a $50,000-$155,000 difference in income (depending on timing of sales).

Figure 2: *Intra-season variance of Port Adelaide Durum values.*



10.2 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 unknowns to establish the target price and then working toward achieving that target price.

Unknowns 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 the grower's control and difficult to predict.

The skills growers have developed to manage production unknowns can be used to manage pricing unknowns. This guide will help growers manage and overcome price uncertainty.

10.2.1 Be prepared

Being prepared and having a selling plan is essential for managing uncertainty. The steps involved are forming a selling strategy and a plan for effective execution of sales.

A selling strategy consists of when and how to sell.

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.

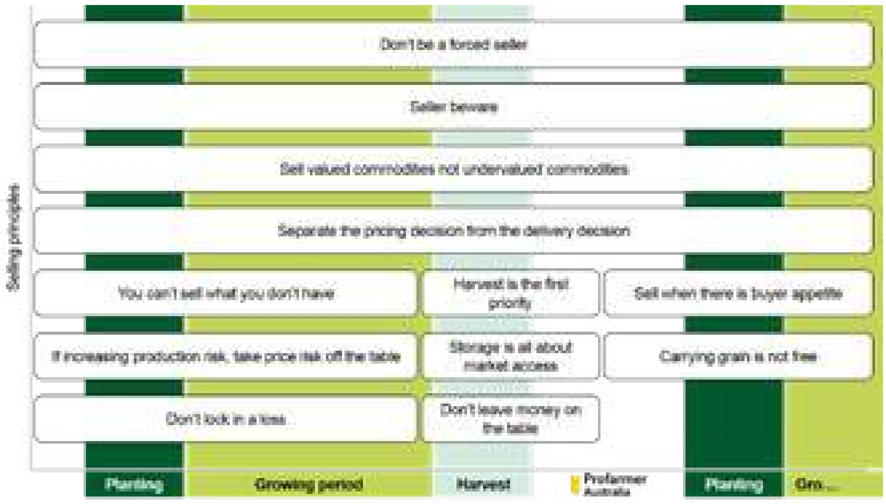
How to sell

This is more dependent on external market factors including:

» Time of year (determines the pricing method)
» Market access (determines where to sell)
» Relative value (determines what to sell).

The key selling principles when considering sales during the growing season and production cycle of the crop are outlined in Figure 3.

Figure 3: *Grower commodity selling principles timeline.*

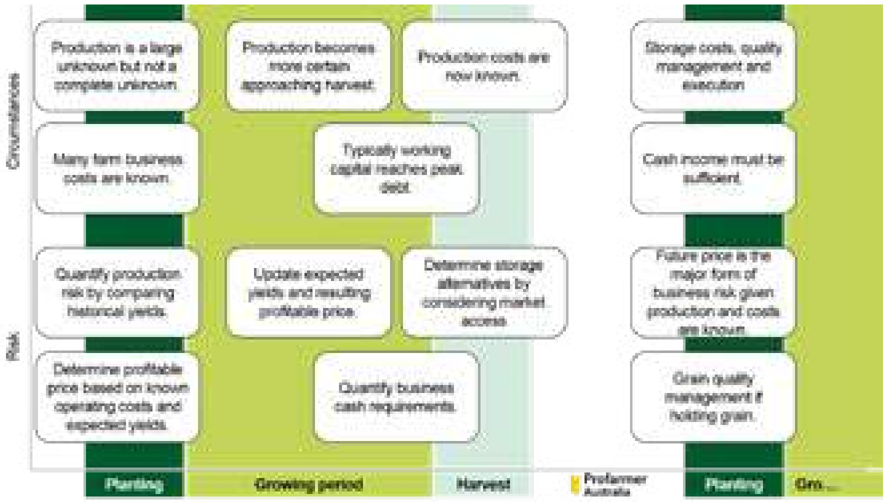


Note to figure 3: The illustration demonstrates the key selling principles throughout the production cycle of a crop.

10.2.2 Establish a business risk profile – when to sell

Establishing a 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 and how to quantify those risks during the production cycle are described in Figure 4.

Figure 4: *Typical farm business circumstances and risk.*



A grower's decision making process for determining when to sell grain will be typically dependent on:

- Does production risk allow sales?
- What portion of production risk allows sales?
- Is the price profitable?
- Are business cash requirements being met?

10.2.3 Production risk profile of the farm

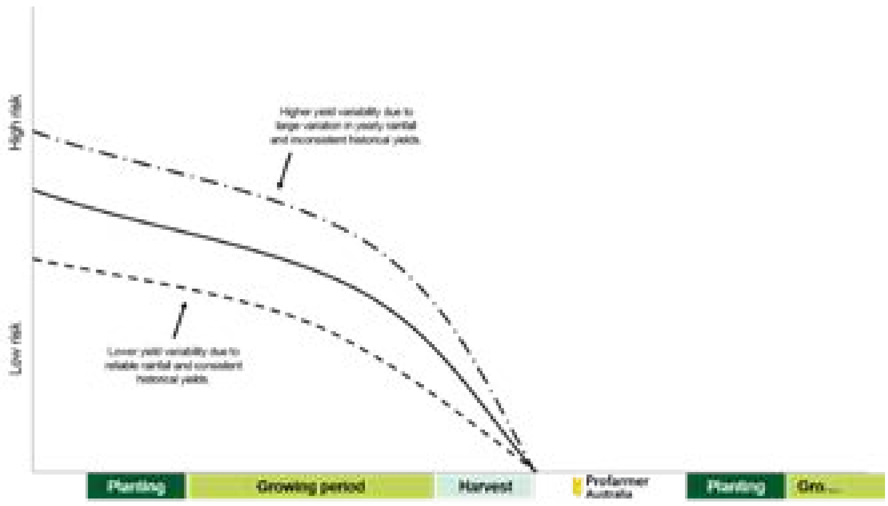
Production risk is the level of certainty around producing a crop and is influenced by location (including climate and soil type), crop type, crop management and time of year.

The general principle is you can't sell what you don't have and it is important to not increase business risk by over-committing production.

Establish a production risk profile, such as that outlined in Figure 5, by:

- Collating historical average yields for each crop type
- Collating a below average and above average historical yield range
- Assessing the likelihood of achieving the average based on recent seasonal conditions and seasonal outlooks
- Revising production outlooks as the season progresses.

Figure 5: *Typical production risk profile of a farm operation.*



As shown in Figure 5, the quantity of crop grown is a large unknown early in the year. However, it is 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 factors including rainfall, yield potential soil type and commodity prices.

10.2.4 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.

The principle is don't lock in a loss. If a grower is committing production ahead of harvest, ensure the price is profitable.

Steps to calculate an estimated profitable price based on total cost of production and a range of yield scenarios is outlined in Figure 6 and more information is provided in the Grains Research and Development Corporation (GRDC) 'Farming the Business' manual. This resource also provides a cost of production template and tips about grain selling versus grain marketing. It is available at this link http://www.grdc.com.au/FarmingTheBusiness

Figure 6: *Calculating the cost of production.*

Estimating Cost of Production - Wheat	
Planted Area	1,200 ha
Estimated 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	$50,000
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

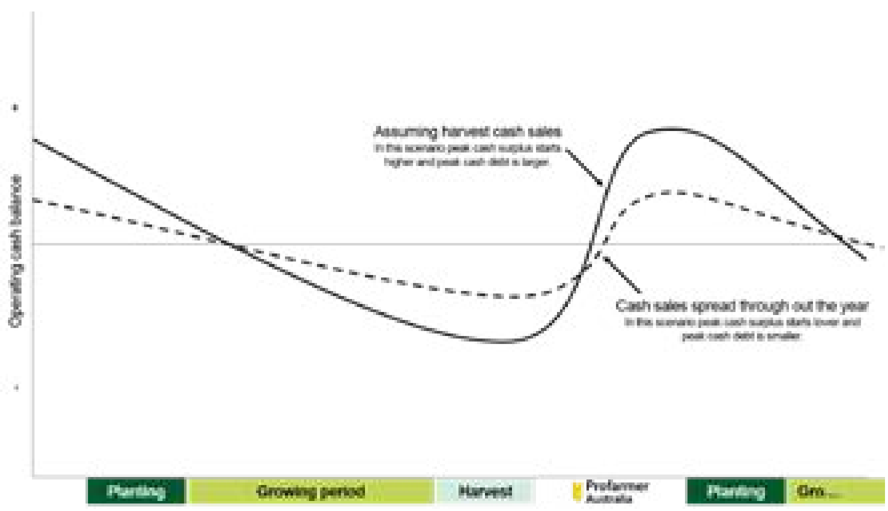
10.2.5 Income requirements

Understanding farm business cash-flow requirements and peak cash debt enables grain sales to be timed so cash is available when required. This prevents having to sell grain below the target price to satisfy a need for cash.

The principle is don't be a forced seller. Be ahead of cash requirements to avoid selling in unfavourable markets.

A typical cash-flow to grow a crop is illustrated in Figure 7. Costs are incurred up-front 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 7: *Typical farm operating cash balance.*



The operating cash flow of a typical farm that assumes a heavy reliance on cash sales at harvest, versus a farm business that spreads sales out throughout the year is also illustrated in Figure 7.

When there is heavy reliance on harvest sales, costs are incurred during the season to grow the crop. This results in peak operating debt levels at or near harvest. This means 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 to generate cash flow.

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 to fulfil cash requirements.

The ‘when to sell’ steps outlined 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.

10.3 Managing your price (how to sell)

The first part of the selling strategy answers the question of when to sell and establishes comfort around selling a portion of the harvest. The second part of the strategy addresses how to sell.

10.3.1 Methods of price management

Pricing products provide varying levels of price risk coverage and these are outlined below.

Fixed price strategies

- Fixed price strategies provide the most price certainty
- Examples include cash, futures and bank swaps.

Floor price strategies

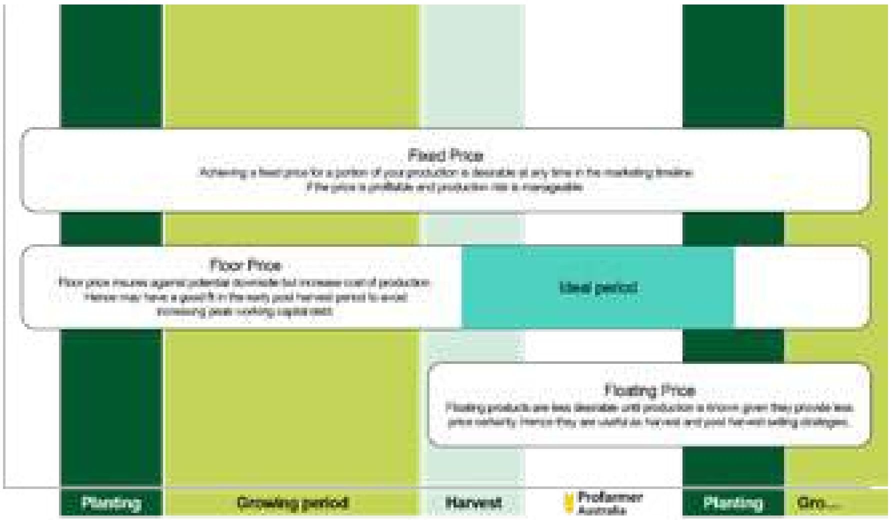
- Floor price products limit price downside but provide exposure to future price upside
- Examples include options on futures and floor price pool products.

Floating price strategies

- Floating price strategies are subject to both price upside and down side
- Examples include some pool products and doing nothing.

A summary of where different methods of price management are suited for the majority of farm businesses is shown in Figure 8.

Figure 8: *Price strategy timeline.*



As illustrated in Figure 8, 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 and the inherent production risk of the business increases. This means growers should achieve price certainty if committing tonnage ahead of harvest. Fixed or floor price products and strategies are favourable. Comparatively, a floating price strategy can be effective in the harvest and post-harvest period.

The principle is if there is increasing production risk, take price risk off the table. When committing unknown production, price certainty should be achieved to avoid increasing overall business risk.

It is advised to separate the pricing decision from the delivery decision. Most commodities can be sold at any time with delivery timeframes negotiable. This means price management is not determined by delivery.

10.3.2 Fixed price

A fixed price is achieved through cash sales and/or selling a futures position (swaps). It provides some certainty around expected revenue from a sale, as the price is largely known. The exception is 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. As shown in Figure 9, a fixed price product locks in price and provides certainty over what revenue will be generated regardless of future price movement.

Figure 9: *Fixed price strategy.*

10.3.3 Floor price

Floor price strategies can be achieved by using 'options' on a relevant futures exchange (if one exists), or through a managed sales program product by a third party (such as a pool with a defined floor price strategy). This pricing method protects against potential future downside, while capturing any upside. The disadvantage is that the price 'insurance' has a cost that adds to the farm businesses cost of production. As shown in Figure 10, a floor price strategy insures against potential future downside in price while allowing price grains in the event of future price rallies.

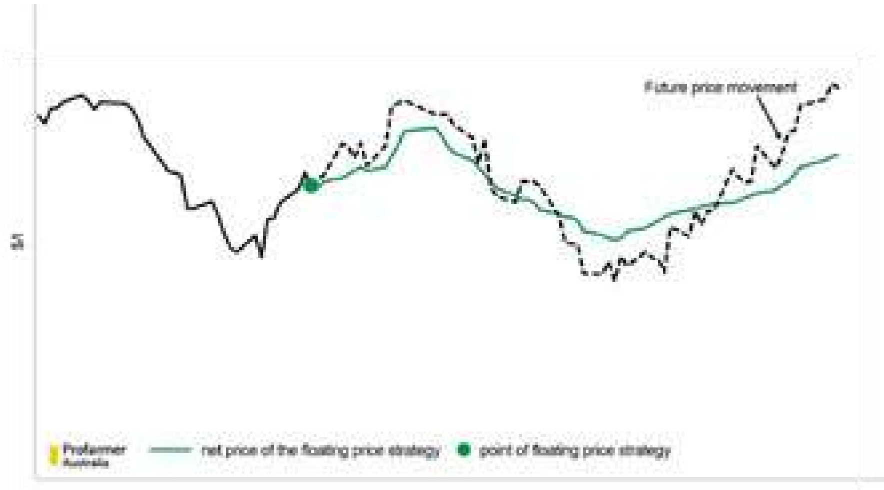
Figure 10: *Floor price strategy.*

10.3.4 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. Floating price products provide the least price certainty and are best suited for use at or after harvest rather than pre harvest. As shown in Figure 11, a floating price will move to some extend with future price movements.

It should be noted fixed price strategies include physical cash sales or futures products and provide the most price certainty but 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 but cost more. Floating price strategies provide minimal price certainty and are best used after harvest.

Figure 11: *Floating price strategy.*



10.4 Ensuring access to markets

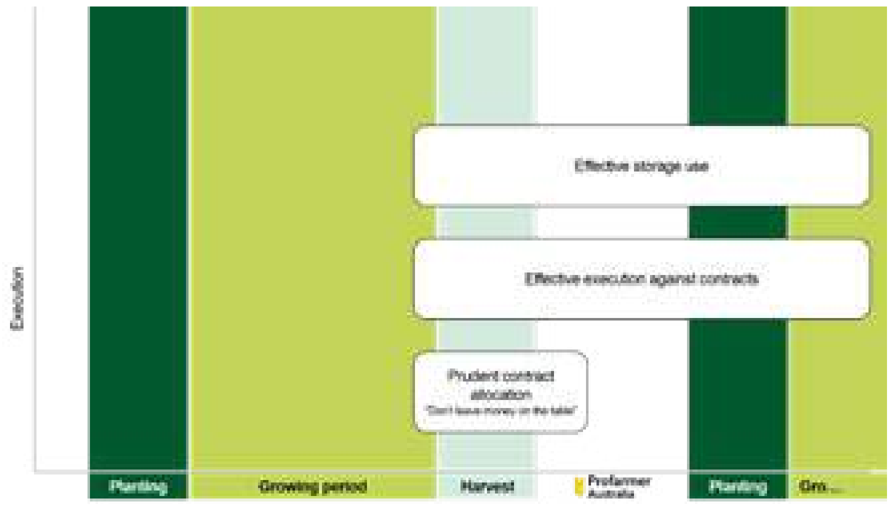
When the selling strategy of when and how to sell is sorted, planning moves to storage and delivery of commodities to ensure timely access to markets and execution of sales. At some point, growers need to deliver the commodity to market. Planning where to store the commodity is important in ensuring access to the market that is likely to yield the highest return. Timing the decision about how to sell is shown in Figure 12 and will be dependent on:

» The time of year determines the pricing method

» Market access determines where to sell

» Relative value determines what to sell.

Figure 12: *Timing effective storage decisions.*



10.4.1 Storage and Logistics

Return on investment (ROI) 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.

The principle is harvest is the first priority. Getting the crop in the bin is the most critical aspect of business success during harvest. Selling should be planned to allow a focus on harvest.

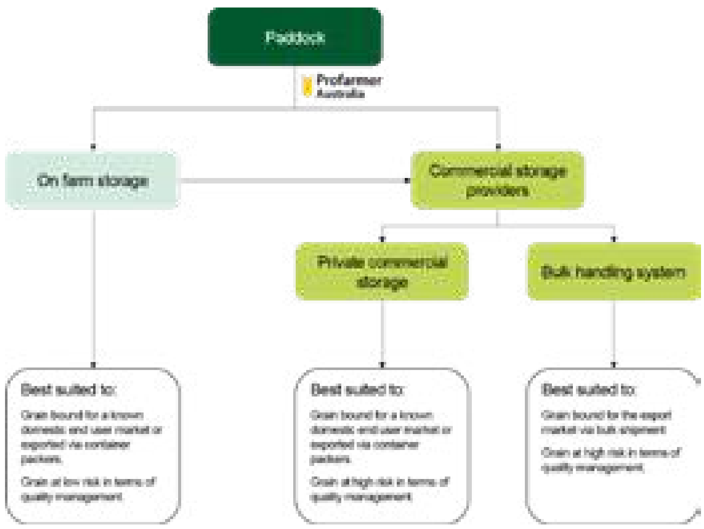
Bulk export commodities that require significant quality management are best suited to the bulk handling system. Commodities destined for the domestic end-user markets, such as feedlots, processors or container packers, may be more suited to on-farm or private storage to increase delivery flexibility.

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 the grower may have to incur the cost of taking the load elsewhere and potentially finding a new buyer. There is potential for a distressed sale which can be costly.

On-farm storage also requires prudent delivery management to ensure commodities are received by the buyer on time with appropriate weighbridge and sampling tickets.

The principle is storage is all about market access and storage decisions depend on quality management and expected markets. Decision-making about on-farm storage is outlined in Figure 13 and more information about options and economics is available at the Grains Research and Development Corporation's (GRDC) Stored Grain information hub at this link: www.storedgrain.com.au

Figure 13: *Grain storage decision making.*



10.4.2 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. The principle is carrying grain is not free and the cost of carry 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. As highlighted in Figure 14, optimising farm gate returns involves planning the appropriate storage strategy for each commodity to improve market access and cover carry costs in pricing decisions.

MORE INFORMATION

Grain Trade Australia 'A Guide to Taking out Grain Contracts': http://www.australiangrainexport.com.au/docs/Grain%20Contracts%20Guide.pdf

Grain Trade Australia 'Grain Trade Rules, Contracts and Vendor Declarations': http://www.graintrade.org.au/contracts

Grain Trade Australia 'Trading Standards': http://www.graintrade.org.au/commodity_standards

Profarmer 'Australian Grain Prices, Analysis and Selling Tactics': http://www.profarmergrain.com.au

GrainCorp 'Grain Transact Resource Centre': http://www.graintransact.com.au

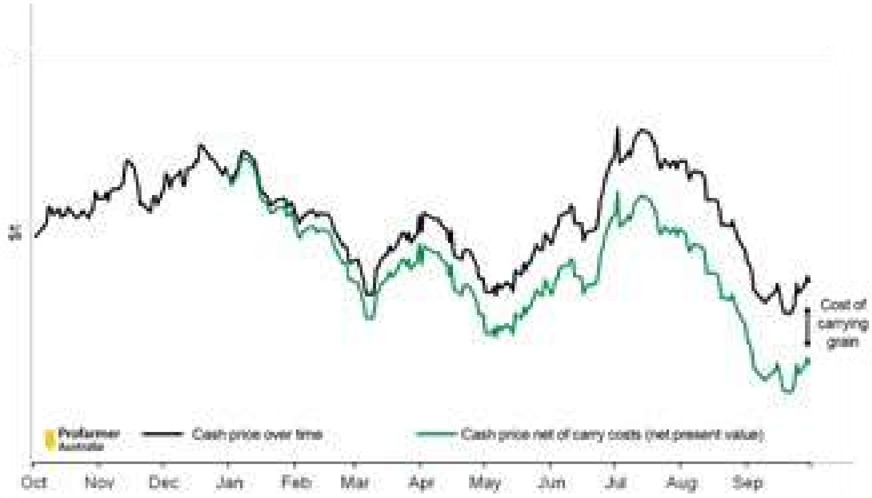
Australian GrainFlow Network: http://www.grainflow.com.au

Emerald Grain: http://emeraldgrain.com/grower-logins/

Clear Grain Exchange: https://www.cleargrain.com.au/get-started

Daily Grain: https://www.dailygrain.com.au/

Figure 14: *Cash values versus cash adjusted for the cost of carry.*



10.5 Executing tonnes into cash

This section provides guidelines for converting the selling and storage strategy into cash by effective execution of sales.

10.5.1 Set-up the tool box

Selling opportunities can be captured when they arise by assembling the necessary tools in advance. The toolbox includes:

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
- Other market information pertinent to the particular commodity.

Professional services

Professional grain selling service offerings and cost structures vary considerably. An effective grain selling professional will put their clients' best interest first by not having conflicts of interest and 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.

Futures account and bank swap facility

These accounts provide access to global futures markets. Hedging futures markets is not for everyone, but strategies that use exchanges such as CBOT can add significant value.

Financial members of Grain Trade Australia (GTA), including buyers, independent information providers, brokers, agents and banks providing over the counter grain derivative products (swaps) can be found at this link http://www.graintrade.org.au/membership Commodity futures brokers can be found at http://www.asx.com.au/prices/find-a-futures-broker.htm

10.5.2 How to sell for cash

As with 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:

Price

Future price is largely unpredictable, so 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, there is a commitment to deliver the nominated amount of grain at the quality specified. 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, this relies on prudent execution management to ensure delivery within the contracted period.

Payment terms

In Australia, the traditional method of contracting requires the title of grain to be transferred ahead of payment. This means counter-party risk must be managed.

Typical cash contracting to GTA standards is shown in Figure 15.

Figure 15: *Typical cash contracting as per Grain Trade Australia standards.*

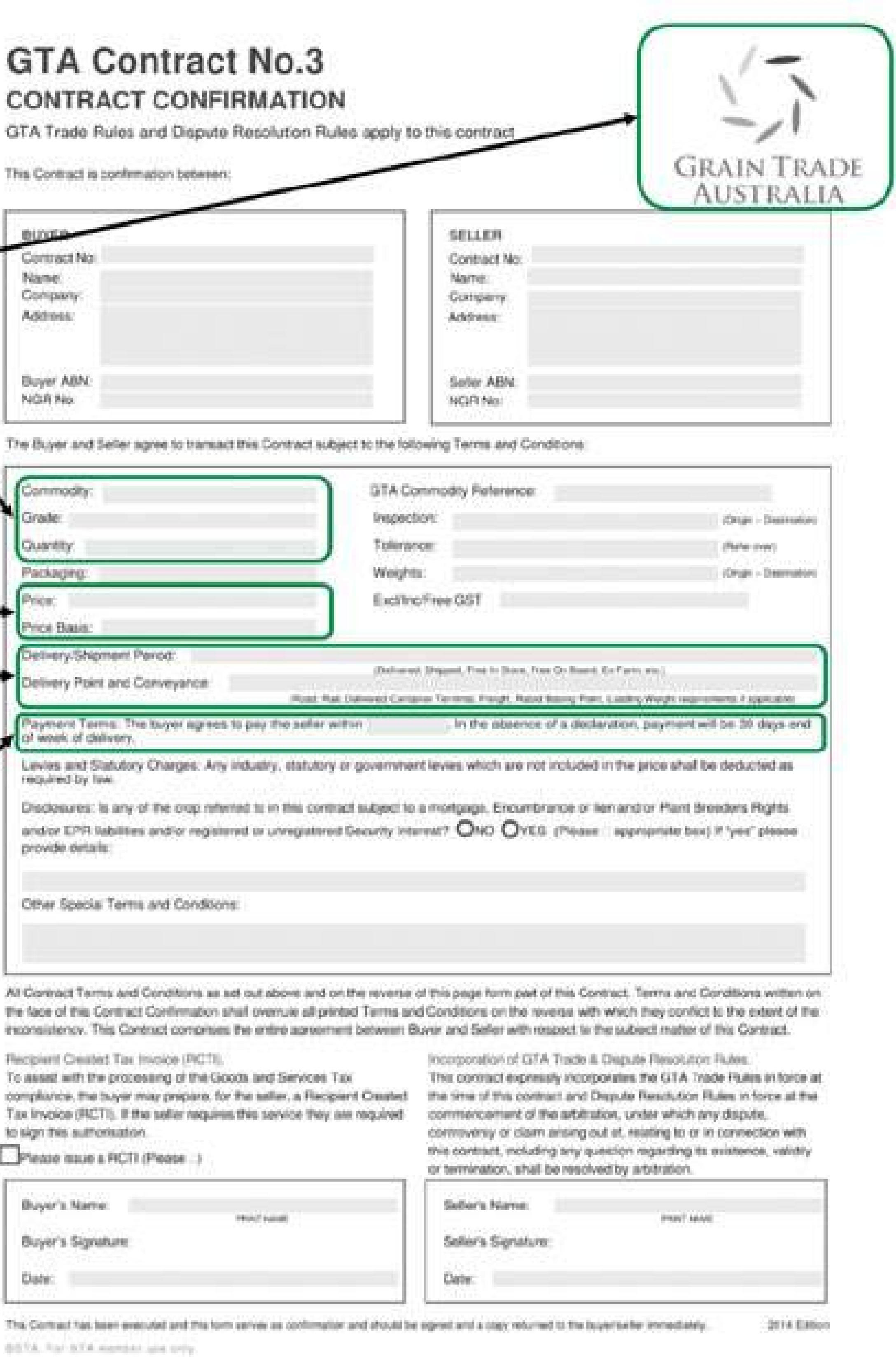
Grain Trade Australia is the industry body ensuring the efficient facilitation of commercial activities across the grain supply chain. This includes contract trade and dispute resolution rules. All wheat contracts in Australia should refer to GTA trade and dispute resolution rules.

Quantity (tonnage) and quality (bin grade) determine the actuals of your commitment. Production and execution risk must be managed.

Price is negotiable at time of contracting.
Price basis or price point is important as it determines where in the supply chain the transaction will occur and so what costs will come out of the price before the growers net return.

Timing of delivery (title transfer) is agreed upon at time of contracting. Hence growers negotiate execution and storage risk they may have to manage.

Whilst the majority of transactions are on the premise that title of grain is transferred ahead of payment this is negotiable. Managing counterparty risk is critical.



GTA Contract No.3

CONTRACT CONFIRMATION

GTA Trade Rules and Dispute Resolution Rules apply to this contract

GRAIN TRADE AUSTRALIA

This Contract is confirmation between:

BUYER	SELLER
Contract No:	Contract No:
Name:	Name:
Company:	Company:
Address:	Address:
Buyer ABN:	Seller ABN:
NGR No:	NGR No:

The Buyer and Seller agree to transact this Contract subject to the following Terms and Conditions:

Commodity: GTA Commodity Reference:
Grade: Inspection: (Origin – Destination)
Quantity: Tolerance: (Refer over)
Packaging: Weights: (Origin – Destination)
Price: Excl/Inc/Free GST
Price Basis:
Delivery/Shipment Period: (Delivered, Shipped, Free In Store, Free On Board, Ex Farm, etc.)
Delivery Point and Conveyance: (Road, Rail, Delivered Container Terminal, Freight, Rated Basing Point, Loading/Weight requirements if applicable)

Payment Terms: The buyer agrees to pay the seller within In the absence of a declaration, payment will be 30 days end of week of delivery.

Levies and Statutory Charges: Any industry, statutory or government levies which are not included in the price shall be deducted as required by law.

Disclosures: Is any of the crop referred to in this contract subject to a mortgage, Encumbrance or lien and/or Plant Breeders Rights and/or EPR liabilities and/or registered or unregistered Security Interest? NO YES (Please appropriate box) If "yes" please provide details:

Other Special Terms and Conditions:

All Contract Terms and Conditions as set out above and on the reverse of this page form part of this Contract. Terms and Conditions written on the face of this Contract Confirmation shall overrule all printed Terms and Conditions on the reverse with which they conflict to the extent of the inconsistency. This Contract comprises the entire agreement between Buyer and Seller with respect to the subject matter of this Contract.

Recipient Created Tax Invoice (RCTI).
To assist with the processing of the Goods and Services Tax compliance, the buyer may prepare, for the seller, a Recipient Created Tax Invoice (RCTI). If the seller requires this service they are required to sign this authorisation.
Please issue a RCTI (Please)

Incorporation of GTA Trade & Dispute Resolution Rules.
This contract expressly incorporates the GTA Trade Rules in force at the time of this contract and Dispute Resolution Rules in force at the commencement of the arbitration, under which any dispute, controversy or claim arising out of, relating to or in connection with this contract, including any question regarding its existence, validity or termination, shall be resolved by arbitration.

Buyer's Name: PRINT NAME	Seller's Name: PRINT NAME
Buyer's Signature:	Seller's Signature:
Date:	Date:

This Contract has been executed and this form serves as confirmation and should be signed and a copy returned to the buyer/seller immediately. 2014 Edition

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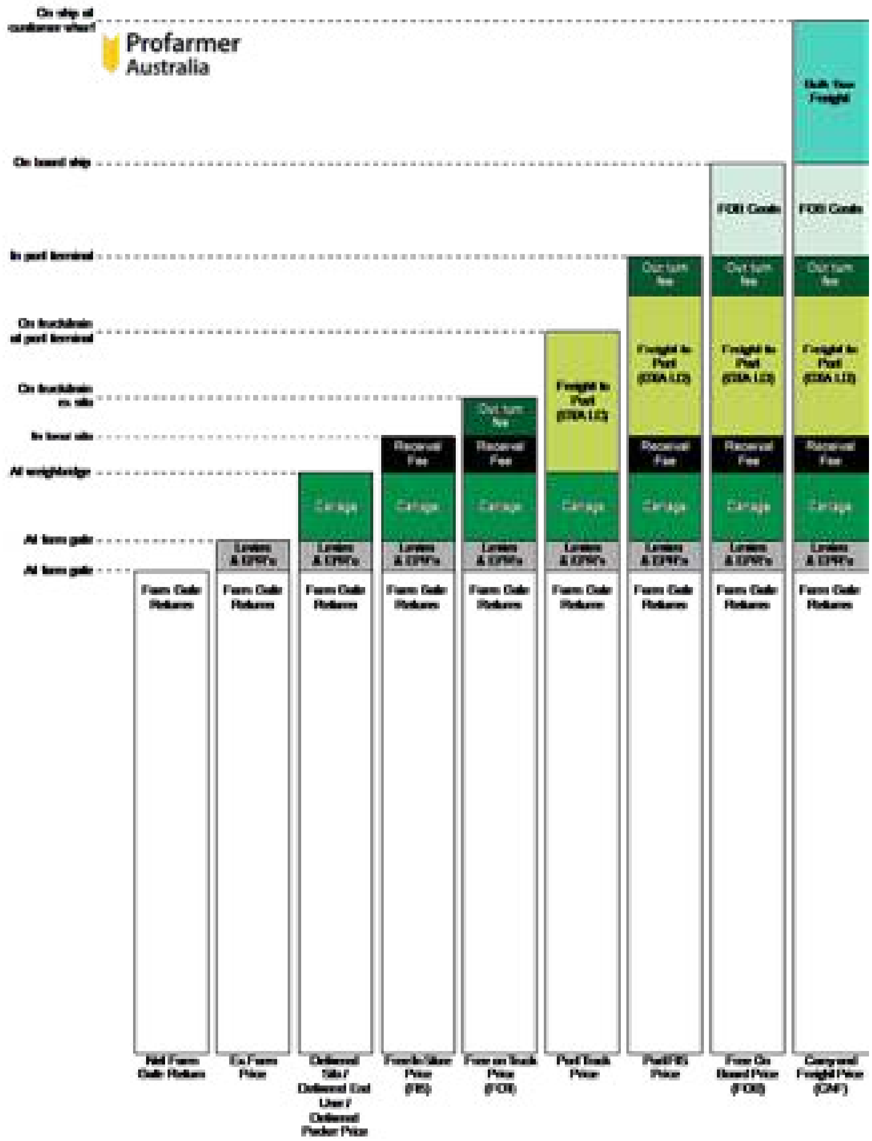
As outlined in Figure 16, the price point in a cash contract will depend on where the transfer of grain title will occur along the supply chain. It shows the terminology used to describe pricing points along the grain supply chain and the associated costs to come out of each price before growers receive their net farm gate return.

Figure 16: *Costs and pricing points throughout the supply chain.*



Cash sales typically occur through three methods:

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 available for all commodities.

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 transfer the grain online to the buyer. Availability depends on location and commodity.

Placing a firm offer

Growers can place a firm offer price on a parcel of grain by approaching buyers with a set tonnage and quality at a pre-determined price. The buyers do not have to accept the offer and may simply say no or disregard the offer.

There are increasingly more channels via which to place a firm offer.

One way this can be achieved anonymously is using the Clear Grain Exchange, which is an independent online exchange. If the firm offer and firm bid matches, 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. Availability 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 counter-party.

Some bulk handler platforms are also providing facilities for sellers to place firm offers to the market. This includes GrainCorp through its CropConnect product.

A grower can also place a firm offer directly with an individual buyer.

10.5.3 Counter-party risk

Most sales involve transferring the title of grain prior to being paid. The risk of a counter-party defaulting when selling grain is very real and must be managed. Conducting business in a commercial and professional manner minimises this risk. The principle is seller beware. There is not much point selling for an extra $5/t if you don't get paid. Counter-party risk management includes:

- Dealing only with known and trusted counter-parties
- Conducting a credit check (banks will do this) before dealing with a buyer they are unsure of
- Only selling a small amount of grain to unknown counter-parties
- Considering credit insurance, or a letter of credit, from the buyer
- Never delivering a second load of grain if payment has not been received for the first.

It is important to not part with a title of grain before payment, or to 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 through which the grower maintains title of grain until payment is received by the buyer, and then title and payment is settled simultaneously.

Above all, act commercially to ensure the time invested in a selling strategy is not wasted by poor counter-party risk management. Achieving $5/t more and not getting paid is a disastrous outcome.

MORE INFORMATION

Grain Trade Australia 'Managing Counter-party Risk 14/7/2014': http://www.graintrade.org.au/sites/default/files/Grain%20Contracts%20-%20Counterparty%20Risk.pdf

Clear Grain Exchange 'Title Transfer Model': https://www.cleargrain.com.au/get-started

GrainGrowers 'Guide to Managing Contract Risk': www.graingrowers.com.au/policy/resources

10.5.4 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 with the highest relative value. This achieves price protection for overall farm business revenue and enables more flexibility to a grower's selling program while achieving the business goals of reducing overall risk. The principle is sell valued commodities – not undervalued commodities. If one commodity is priced strongly relative to another, focus sales there. Don't sell the cheaper commodity for a discount.

10.5.5 Contract allocation

Contract allocation means choosing which contracts to allocate 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.

Consideration needs to be made based on the quality or grades you have available to deliver, the contracts you already have in place and how revenues will be calculated on each contract. Key considerations include whether the contract calculates revenues based on a sliding scale, or on pre-determined quality 'buckets'. Whenever you have more grain to allocate than pre-committed to contracts, it is important to consider the premiums and discounts available in the current cash market as part of your contract allocation decision.

The principle is don't leave money on the table. Contract allocation decisions don't take long and can be worth thousands of dollars to your bottom line.

10.5.6 Read market signals

The appetite of buyers to buy 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 stand aside from the market when buyers are not that interested in buying the commodity.

The principle is sell when there is buyer appetite. When buyers are chasing grain, growers have more market power to demand a price when selling.

Buyer appetite can be monitored by:

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 offering prices $5/t above the next best bid, it may mean cash prices are susceptible to falling $5/t if that buyer satisfies its buying appetite.

Monitoring actual trades against public indicative bids

When trades are occurring above indicative public bids, this might indicate strong appetite from merchants and the ability for growers to offer their grain at price premiums to public bids.

Sales execution

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 counter-party 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 prevent selling at a discount.

10.6 Market dynamics and execution

10.6.1 Price determinants for western durum wheat

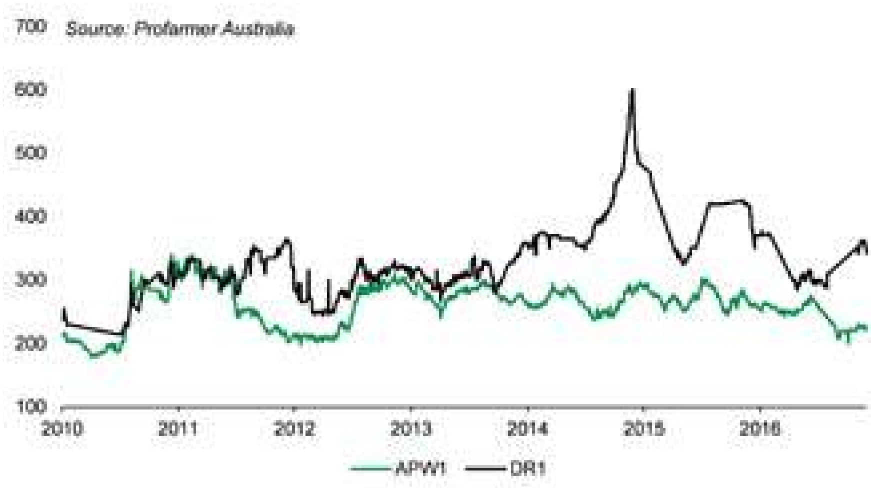
The durum wheat market in WA is in its infancy, with crops being produced on a very small scale. However, if durum wheat production were to be successful, it has the potential to be an important niche crop in WA production systems. It would provide growers with access to a market that has historically been supplied in Australia by product from South Australia and New South Wales.

Durum is a specialty wheat used primarily for the production of pasta products. Due to its specialised use, demand for durum tends to be inelastic and finite. This means there is a relatively fixed requirement for durum year-on-year and there are few substitutes.

Durum wheat values are influenced by the price of bread wheats, such as APW1, but these two wheat types ultimately have different markets. This means, at times, the price relativities between the two can separate reflecting differences in the supply and demand dynamics of each market.

For example, during the 2014-15 season, untimely rains saw European Union durum wheat production fall to historically low levels and its import requirement rose to its highest level in five years. This coincided with weather-damaged crops in Canada and the United States of America and a smaller crop in Australia. This meant the production of durum wheat globally was not adequate to cover demand and resulted in a $200/t or more premium for durum wheat in Australia compared to APW1 varieties. This was despite ample supply of Australian bread wheats. Figure 17 highlights the fluctuating value of durum wheat out of Port Adelaide.

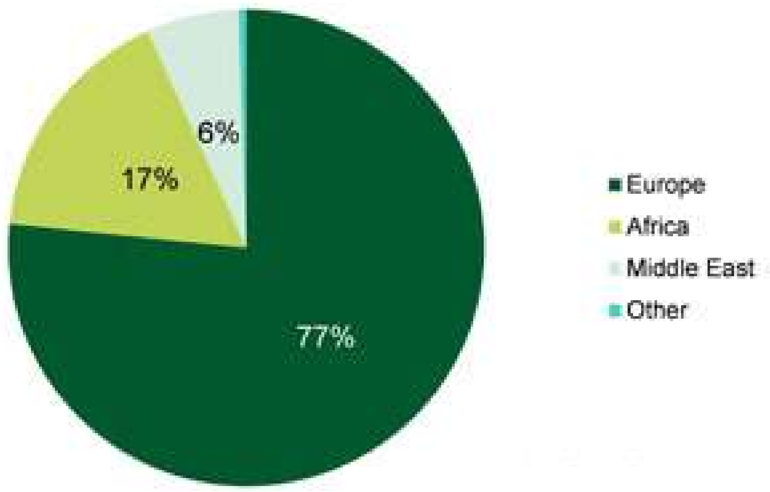
Figure 17: *Port Adelaide Durum Values ($/t).*



The major production nations of durum wheat are Canada, the European Union (predominantly France and Italy), North Africa and Australia. Major consumers are the European Union and North Africa. Australian production is split between South Australia at 40-50 percent and northern NSW and southern Queensland making up the remaining 50-60 percent of the crop. In a typical year, Australia exports 60-70 percent of its durum wheat production, with a small number of local food manufacturers consuming the remaining 30-40 percent.

Australian export destinations for durum wheat are shown in Figure 18.

Figure 18: *Export destinations for Australian Durum.*[1]



In years when global durum wheat supply exceeds the finite demand, Australian durum wheat values tend to be weak relative to bread wheat varieties. In this scenario, Australian durum is discounted to compete for a smaller amount of international trade activity, as well as competing for alternate homes in the domestic market (such as stock feed markets). Alternatively, when global durum wheat supply fails to meet demand, durum wheat can trade at strong premiums to bread wheat as the market competes to secure its demand requirements from a smaller global crop. This means a major determinant of Australian durum wheat values is the price at which international trade is transacting. This is influenced by:

- Global supply versus demand
- Quality of the global crop
- Timing of the Australian export program.

10.6.2 Ensuring market access for western durum wheat

Due to the inelastic nature of durum wheat demand, consumers and exporters traditionally focus accumulation programs on the period immediately leading up to, during and after harvest when supply is the most certain. Hence, appetite for durum tends to be strongest from October to January each marketing year.

While Australia-wide, more than 95 percent of durum wheat exports are executed through bulk export vessels – rather than container exports – the small nature of the crop in WA means that any exports that occur tend to take place in containers. This means private commercial storages or on-farm storage facilities can provide efficiencies to market.

Being a specialty crop, there are fewer buyers of durum wheat than other grades of wheat. This means liquidity risk is a particularly important consideration for durum wheat growers. Liquidity risk is the risk that buyers reach their accumulation requirements and step out of the market. The price may fall sharply as a result, or buyer appetite could dry up altogether.

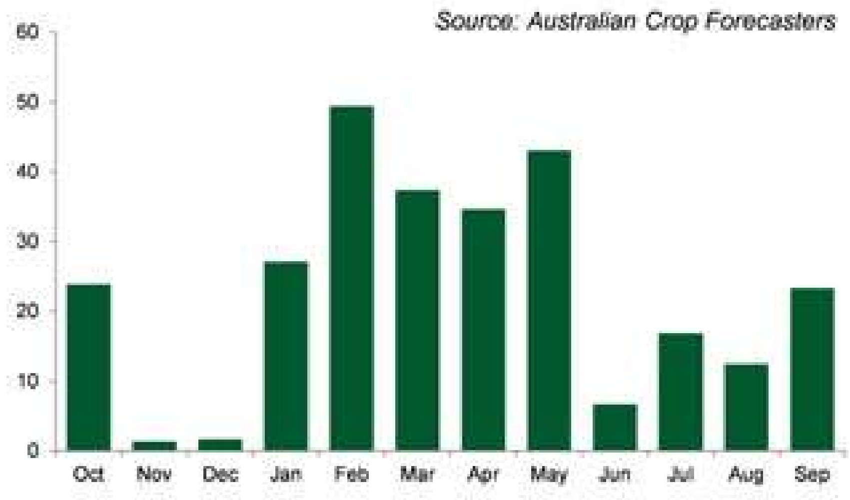
For growers in WA considering planting a durum wheat crop for the first time, it is prudent to research potential buyers prior to sowing the crop. Initiating conversations with buyers prior to planting a crop will provide insights into production and storage requirements, as well as potential homes for your crop once it has been produced.

1 Australian Crop Forecasters, Australian Crop Report Package, http://www.cropforecasters.com.au/

With the majority of WA container packing facilities located in or around Perth, WA growers seeking to market durum wheat should consider their access to these facilities as part of their overall marketing plan.

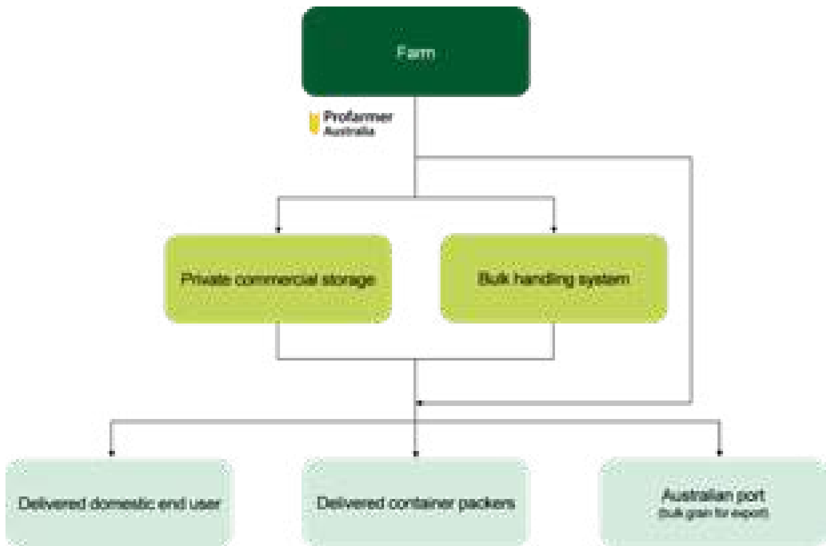
The 10-year average monthly export pace for Australian durum wheat is outlined in Figure 19.

Figure 19: *The 10 year average monthly export pace for Australian Durum.*[2]



Australian durum wheat exports are typically strongest between January and May in each marketing year, as exporters look to move the crop shortly after the Australian harvest but ahead of the harvest of the northern hemisphere crops. The supply chain flow is outlined in Figure 20 and it is advised that storage decisions be determined by assessing market access.

Figure 20: *Australian durum wheat supply chain flow.*



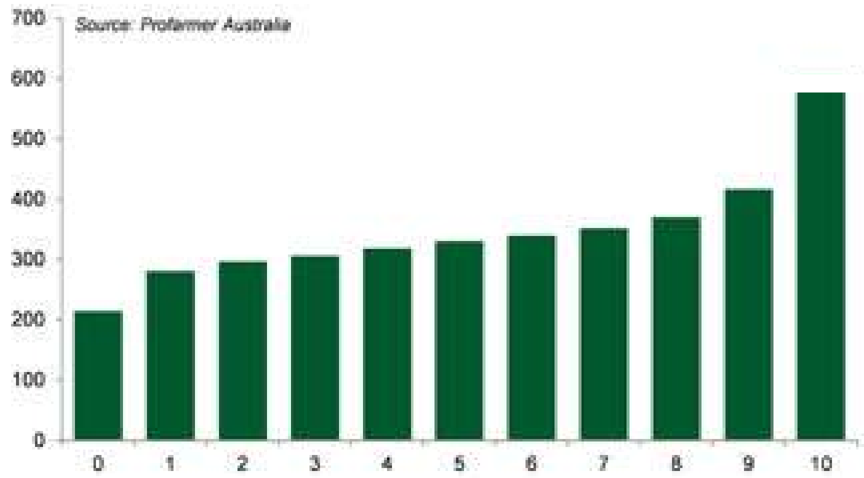
2 Australian Crop Forecasters (2017), 'Australian Crop Report Package', http://www.cropforecasters.com.au/

10.7 Executing tonnes into cash for western durum wheat

Pricing in the durum wheat market is not always transparent. Few buyers and a number of transactions taking place outside the public indicative bid can make it difficult to gauge fair market value.

Price discovery for durum wheat in WA can be difficult given the small size of the market, particularly relative to other grains produced. This means South Australian markets, which have much greater market depth, can be an important source of price discovery – especially for those growers seeking to understand export values. For growers in WA considering planting a durum wheat crop for the first time, the selling process will be best started prior to planting the crop. This can be achieved by researching potential buyers and developing relationships with these buyers prior to planting a crop. These relationships can provide important insights into production and storage requirements, as well as potential homes for the crop once it has been produced. The deciles for sales of durum wheat out of Port Adelaide are shown in Figure 21. These deciles provide an indication of price performance relative to historical values. Where a Decile 1 indicates values in the bottom 10 percent of historical observations, a Decile 9 would indicate the top 10 percent. This chart is based on price observations from August 2009 to 2016.

Figure 21: *Port Adelaide durum wheat deciles.*



Current Research

Project Summaries https://grdc.com.au/research/projects

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 the 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 https://grdc.com.au/research/projects

Final Report Summaries https://grdc.com.au/research/reports

In the interests of raising awareness of the GRDC's investments among growers, advisers and other stakeholders, the GRDC has made 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 https://grdc.com.au/research/reports

Online Farm Trials 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 'Online trials' http://www.farmtrials.com.au

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