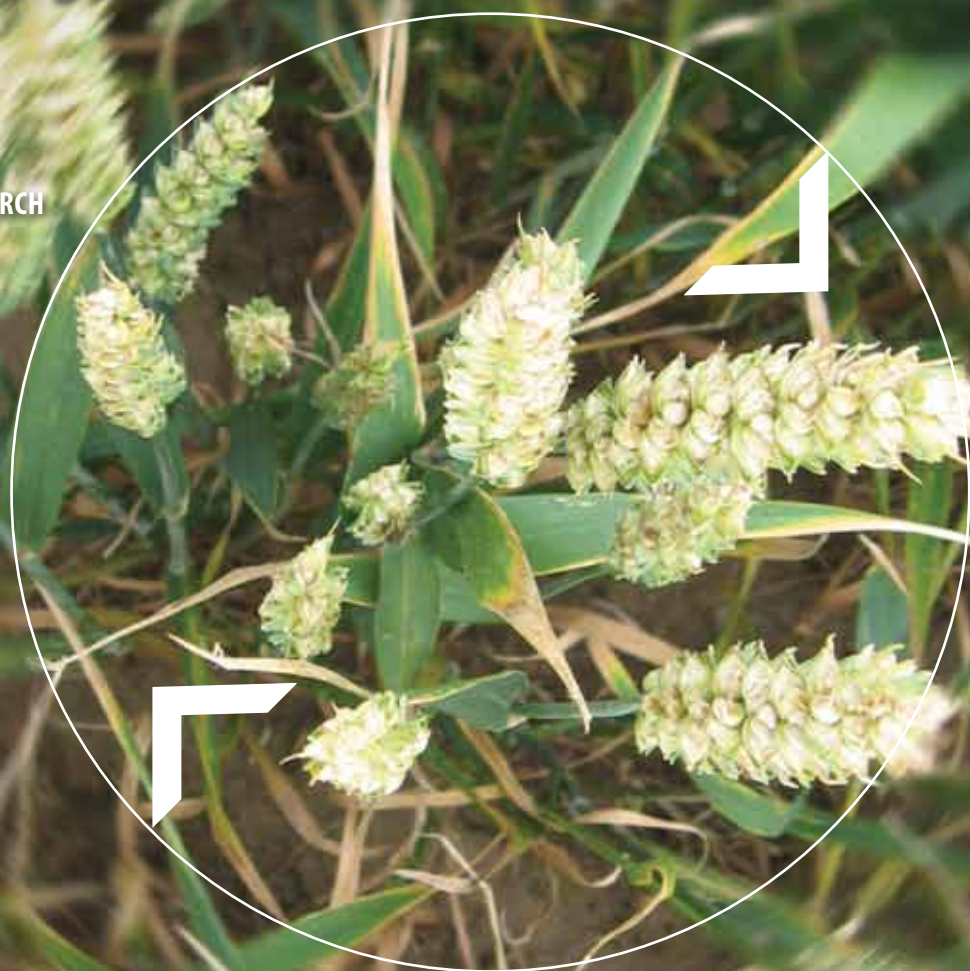


Advancing the Management of Crop Canopies

Keeping crops greener for longer

By Nick Poole
FOUNDATION OF ARABLE RESEARCH

and James Hunt
CSIRO



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A CEREAL CROP MANAGEMENT GUIDE

Introduction

This guide has been produced as part of the GRDC funded project SFS 00017, examining the role of disease management and canopy management across Australia's grain growing regions and brings together key results from project trials carried out between 2008 to 2011. The majority of data presented was generated in the medium to higher-rainfall cropping regions.

The content of this guide covers the link between growth stage and crop physiology and the implications for canopy management and disease control in wheat and barley, the influence of row spacing on canopy management, grazing long season wheat and how new technologies can be used to manage the crop canopy. The booklet is the third in a series of GRDC publications, the two previous being *Cereal Growth Stages – the link to crop management* (2005 – GRDC project SFS00006) and *Disease Management and Crop Canopies – What are the interactions?* (2009 – GRDC project SFS00015). The guide is split into three principal sections covering crop physiology, disease management and canopy management.

N. Poole, FAR Australia

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In putting the publication together FAR would like to thank Michael Perry for his excellent editorial amendments and Rosie Fenton for the graphic design.

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N. Poole – FAR Australia, June 2012

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1. Understanding Crop Physiology – The Key to Making Better Input Decisions

James Hunt, CSIRO and Nick Poole, FAR.

Linking the Zadoks Cereal Growth Stage Key to plant physiology

The Zadoks growth stage key provides a common reference to describe the crop's development and the stages at which to apply key inputs. However, being based on the plant's external form, it does not give us the necessary insight into the internal development of the embryo ear that is so critical to crop management. This section of the booklet links the key external growth stages with the key periods of internal development, the principal periods when yield potential is determined, key input timings and some project benchmarks for comparison.

Understanding plant growth and development

Plants grow as green leaves intercept energy from the sun and use that energy to capture carbon (from atmospheric carbon dioxide) and manufacture carbohydrates that are used to grow the leaves and other structures of the plant. In assimilating carbon, water is inevitably lost to the atmosphere. Over the life cycle of the plant the allocation of carbon changes as the plant moves through a series of developmental stages. In cereals the key developmental stages are associated with changes in the shoot apex as the head is formed and the stems elongate. The latter is a critical developmental phase as potential yield (number of grains and grain size) is determined at this time. Flowering (anthesis) in cereals is another critical developmental stage and post-anthesis growth is allocated almost entirely to grain filling.

The physiological basis for canopy management

Growth in cereals can be thought of in two distinct parts:

1) pre-flowering (pre-anthesis) growth, which is the growth that goes into leaves, roots and stems before a crop flowers and sets yield potential; and 2) post-flowering growth, the majority of which goes into grain.

The aim of canopy management is to get the balance right between pre and post-anthesis growth right in order to maximise grain yield, quality and harvestability in any given season. In drier environments crop canopies that produce excessive growth (tillers) by virtue of paddock fertility (soil nitrogen or applied nitrogen) use more of the water available at pre-flowering, leaving less for grain fill when the plant goes directly into the developing grain stage. This results in lower yields and poor grain size. Conversely overly thin crop canopies that have adequate water available, produce insufficient crop canopy pre-flowering to fully take advantage of the water available for grain fill post-flowering.

Linking the Zadoks cereal growth stage key to plant physiology

The Zadoks growth stage key gives us a common reference to describe the crop's development and at what growth stages to apply key inputs. However, as it is based on the plant's external form, it does not give us the necessary insight into the internal development of the embryo ear which is so critical to crop management. This section of the booklet links: the visible, identifiable external growth stages with the key periods of internal development, and the principal periods when yield potential is determined, and key input timings and some project benchmarks for comparison.




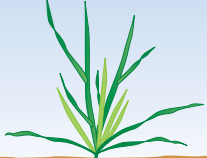
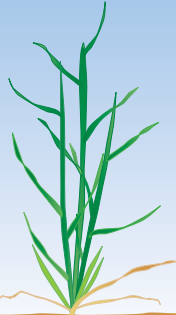
Embryo ear in wheat at GS30.



Embryo ear in wheat at GS32 (dissected on left, intact on right).



Key Input Timings

	Pre-emergent herbicides	Early post-emergent 1st doses of N for crops with low soil nitrogen		Key timing for N, Fungicides and PGR's GS26–32	Flag leaf fungicide GS39	1st awns GS49 second timing for foliar fungicide in barley
						
Zadoks Growth Stage	GS00–09	GS10–19	GS20–29	GS30–39	GS40–49	
External Growth Stages	Germination	Seeding growth	Tillering	Stem elongation	Booting	
Development phase	Vegetative growth			Stem elongation and ear development		
Ear development			Ear initiation (double ridge) GS22–24	Terminal pikelet (GS30–31)	Ear development	

Flowering in wheat (glumes removed).



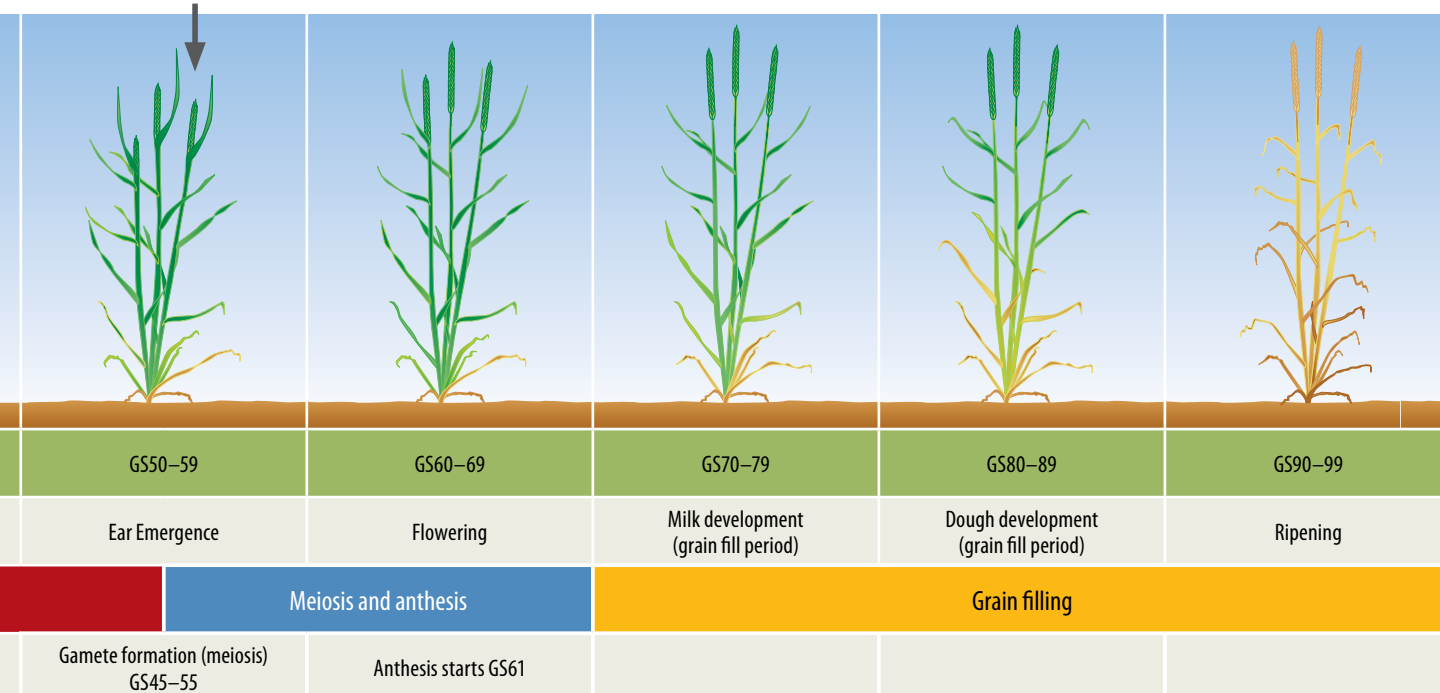
Early grain fill – watery ripe (GS71) awned wheat.



Later grain fill – late milky ripe (GS77).



N application for
Protein GS45–59



Example dry matters (DM), yields and harvest indices (HI) – SFS 00017 and Riverine Plains WUE sites 2008–10

Trial Sites	Year	GSR mm	GS31 DM	GS39 DM	GS61 DM	GS99 DM	Yield t/ha	HI (%)
Coreen, NSW	2010 (2nd Wheat)	570	2346	9033	112,41	15,038	5.1	33.7
Coreen, NSW	2010 (1st Wheat)	473	1455	4015	12,559	16,466	6.2	37.8
Bungeet, Vic	2009	570	2965	9068	10,476	9696	3.0	31.3
Coreen, NSW	2009	286	3112	7151	5500	8799	2.6	29.9
Cressy, Tas	2009	234	1750	4300	17,000	22,000	8	36.4
Inverleigh, Vic	2009	589	3500	10,000	13,830	10,333	3.2	30.9
Lubeck, Vic	2009	427	2930	8740	8587	9141	3.2	35.3
Tarlee, SA	2008	202	1735	5709	10,395	–	5.1	–

Key growth stages in relation to disease control and canopy management

The key growth stages for both disease control and canopy management in cereals are during GS30 (the start of stem elongation) to GS61 (start of flowering). These growth stages are particularly important when making canopy management and disease control decisions and will be referred to several times in this booklet.

Early stem elongation GS30–33 (pseudo stem erect – third node on the main stem)

The start of stem elongation is particularly important for decisions on fungicide and nitrogen inputs, as it marks the emergence of the first of the important yield contributing leaves and the point at which nitrogen uptake in the plant strongly increases. In order to correctly identify these growth stages more precisely, main stems of the cereal plants are cut longitudinally and the position of nodes (joints in the stem) and the length of internodes (cavity in the stem between nodes) are measured with a ruler.

Dimensions defining stem elongation with internal stem base dimensions.

GS30 The tip of the developing ear is one centimetre or more from the base of the stem where the lowest leaves attach to the shoot apex.

GS31 The first node can be seen 1cm or more above the base of the shoot (with clear internode space below it) and the internode above it is less than 2cm.

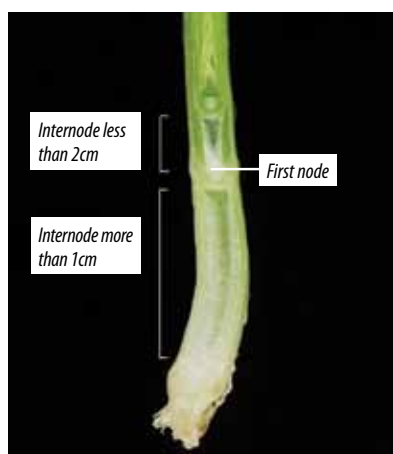
Development Phase	Decimal Growth Stage	Description
Stem elongation GS30–39	GS30	Pseudo stem erect (embryo ear at 1cm) – start of stem elongation
	GS31	1st node on main stem
	GS32	2nd node on main stem – leaf 3 emerges on main stem – 2 leaves below the flag leaf this is referred to as Flag-2 or F-2
	GS33	3rd node on main stem – leaf 2 (F-1) emerges on main stem
	GS37	Flag leaf just visible on main stem
	GS39	Flag leaf fully emerged on main stem with ligule showing
Booting GS40–49	GS41	Flag leaf – leaf sheath extending
	GS45	Mid boot – ear swelling in top of main stem
	GS49	1st awns emerging (barley/awned wheat)
Ear emergence GS50–59	GS59	Ear fully emerged on main stem
Anthesis (flowering) GS60–69	GS61	Start of flowering on main stem (approx 1/3 of the way up the ear)



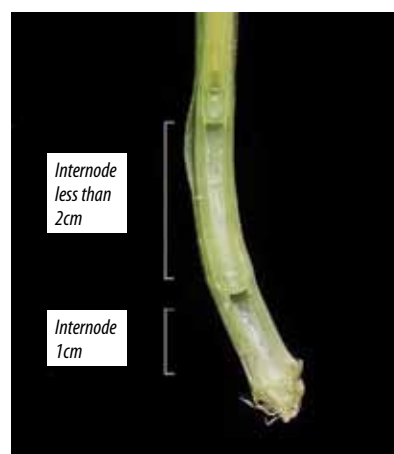
Preparation of main stem for measurement.



GS30 – Main stem with embryo ear at 1cm .

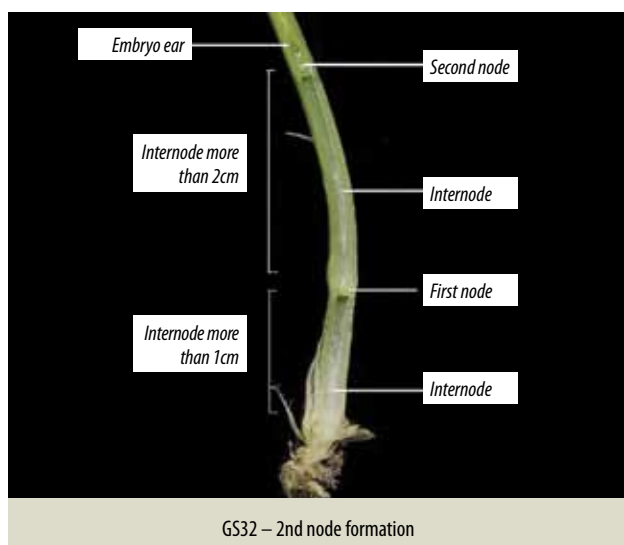


GS31 – Early first node formation.



GS31 – second node has less than 2cm from first node.

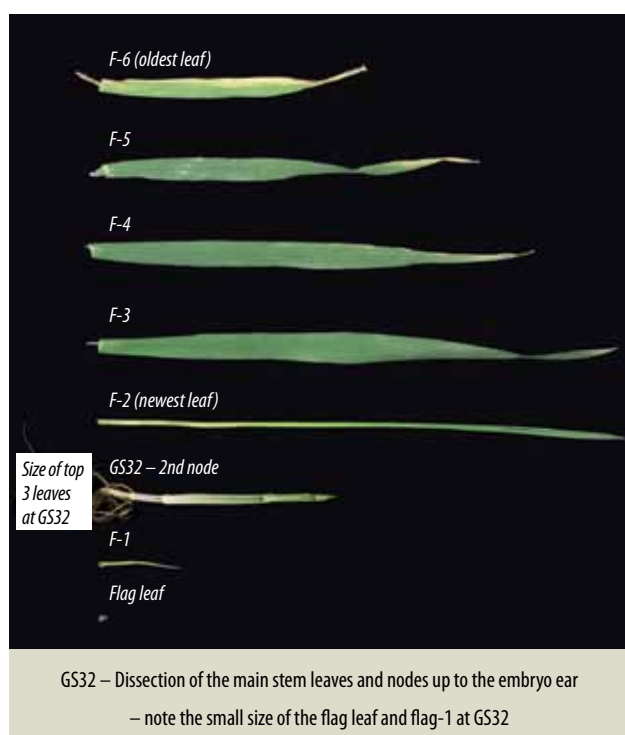
GS32 The second node can be detected and the internode below it exceeds 2cm, however the internode space above the node has not yet reached 2cm.



Third node (GS33) and all subsequent nodes, for example GS34, GS35 and GS36, are defined in the same way as GS32 the node has to have a clear 2cm space of internode space below it before it is distinguished as the next nodal growth stage.

Leaf dissection from GS32

Identifying the most important leaves (top three leaves) before the emergence of the final flag leaf can be done by referring to the nodal growth stage. However to ensure correct identification dissect the un-emerged leaves from second node (GS32) onwards. Before GS32 the leaves yet to emerge are generally too small to properly identify. Note how small the flag leaf is at GS32.



KEY POINTS

- The Zadoks Growth Stage key does not run chronologically from GS00 to GS99, for example when the crop reaches three fully unfolded leaves (GS13) it begins to tiller (GS20), before it has completed 4, 5, 6 fully unfolded leaves (GS14, GS15, GS16).
- It is easier to assess main stem and number of tillers than it is 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, for example 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 stem elongate (GS30).
- As a consequence of growth stages overlapping it is possible to describe a plant with several growth stages at the same point in time. For example, a cereal plant at GS32 (2nd node on the main stem) with three tillers and seven leaves on the main stem would be at GS32, GS23 and GS17, yet practically would be regarded as GS32, since this describes the most advanced stage of development.
- Note: after stem elongation (GS30) the growth stage describes the stage of the main stem, it is not an average of all the tillers. This is particularly important with fungicide timing, for example GS39 is full-flag leaf on the main stem, meaning that not all flag leaves in the crop will be fully emerged.
- Use a ruler to measure node movement in the main stem to define early stem elongation growth stages.
- Take care not to confuse the basal node at the stem base with the first true node. Basal nodes are usually signified by a constriction of the stem below the node with an incompletely formed internode space, it is the point where the lowest leaves attach to the stem. Further, basal nodes will often grow small root tips. This is not the first node.
- Nodal growth stage can give an approximate guide to which leaf is emerging from the main stem, this can save time with leaf dissection when it comes to making decisions on fungicide application pre-flag leaf (when all leaves are emerged).
- The rate of development influences the time between growth stages – later sowings spend less time in each development phase including grain fill, and potentially have lower yield.
- Though it will vary between varieties and regions (due to temperature), stem elongation leaves emerge approximately five to 10 days apart (10 under cooler temperatures at the start of stem elongation and nearer five to seven days as the flag comes out.)
- The period of time between leaf emergences is referred to as the phyllochron and is approximately 100–120 (°C days), though it can be longer or shorter depending on variety. Barley varieties tend to have shorter phyllochrons, so leaves tend to emerge slightly quicker.

Understanding plant growth and development

Plants grow by intercepting solar radiation and must use water to do this. When plants are actively growing, they open the small holes (called stomata) on their leaf surfaces to let in carbon dioxide from the atmosphere, and this carbon dioxide is captured by the leaf's mesophyll cells and converted to dry matter through the process of **photosynthesis**. While the stomata are open, water evaporates from the mesophyll cell surfaces and escapes as vapour into the atmosphere. This process is called **transpiration**.

The amount of water a crop transpires per day is determined by the amount of leaf area a crop has per unit area of ground, water supply and the evaporative demand of the atmosphere (determined by the ambient temperature, solar radiation and wind). The amount of leaf area a crop has is measured as leaf area index (LAI) and is expressed in square metres of leaf area per unit of ground (m^2/m^2), for example a crop with a LAI of 5.0 has 5m^2 of leaf area per 1m^2 of ground. However, as the green area of the crop canopy is also composed of stems, leaf sheaths and the heads, the overall green area of canopy is described as the green area index (GAI). Cereal crops also have stomata on their stems, heads and leaf sheaths, and these areas contribute significantly to plant growth, particularly after anthesis.

The rate at which plants are able to grow per unit of water transpired is called the **transpiration efficiency (TE)** and is expressed as kilograms per hectare of dry matter per millimetre of transpiration ($\text{kg}/\text{ha}.\text{mm}$). Across a growing season, wheat plants generally have a transpiration efficiency for above ground dry matter of between 50 and $60\text{kg}/\text{ha}.\text{mm}$. Factors that affect transpiration efficiency include nutrition (for example nitrogen stressed crops do not transpire as efficiently as crops with adequate nitrogen), the temperature and humidity of the atmosphere (the drier and warmer the atmosphere, the less efficient the plants) and the genetic make-up of the crop

variety, for example the varieties Drysdale^{db}, LongReach Scout^{db} and LongReach Spitfire^{db} were all selected for their ability to convert water into dry matter efficiently.

Pre-anthesis growth – when yield potential is determined

Yield potential (as opposed to achieved yield) is determined in the growth phase before anthesis during the formation and growth of the ear. Yield potential can best be thought of

in terms of the number of grains per unit area and the size (weight) of each grain. There are several critical times during crop development where grain number and size are determined.

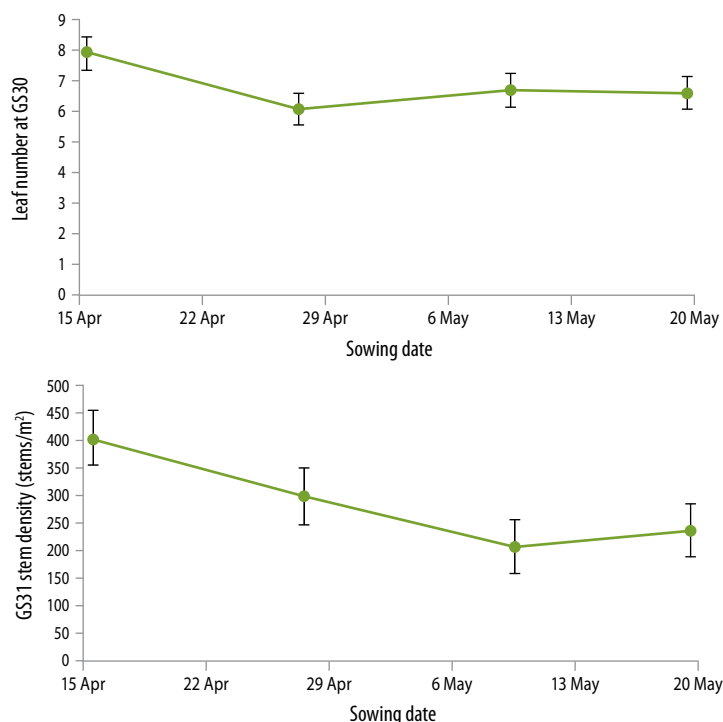
Crop establishment

The first step in establishing yield potential is that of crop establishment, i.e. how many plants per square metre as this directly effects the number heads per metre squared a crop can produce.



How does sowing date influence tiller number and final head number?

Earlier sowing results in a greater number of tillers that survive to produce a head. With winter wheat and some spring cultivars, earlier sowing results in more leaves prior to first node GS31, and since each leaf has a tiller bud, the crop has more time to grow tillers before the appropriate development stimuli (vernalisation, day length and temperature) signal for the crop to enter stem elongation. Generally, with spring wheat the cultivar's sowing date has less influence on tiller number since leaf number and resultant tiller number is more predetermined (the crop has less requirement for vernalisation prior to stem elongation). However, tillers from early sowings of spring cultivars have longer to grow and as a consequence their survival to produce a head is usually greater from early sowings.



Influence of sowing date on leaf number and tiller number at GS30 and GS31 respectively – Temora, NSW (Hunt et al 2011).

Tillering

The second stage is during tillering, which starts when plants have three leaves (GS13) and finishes when the plants stem starts to elongate (GS30). Tiller production is a very important way by which cereal plants adapt their growth to different environments and seasons. When resources for growth are plentiful, particularly water and nitrogen, plants produce many tillers. Intra-plant competition also affects the number of tillers produced: when plants are very close together, for example at high sowing densities, they may produce few or no tillers, when they are planted further apart they may produce many (>10 per plant). In this way plants are able to compensate for low densities and still produce a large number of grains/m². This is why wheat yield is relatively insensitive to plant density, particularly when nitrogen is plentiful.

Cereal crops invariably produce an excess of tillers, and some always die, but the number of tillers produced is a good indicator of the number of stems and heads (also referred to as culms, spikes or ears) a crop has, and is thus an important component of yield potential. However, maximising heads per square metre can be an inefficient way of creating yield potential because each head needs a stem to support it (growth that does not go into grain) and also has leaves that will transpire, leading to greater water demand and use. Crops with high head densities are also more likely to lodge, be difficult to harvest, and high stubble loads may cause problems when sowing the next crop using no-till techniques.

Stem elongation

The third phase critical to yield potential is during stem elongation when the number of spikelets and florets (a floret is an individual flower) that will form grain on each head is determined. The final phase critical to yield potential is just prior to the crop flowering when potential grain size is determined. Consequently, stresses experienced by the plant from stem elongation to flowering will reduce both the number of grains formed per head and potential grain size, resulting in reduced yield potential.

Pre-anthesis growth also contributes directly to yield through storage of water soluble carbohydrates (WSCs), which accumulate prior to anthesis and are stored in the stem. They are then translocated to grain after anthesis. However, WSCs only account for at best ~30% of pre-anthesis dry matter, making the conversion of pre-anthesis growth into grain yield reasonably inefficient.

Pre-anthesis growth is also important for reducing evaporation from the soil surface. The amount of evaporation from the soil surface is largely determined by the amount of solar radiation hitting the soil and wind speed over the soil surface. A growing crop decreases both of these and as a result reduces evaporation from the soil surface, although the difference in evaporation between a vigorous and un-vigorous crop is reasonably small (~20mm at best). Row spacing will also influence soil evaporation since it determines how much of the soil surface is directly exposed to radiation.

The effect of canopy development on soil evaporation is less important where crops mainly grow on stored soil water and/or have large amounts of stubble retained on the soil surface.

Post-anthesis growth

During post-anthesis growth, sugars produced by photosynthesis in the leaves, sheaths, stem and ear are directly transported to filling the grain and stored there as starch. Also during this time, sugars produced by photosynthesis prior to flowering are stored in the stem (WSCs) and proteins in the leaves are transported to filling the grain. **This grain filling period is critical to realising yield potential, and because products of growth are transported directly into the grain, water is used very efficiently for growth during this time.** Crops that have produced a lot of tillers and dry matter prior to flowering, and have a large yield potential (grains/m²), are at risk of not being able to fill grain following flowering because they are typically low in WSCs and have a large amount of leaf area that uses water quickly

and can rapidly exhaust supplies. ‘Haying off’ is the term used to describe crops with large canopies that are unable to fill grain due to low WSCs and a limited supply of water for post-anthesis growth.



How does the contribution of water soluble carbohydrates to grain yield change between high and low-rainfall regions?

In drier environments water stress post-flowering reduces the green area duration (GAD) of the crop and the ability of the crop to fill the grain directly through photosynthesis. As a consequence, the relative importance of the water soluble carbohydrates accumulated pre-flower increases. Therefore yields will be lower due to reduced crop canopy duration but a higher proportion of the yield will come from the WSC stored pre-flowering. Conversely, with greater water supply post-flowering the relative contribution of WSC declines as more carbohydrate-based dry matter goes directly into developing the grain since GAD is increased.

Harvest index

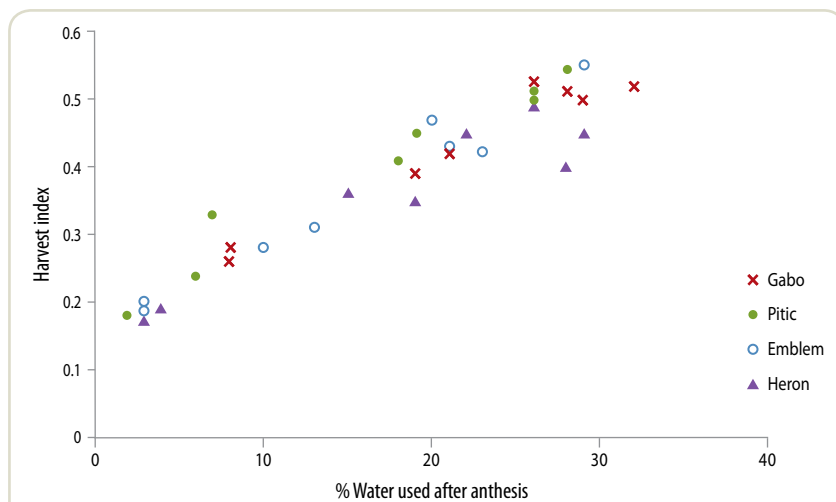
Unless a crop is cut and sold for hay, dry matter that does not end up in grain or is a supporting structure for a fertile head is an inefficient use of water and growth. The proportion of grain to total dry matter produced by a crop is expressed as the harvest index (HI):

$HI = \text{grain yield} / \text{total dry matter at maturity}$.

For example, at maturity a crop yielding 4 tonnes per hectare of grain may have 9t/ha of supporting leaf and stem. The harvest index would be $4 / (9 + 4) = 0.307$. The weight of root material is not included in the calculation of harvest index.

Managing for a high harvest index is a key way of improving water use efficiency and yield in water limited environments.

When nutrients, diseases and extremes of temperature are not limiting, harvest index is directly related to the balance between pre and post-anthesis water use and growth. Roughly speaking, a 2:1 ratio of pre to post-anthesis water-use will optimise harvest index (that is two-thirds of water used prior to anthesis and one-third used after anthesis).



The relationship between harvest index (proportion of crop harvested as grain) and % water used by the crop after anthesis.

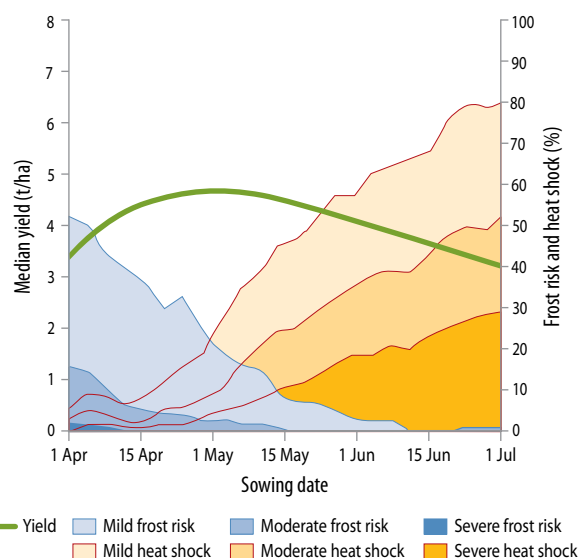


Head at anthesis (with glumes removed).



Why sow early?

Sowing the crop earlier in the autumn improves early crop growth. Canopy growth and rooting occurs earlier and shifts the grain fill development period forward relative to later sowings. Provided this increased vegetative growth in the autumn and winter is controlled, it results in better exploitation of stored water and shifts the grain fill period earlier in the spring, which is usually cooler and more conducive to optimising grain fill conditions. Obviously this has to be balanced against frost risk, but in regions where frost risk probabilities are low, yield potential is lost with later sowing. Yield Prophet® simulations based on the APSIM model has increasingly been used to illustrate that sowing dates in Australia could be brought forward to make better use of stored water and that frost risk is easily overstated relative to heat stress during grain fill. Canopy management, herbicide management, disease control and pest control require far more attention to detail in order to secure the increased yield potential.



Yield Prophet® simulation on the influence of sowing date – Yitpi[®] at Kerang assuming 50mm of stored soil water at sowing.

The physiological basis for canopy management

What is canopy management?


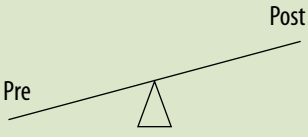
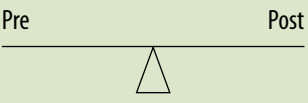
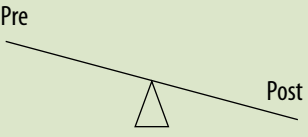
The 'canopy' of a crop refers to its above ground parts that intercept radiation – leaves, sheaths, stems (or peduncles) and heads. Canopy management is a term used to describe a range of agronomic management techniques that manipulate the way in which a crop's canopy grows at different times during the season.

This manipulation affects the size and duration of the green area of the canopy which is expressed in terms of green area index (GAI) and green area duration (GAD).

As discussed earlier, growth in cereals can be thought of in two distinct parts; 1) pre-anthesis growth, which is the growth that goes into leaves, roots and stems before a crop flowers and during which (particularly during the later stages) the crop sets up its yield potential; and 2) post-anthesis growth, the majority of which goes into filling the grain.

The aim of canopy management is to get the balance between pre and post-flowering (post-anthesis) growth right in order to maximise grain yield, quality and

harvestability in any given season. In drier environments crop canopies that produce excessive growth (tillers) by virtue of paddock fertility (soil nitrogen or applied nitrogen), use more of the water available pre-flowering leaving less for grain filling when plant growth goes directly into the developing grain. This can result in lower yields and poor grain size with higher screenings. Conversely overly thin crop canopies that have adequate water available, produce insufficient crop canopy pre-anthesis to fully take advantage of the water available for grain fill post-anthesis.

	<ul style="list-style-type: none"> • Too much pre-anthesis growth • Large vegetative canopy early • Excessive water use pre-anthesis 	<ul style="list-style-type: none"> • Sufficient canopy to intercept sunlight pre-anthesis • With sufficient soil water for post-flowering (post-anthesis) growth 	<ul style="list-style-type: none"> • Insufficient crop canopy growth pre-anthesis • Small canopy unable to fully intercept sunlight pre and post-anthesis
			
	Canopy too large for water available – result low yields, poor grain size, and high screenings.	Getting it just right!	Canopy too small for water available – result lower than expected yields and poor competition with weeds.

What can we do to influence a crop's canopy?

There are a number of crop management factors that can influence the size and duration of the canopy, increasing or decreasing the green surface of the crop depending on how the management lever is applied:

Management	Increase Canopy Size – GAI	Decrease Canopy Size – GAI
Plant density	Higher plant populations	Lower plant populations
Cultivar vigour and tillering behaviour	High vigour or high tillering capacity	Low vigour or low tillering habit
Plant configuration	Narrower row spacing	Wider row spacing
Time of sowing	Earlier sowing	Later sowing
Nitrogen fertiliser amount and timing	Higher N rates / early timing	Lower N rates / later timing (increased duration GAD)
Soil fertility (paddock history)	High fertility	Low fertility
Root and foliar disease	Healthy canopy – fungicides for disease control	Diseased canopy
Herbicide	No damage	Herbicide damage
Grazing with livestock	Ungrazed increases canopy size	Grazing decreases canopy size
Plant growth regulators	Standing canopy gives higher effective GAI	Lodged canopy less effective – smaller GAI

Step 1

Canopy management recognises that the most efficient (high harvest index) way of achieving yield potential is through optimising grain number per head and grain size, rather than head density (tillers). The first step in managing a wheat crop's canopy is to determine the number of heads required to achieve a realistic yield given the environment in which a crop is growing. Under Australian conditions, a wheat head is capable of carrying two grams of grain (10 spikelets long x 3 florets wide x 2 sides x 35 milligrams = 2.1g). Therefore 350 heads/m² is all that is required to achieve 7t/ha of grain yield. Any more than this number will be an inefficient use of resources.

Step 2

The second step is to manage the crop in its early stages of growth to try and achieve this target head density. Management factors that contribute to tiller, stem and head number include:

- plant density;
- sowing time;
- cultivar tillering behaviour;
- soil fertility (particularly nitrogen) and water availability (largely determined by paddock history);
- fertiliser amount and timing (particularly nitrogen);
- herbicides and the amount of crop damage they cause; and
- grazing with livestock.

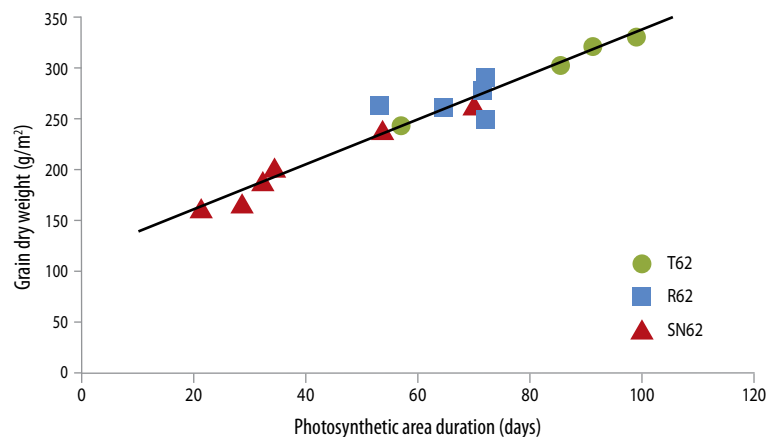
These management factors are the agronomic 'levers' that can be adjusted in order to achieve a target head density for a given environment and season. For example, if a paddock with high soil nitrogen and stored soil water (for example, following a legume pasture or pulse crop) is to be sown early, head number can be managed downward by reducing seeding rate, selecting a reduced tillering variety, applying no nitrogen fertiliser at seeding or grazing during tillering. Type and timing of pre-emergent and post-emergent herbicides will also have an effect. For a wheat crop to be sown late

into cereal stubble with low soil nitrogen, head number can be managed upward by increasing seeding rate and applying nitrogen fertiliser at sowing.

Step 3

The third step is to ensure that the crop does not get stressed from the start of stem elongation through to flowering (GS30–60). A well managed crop should be intercepting all solar radiation by the time the flag-leaf emerges and, provided it does not get stressed by late herbicide applications, extreme temperatures, water or nutrient availability, it will maintain a high yield potential through an adequate number of grains per head and large potential grain size. This means top-dressing nitrogen fertiliser matched to water supply, avoiding late herbicide applications, and applying foliar fungicides if required.

The second aim of this third step is to make sure the crop canopy stays as green as possible for as long as possible after flowering. The overriding determinant of canopy greenness and duration in most regions of Australia is water availability, but the management factors with the greatest influence are nitrogen availability and foliar disease control. This is why it is important to match nitrogen fertiliser to water availability during stem elongation, and to protect photosynthetic area with foliar fungicides, particularly in years/locations of high yield potential. How long a canopy stays green can be measured



Relationship between grain weight and photosynthetic area duration (days).

with green area duration (GAD, m²/m² days) or NDVI days (see sections on crop sensors and photosynthetic area duration) and is very strongly correlated to yield. The importance of maintaining a green canopy after flowering is that a crop is using water and producing starch from photosynthesis that can be translocated directly into grain growth. Crops that are able to grow during this time can also translocate protein from leaves and water-soluble carbohydrates from the stem into grain. Water that is available during this period is used very efficiently to support the production of grain – at up to 60 kg/ha of grain per hectare for each millimetre of water used.



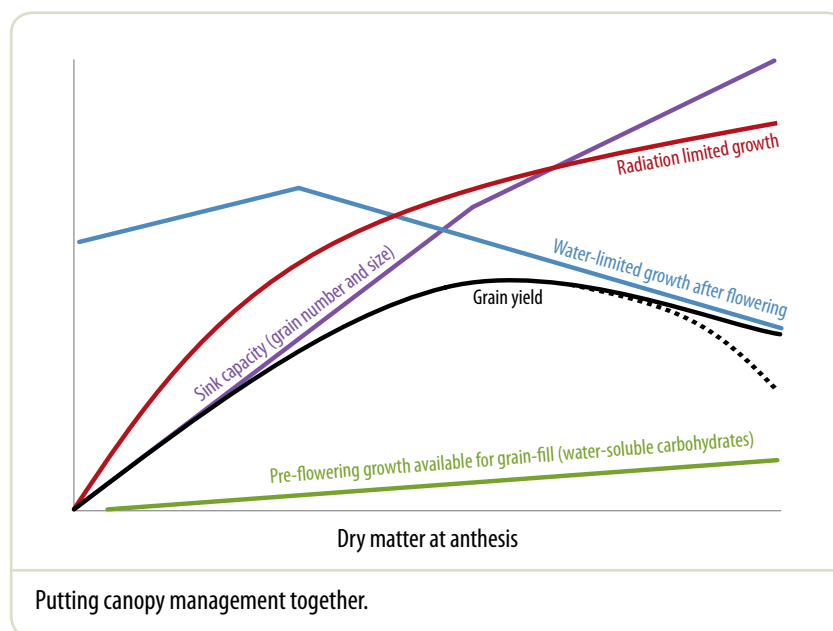
Fungicides as canopy management tools

Although fungicides protect yield potential by controlling disease infection, they are in effect canopy management tools. By protecting the crop from disease they increase the green leaf retention or green leaf duration (GAD). Provided soil water is available to the crop, fungicides exert their greatest influence on yield post-flowering (in many cases long after the nature of the disease can be identified) by allowing the green leaves to manufacture carbohydrate and translocate that carbohydrate directly into the developing grain (see section 2, page 12).

Putting it all together

You can see from these three steps why delaying nitrogen applications until after the end of tillering is one of the most important tools used in canopy management. In highly productive environments restricting the supply of applied nitrogen during tillering reduces the number of tillers that are produced to a manageable level, this is particularly important where crops are sown earlier and soil nitrogen levels are high. Applying nitrogen at the start of stem elongation ensures that the crop will not become stressed during this critical period for yield potential (maintain grain number per head and potential grain size), and will keep its canopy as green as possible for as long as possible after anthesis to maximise growth for filling grain.

The way in which we traditionally managed crops in southern Australia (rotating with legume-based pastures, high seeding rates, high rates of phosphorous and nitrogen fertiliser at seeding) tends to over-emphasise



pre-anthesis growth – hence the need for canopy management to ensure that pre and post-anthesis growth are balanced to achieve efficient conversion of water into grain. The figure above is a schematic diagram of the trade-offs that are made in order to optimise a crop's growth for grain yield.

The success of canopy management of a given wheat crop is best measured by the harvest index. A good harvest index (>0.4 in Australia) and water use efficiency indicate that the distribution of pre and post-anthesis water use and growth was optimal, and that nitrogen supply was matched to water-limited demand.

KEY POINTS

Canopy management in a nutshell

1. Select a target head density for your environment (350 to 400 heads per square metre should be sufficient to achieve optimum yield even for yield potential of 7 tonnes per hectare).
2. Adjust canopy management based on paddock nutrition, history and seeding time to achieve target head density.
3. Established plant populations for wheat of between 80 and 200 plants/m² would cover most scenarios.
4. Lower end of range (80–100 plants/m²) – earlier sowings/high fertility and or low yield potential low-rainfall environments.
5. Higher end of the range (150–200 plants/m²) – later sowings, lower fertility situations and or higher rainfall regions.
6. During stem elongation (GS30–39), provide the crop with necessary nutrition (particularly N at GS30–33 pseudo stem erect – third node), matched to water supply and fungicides to:
 - a. maximise potential grain size and grain number per head;
 - b. maximise transpiration efficiency;
 - c. ensure complete radiation interception from when the flag leaf has emerged (GS39); and
 - d. keep the canopy green for as long as possible following anthesis.

Keeping tiller number just high enough to achieve potential yield will help preserve water for filling grain and increase the proportion of WSCs.

The timing of the applied N during GS30–33 window can be adjusted to take account of target head number; earlier applications in the window (GS30) and can be employed where tiller numbers and soil nitrogen seems deficient for 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 will result in less tillers surviving to produce a head.

2. Disease Management – Ensuring Profitable Intervention

Foliar fungal diseases and leaf area duration

In disease susceptible cereals, the benefit of a fungicide for disease control impacts most strongly on yield if it creates differences in green leaf duration after anthesis. However, for any given disease pressure, the principal driver of leaf area duration (LAD) is soil water availability and temperature, not fungicide. The decision to apply a fungicide to prolong green area duration must be made in the knowledge that soil water and temperature have an overriding influence and that fungicide application is an insurance input. Any benefit will be observed only after it is known whether a fungicide was required.

How should fungicide strategies be adjusted when moving from a high-rainfall zone to lower-rainfall regions?

In regions of lower-rainfall the LAD of the crop canopy is reduced post-anthesis, in effect the flag leaf and flag-1 do not stay as green for as long. Under these circumstances the post-anthesis contribution to yield (in terms of photosynthesis) of the two top leaves is reduced (although, pre-anthesis, these leaves may have contributed to the soluble stem carbohydrate reserves that are mobilised to the grain). Under these circumstances the value of any fungicide application will also be reduced, therefore strategies for fungicide application need to change:

- in the lower-rainfall zones where stressed grain-filling periods are more typical, the target for a single fungicide can be earlier than flag leaf emergence (GS37–39), since the flag is relatively less important to protect from disease. In these cases the emergence of the flag-2 and flag-1 leaves (second-third node GS32–33) become more critical if growers are restricted to a single application; and
- in the high-rainfall zone (HRZ) the optimum timing for a single spray tends to be later at flag leaf emergence (GS37–39) since earlier sprays fail to protect the flag leaf, which, given better grain filling conditions, becomes a far more important source of carbohydrate.



Management strategies for rust control

Stem rust

Fungicides can be employed successfully to control stem rust in wheat (*Puccinia graminis f.sp. tritici*) but timing in relation to disease development is crucial. However, fungicide activity will be limited in scenarios where the disease is well established at the time of application. There are key differences in the performance of foliar fungicides against this disease.

Stripe rust

For stripe-rust-susceptible cultivars, foliar fungicides applied on the basis of growth stage offer greater opportunities to protect the crop canopy (and pre-plan strategy for larger acreages) than basing decisions on disease thresholds. Stripe rust infection occurring at earlier growth stages (pre-flag leaf emergence) can result in to greater yield loss and the need to consider two foliar fungicide applications for stripe rust control (assuming a superior at-sowing fungicide has not been applied). Research with very susceptible (VS), susceptible (S) and moderately susceptible (MS) cultivars has shown that later sowings can give greater response to fungicides than earlier sowings due to initial infection occurring at earlier growth stages.

Management strategies for disease control in barley

In project trials using the susceptible cultivars Baudin^{db} and Vlamingh^{db} the most cost-effective fungicide programs have been based on applying two foliar fungicide sprays, the first at early stem elongation (GS30–31) with a second dose three to four weeks later at first awns emerging (GS49). The FAR trials conducted in southern Western Australia by Kalyx revealed that a two-spray strategy based on Prosaro[®] and Amistar Xtra[®] was particularly cost-effective in control of leaf rust and mildew. The value of foliar fungicides in lower-rainfall regions (for example the Victorian Mallee) has been marginal, particularly when the target disease has been spot form of net blotch.

Impact of powdery mildew resistance on triazole fungicides

In 2010 it was announced that strains of powdery mildew resistant to triazole fungicides had been isolated from barley crops in south western WA, predominantly the south coastal region and western areas of the Great Southern region. In 2012, a mutation in barley powdery mildew conferring resistance to triazole fungicides was found in eastern Australia. Although the situation may change as more information becomes available, at present not all triazole fungicides in the demethylation inhibitors (DMI) fungicide family are affected.

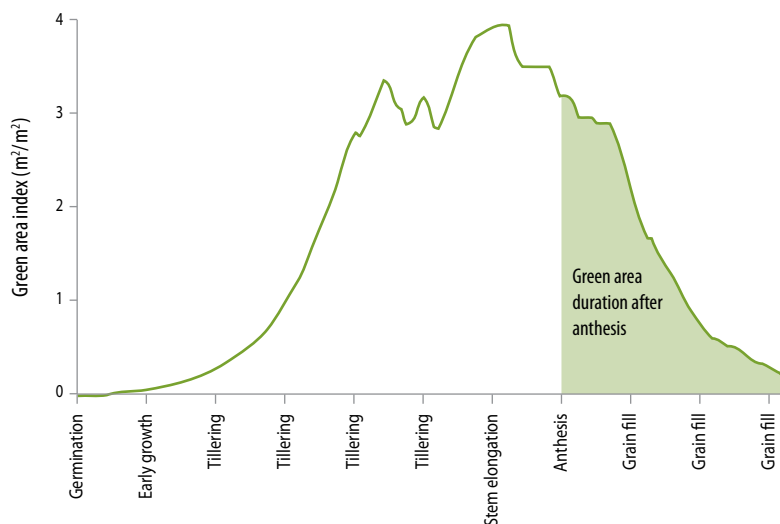
Foliar fungal diseases and leaf area duration

James Hunt, CSIRO, Nick Poole and Tracey Wylie, FAR.

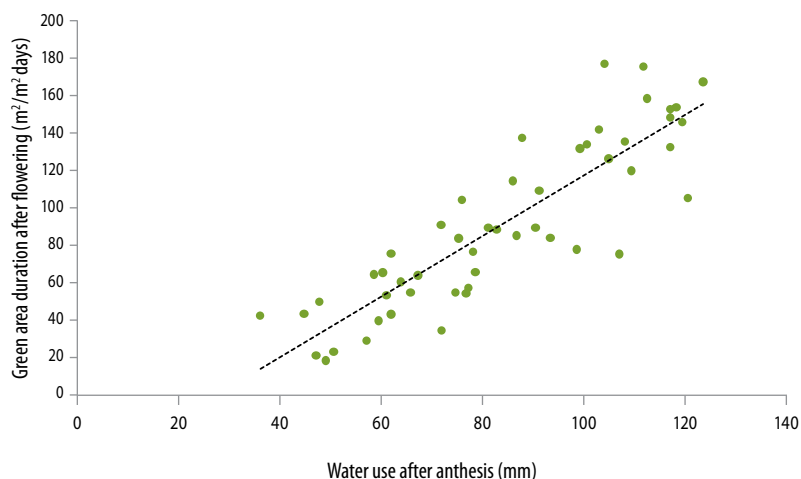
Grain yield of cereal crops is strongly linked to the amount of light the green areas of the crop canopy are able to intercept after anthesis and the amount of carbohydrate produced. The amount of radiation that is intercepted is determined by the amount of green (photosynthetic) area in the canopy and the length of time that this green area is maintained. The photosynthetic area of a crop canopy can be measured as the leaf area index (LAI), which is the amount of leaf area in square metre per square metre of ground (see section 1 'The physiological basis for canopy management'). In cereal crops, plant stems, leaf sheaths and heads also intercept radiation and contribute significantly to yield, so the term green area index (GAI) is more useful. The amount of time over which a crop canopy stays green after anthesis can be expressed as green area duration (GAD), and can be measured in m^2/m^2 days. For example, a crop that has a GAI of 2m^2 of green area for every square metre of ground over a period of five days will have a green area duration of $10\text{m}^2/\text{m}^2$ days.

Grain yield is very strongly related to the GAD of a crop's canopy after it has flowered, as GAD is a measure of how much light a crop is able to intercept and potentially how much carbohydrate can be produced through photosynthesis. Almost all photosynthate produced after anthesis is partitioned into grain (see section 1 'The physiological basis for canopy management').

In water-limited environments, the amount of photosynthetic area that a crop is able to maintain post-anthesis is primarily determined by water availability. Provided that water supply is sufficient, then nitrogen supply, extreme temperatures and foliar fungal diseases also become important determinants of GAD.



The simulated development and decline in green area index during different growth stages of a barley crop. Green area duration after anthesis is represented by the shaded area.



The relationship between water use after anthesis and green area duration after anthesis for barley at Munglinup, southern Western Australia. In water limited environments, green area duration after anthesis is primarily determined by water availability after anthesis.

How do fungicides work?

Foliar fungal diseases of wheat and barley such as stripe rust, leaf rust and powdery mildew act to reduce yield by reducing the post-anthesis GAD of the canopy and the amount of light the canopy intercepts – and its capacity to produce carbohydrate to put into growth of grain. Foliar fungicides applied during stem elongation act by protecting leaf area and thus maximise light interception and growth.

Foliar disease management in Australia is further complicated because grain yields in most areas and seasons are limited by water supply. As a result, water supply in the post-anthesis period is the ultimate driver of GAD and radiation interception. This is a problem for managers who must decide at flag leaf emergence (GS39) whether to apply foliar fungicide. Fungicide application will potentially increase GAD and yield, but water deficiency may be a stronger limit to GAD. Under which circumstances no increase in yield from fungicide protection is likely.

While it is impossible to accurately forecast how much water a crop will have for growth after anthesis due to the variability of spring rainfall, it is possible to use a crop simulator such as APSIM/Yield Prophet® to accurately simulate the relationship between GAD post-anthesis and grain yield due to water availability. It can predict a likely range of outcomes based on soil water, nitrogen and crop growth to date.

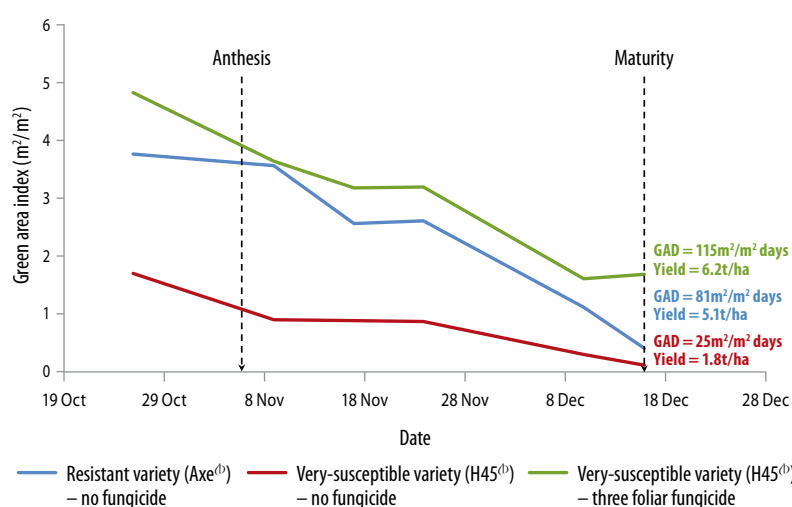
Experiments conducted as part of this project have demonstrated that a reduction in GAD due to foliar fungal diseases has exactly the same effect on yield as water stress. Consequently the relationship between GAD post-anthesis and yield derived from APSIM can be used to estimate how a foliar disease may reduce yield.



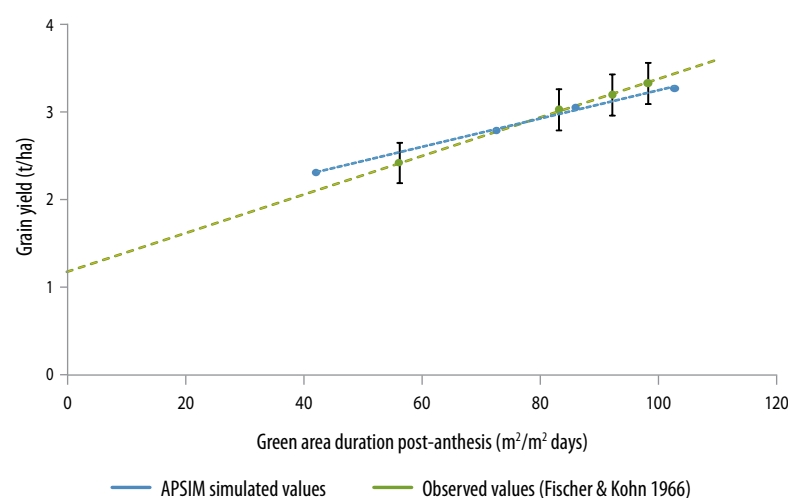
Three foliar fungicides.
Green cover = 57%



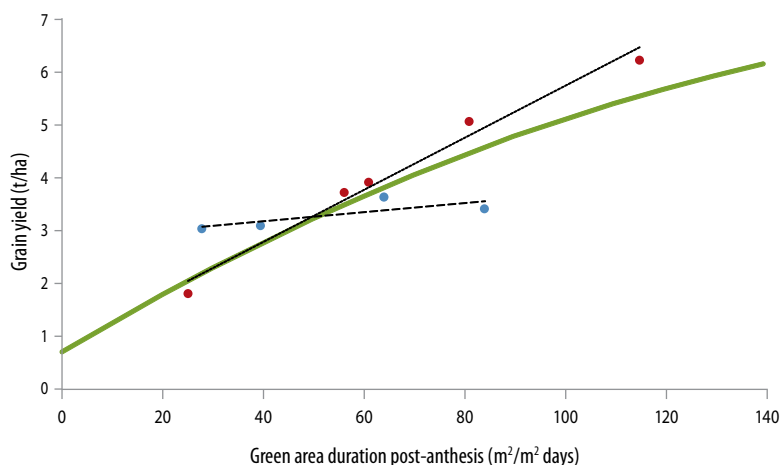
Zero foliar fungicides.
Green cover = 13%



Green area index of wheat post-anthesis with different stripe rust management treatments.



APSIM is able to accurately simulate the relationship between green area duration after anthesis and grain yield due to water availability, as measured in field experiments.



• Wheat & stripe rust – Canberra, 2010 • Barley & leaf rust – Munglinup, 2010 — APSIM, general relationship

The relationship between green area duration as determined by water availability and yield and simulated by APSIM, is the same as the relationship between leaf area duration as determined by foliar fungal pathogens and yield as measured in field experiments at Canberra and Munglinup in 2010.



Green leaf retention calculator

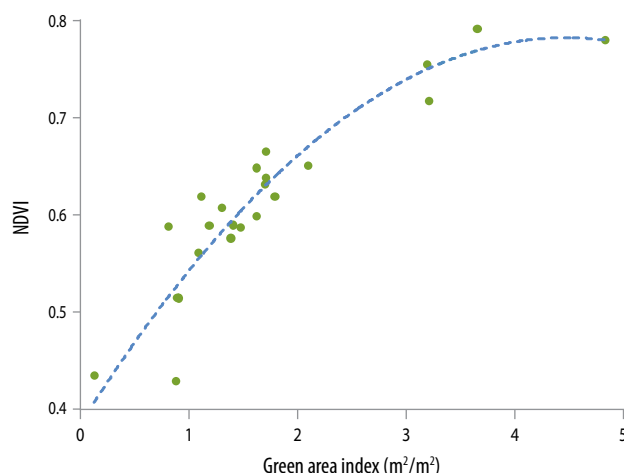
The relationship between green area duration (GAD) post-anthesis and yield derived from APSIM can be used to estimate how a foliar disease may reduce yield. Yield reduction can be estimated from the table below by nominating an expected yield of a healthy crop, and the anticipated level of GAD reduction due to foliar fungal infection. Future research aims to nominate likely reductions in GAD for different timing of infections and cultivars of different susceptibility.

Expected yield of healthy crop (t/ha)	Expected reduction in green area duration post-anthesis (%)							
	5%	10%	20%	30%	40%	50%	60%	70%
Estimated yield of diseased crop (t/ha)								
1.0	1.0	1.0	1.0	0.9	0.9	0.9	0.8	0.8
2.1	2.1	2.0	1.8	1.7	1.6	1.4	1.3	1.1
3.3	3.2	3.0	2.8	2.6	2.3	2.1	1.8	1.5
4.4	4.3	4.1	3.8	3.5	3.1	2.8	2.4	2.0
5.5	5.3	5.1	4.8	4.4	3.9	3.5	3.0	2.5
6.3	6.2	6.0	5.7	5.2	4.8	4.2	3.6	3.0
6.9	6.8	6.7	6.4	6.0	5.5	4.9	4.3	3.5



Could crop sensors help to better visualise green leaf duration?

A problem confronting managers contemplating fungicide application is that it is hard to visualise green area duration (GAD) let alone estimate the impact that a fungal disease will have on a given cultivar of a given susceptibility at a given growth stage. Fortunately, crop sensors (GreenSeeker®, Crop Circle™ etc.) may provide a cheap and easy way of visualising GAD, as NDVI (the Normalised Difference Vegetation Index – the output from scanners) is closely related to GAI. NDVI data can be gathered from pathology trials, and some general rules of thumb developed which would allow Yield Prophet® to be used at stem elongation to estimate the likely response to applying fungicides. Initial indications from wheat have been promising; however, the relationship was not as clear in barley where the angle of the head later in grain filling obscured the NDVI readings from the leaves in the canopy.



Green area index and NDVI of H45^{cl} wheat with different stripe rust management treatments at Canberra in 2010. There is a very good relationship between NDVI as measured by crop sensors such as the GreenSeeker® and Crop Circle™ and GAI ($R=0.88$). Crop sensors may provide a rapid method for measuring the effect of foliar fungal pathogens on GAD.

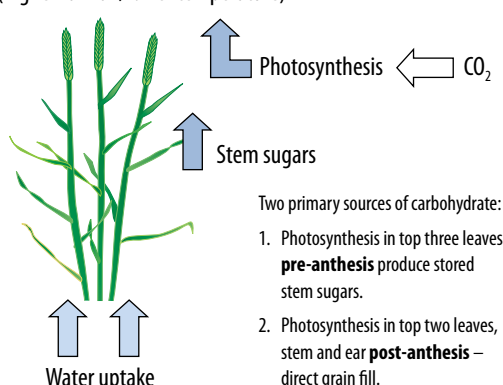
How should fungicide strategies be adjusted when moving from a high-rainfall zone to lower-rainfall regions?

Fungicides do not create yield they only protect an inherent yield potential that the crop would have produced in the absence of disease. This is achieved by protecting the plants sources of carbohydrate production for grain fill; the leaves, leaf sheaths, stem and head.

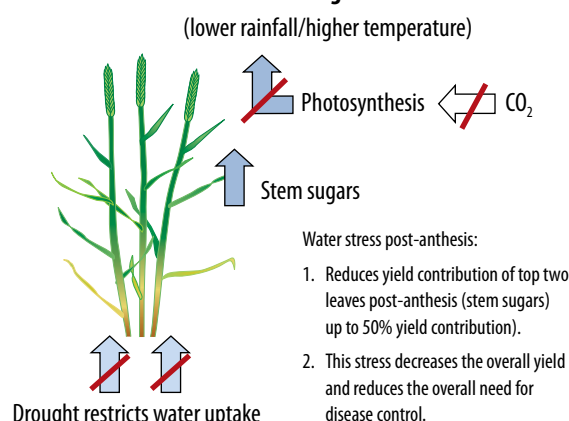
In terms of disease management the plant has two distinct sources of carbohydrate for grain fill: soluble stem carbohydrate reserves that are stored prior to peak anthesis (flowering) at GS65 and the carbohydrate produced by the leaves, stem and head for direct grain filling after anthesis (GS71–89).

Before anthesis (GS60–69) the plant is using most of its resources to develop a bigger crop canopy (since there are no fertilised grain sites yet to fill). At head emergence (GS50–59) when the canopy usually reaches its maximum size, carbohydrates are increasingly diverted to storage in the stem.

Non-stressed grain fill (higher rainfall/lower temperature)



Stressed grain fill (lower rainfall/higher temperature)



Reproduced from graphics courtesy Dr Neil Fettell.

How much yield contribution comes from pre-flowering (pre-anthesis) soluble sugars in wheat?

The relative importance of stored soluble

stem carbohydrates increases in regions where crops are typically stressed during grain fill. The total contribution of stem stored carbohydrate accumulated pre-anthesis

changes little between stressed and non-stressed but its relative importance increases considerably under more stressful grain fill conditions.

Variety	Water Status	Yield t/ha	Pre-anthesis carbohydrate contribution t/ha	Pre-anthesis contribution as a % total grain fill
Wheat	Stress	3.41	1.16	33%
	No stress	4.46	1.06	22%
Triticale	Stress	3.02	1.39	51%
	No stress	5.01	1.60	21%

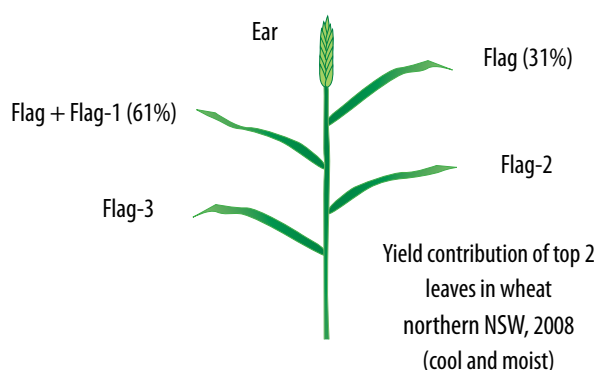
The role of stored soluble stem carbohydrate reserves in stressed and non-stressed grain fill periods. (N. Fettell, NSW – Cereal Disease Management Workshops for Advisers – ICAN 2011)

Contribution of the top leaves to final yield in wheat – how the value changes dependent on region and season?

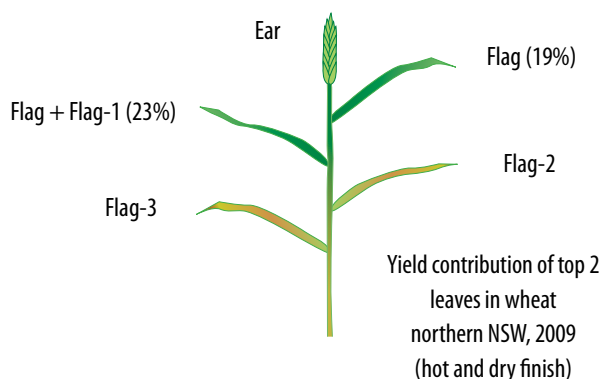
Although lower-rainfall regions typically experience greater stress during the grain fill period it is also common for the same region to exhibit a soft finish in one season and a hard finish in the next. Studies in northern NSW have shown large differences in the yield contribution of the top two leaves dependent on season. In addition, in a season with a softer finish in a northern NSW environment, the yield contribution of the flag and flag-1 was more evenly weighted than in a longer season soft finish such as might be experienced in the UK where the flag leaf has typically greater importance than flag-1.

In regions of lower rainfall and greater heat stress the contribution of the top two leaves (flag leaf and flag-1), stem and head are reduced post-anthesis (GS70 onwards), relative to the high-rainfall zone (HRZ). This results in lower yield overall and greater dependence on the redistribution of stored soluble stem carbohydrates accumulated prior to anthesis. In contrast in the HRZ and/or where heat stress is less problematic the photosynthetic activity of the crop canopy post-anthesis has far more influence on final grain yield and the need for fungicide protection in the top two leaves of the crop canopy where a disease pathogen is present.

Contribution of top two leaves to yield in wheat – Non stressed grain fill – Tamworth, northern NSW, 2008



Contribution of top two leaves to yield in wheat – Stressed grain fill – Tamworth northern NSW 2009



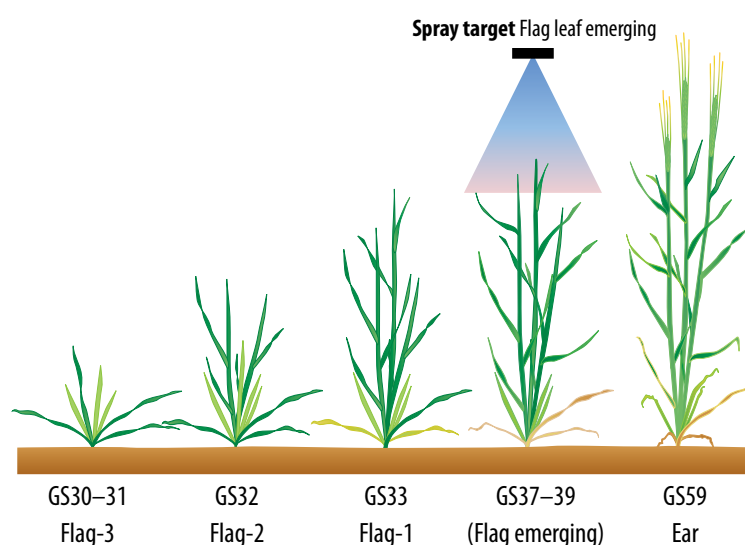
Courtesy of A. Bowring NSW I & I.

What are the consequences of stressed grain fill periods on the need for disease management?

In regions of lower rainfall, green area duration (GAD) of the crop canopy is reduced at post-anthesis. In effect the flag leaf and flag-1 do not stay as green for as long. Under these circumstances:

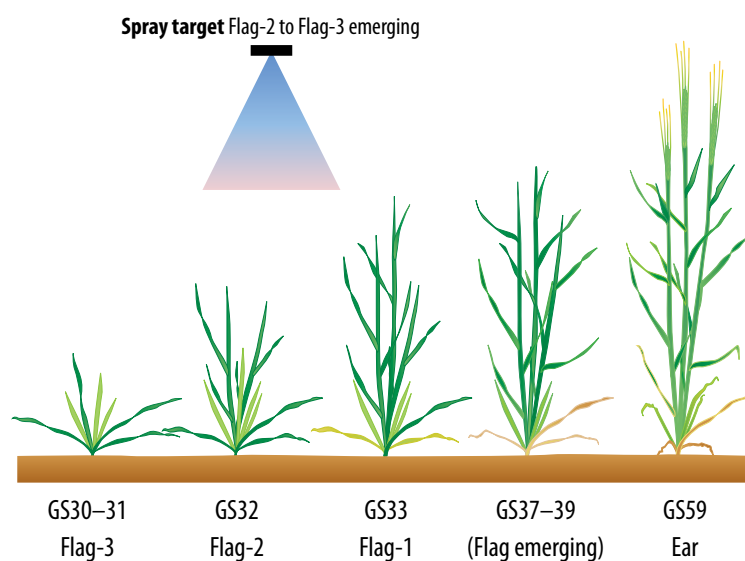
- The contribution to yield (in terms of photosynthesis) of the two top leaves is reduced post-anthesis, **note this does not mean that they do not contribute to the soluble stem carbohydrate reserve pre-anthesis.**
- With less duration of these top two leaves post-anthesis (GS70 onwards) overall yield is reduced, but more importantly the value of any fungicide application will also be reduced.
- Though the top two leaves are still important for the production of stored carbohydrates particularly just prior to anthesis (GS55–59), it takes time for disease to establish in the flag leaf and flag-1 meaning that both leaves stay relatively clean up to anthesis after which drought or heat stress curtail GAD.
- Lower rainfall and/or heat stress also reduces the ability of disease to re-infect the crop, due to the reduced humidity in the canopy.
- Fungicides applied to the top three leaves have less opportunity to express their benefit if the leaves they are protecting senesce prematurely.
- If limited to a single foliar fungicide spray, (whether the region is typically a low-rainfall or high-rainfall zone (HRZ)) the target growth stage can be influenced.
 - In the HRZ the optimum timing for a single spray tends to be later, at flag leaf emergence (GS37–39). Earlier sprays provide no direct protection to the flag leaf which, given better grain fill conditions, is a far more important leaf.
 - In the lower-rainfall zones, where stressed grain fill periods are more typical, the target for a single fungicide can be earlier than flag leaf emergence (GS39), since the flag is relatively less important post-anthesis. In these cases flag-2 and flag-1 emergence (second–third node GS32–33) should be the focus of fungicide application.

Focus on the emerging flag leaf on the main stem GS37–39



Non-stressed grain fill – Target for a single fungicide application to give greatest return (assuming only one application can be made for a given stripe rust infection occurring at GS32–33).

Focus on the two emerging leaves below flag GS32–33



Stressed grain fill – Target for a single fungicide application to give greatest return (assuming only one application can be made for a given stripe rust infection occurring at GS32–33).

Please note: Applications of two fungicides at GS31–32 followed by GS39 are likely to give greater returns where susceptible cultivars have developed infection prior to GS33 in a non-stressed grain fill period. **However this schematic assumes that the grower is limited to a single spray.**



Management strategies for rust control

Nick Poole and Tracey Wylie, FAR.

Stem rust control in wheat

Stem rust is a significant disease, and for crop managers, the following questions are important.

- How does a fungicide product and rate influence stem rust control?
- How important is fungicide timing for stem rust control?
- Is post-infection control of the disease possible at later growth stages?
- What is the role of cultivar resistance in the control of stem rust?

Following favourable conditions for stem rust development in 2010, six project trials were set up to gather fungicide efficacy data for stem rust control. Fungicide products were evaluated across a range of rates (**N.B. the use of a fungicide or use at rates lower than the label does not constitute a recommendation in this guide**). Since the disease developed late in the season, there was less opportunity to test the influence of fungicide timing, however, some data was collected.

How does fungicide product and rate influence stem rust control?

Seven fungicides were evaluated in 2010 at four trial sites: 1. Booleroo, SA, 2. Jamestown, SA, 3. Quambatook, Victoria (Mallee) and 4. Inverleigh, Victoria (high-rainfall zone (HRZ)). At three sites fungicides were applied before stem rust infection was visible in the crop, however at the Booleroo site products were sprayed at very low levels of infection (less than 10% sheaths infected). Fungicide products were applied at three rates (low, intermediate and high). In many cases the high rate was the label rate for stem rust control for products registered for stem rust control.

2010 Trial Sites – Fungicide treatments and application rates. Label rates for stem rust control are highlighted (note Amistar Xtra® and Opus® are not currently registered for stem rust control in Australia).

Trt	Fungicide treatment and rate	Rate description	Active ingredient
1.	Prosaro® 75mL/ha + A	Low	Prothioconazole + tebuconazole
2.	Prosaro® 150mL/ha + A	Mid	
3.	Prosaro® 300mL/ha + A	High	
4.	Opus® 125mL/ha	Low	Epoiconazole
5.	Opus® 250mL/ha	Mid	
6.	Opus® 500mL/ha	High	
7.	Amistar Xtra® 200mL/ha	Low	Azoxytrobins + cyproconazole
8.	Amistar Xtra® 400mL/ha	Mid	
9.	Amistar Xtra® 800mL/ha	High	
10.	Tilt® 125mL/ha	Low	Propiconazole
11.	Tilt® 250mL/ha	Mid	
12.	Tilt® 500mL/ha	High	
13.	Tilt Xtra® 125mL/ha	Low	Cyproconazole + propiconazole
14.	Tilt Xtra® 250mL/ha	Mid	
15.	Tilt Xtra® 500mL/ha	High	
16.	Folicur® 72.5mL/ha	Low	Tebuconazole
17.	Folicur® 145mL/ha	Mid	
18.	Folicur® 290mL/ha	High	
19.	Opera® 250mL/ha	Low	Pyraclostrobin + epoiconazole
20.	Opera® 500mL/ha	Mid	
21.	Opera® 1000mL/ha	High	
22 to 24.	Untreated		

A – Adjuvant applied.

2010 Trial Sites – Application details (date, growth stage, water rate and nozzle settings).

Trial	Site	Application Date	Growth Stage	Water rate L/ha	Nozzles and Pressure
Trial 1	Booleroo, SA	19 Oct	GS72 (early milky ripe)	107	015 flat fan nozzles, 1.5 bar
Trial 2	Jamestown, SA	26 Oct	GS71 (watery ripe)	107	015 flat fan nozzles, 1.5 bar
Trial 3	Quambatook, Vic	27 Oct	GS69 (end of flowering)	160	DG 110-02, 2.0 bar
Trial 4	Inverleigh, Vic	10 Nov	GS55 (50% ear emergence)	100	110-02 flat fan, 3.0 bar
Trial 5	Corack, Vic	5 Nov	GS77 (late milky ripe)	160	DG 110-02, 2.0 bar
Trial 6	Gippsland, Vic	11 Nov	GS82 (50% ear emergence)	100	110-02 flat fan, 3.0 bar

Trial 5 was used to assess late fungicide application post-infection. Trial 6 examined the interaction between fungicide control and cultivar resistance.

The infection came in late at all of these trial sites, first infection being evident from early grain fill (GS71). In the three shorter season environments, Booleroo, Jamestown and Quambatook physiological maturity arrested the disease, which had steadily increased until that stage.

Yipti[®] (S – susceptible stem rust rating) was the cultivar used in all the trials, except in the HRZ (Trials 4 and 6) where Beaufort[®] (S – susceptible stem rust rating) and other wheat cultivars were used.

Stem rust development in the untreated plots at the four primary trial sites (relative to the date of fungicide application in the trial) – assessed on the flag leaf sheath.

Trial Site	Assessment method	% Stem rust in untreated (relative to days following fungicide application)			
		0 days	7 days	14 days	22–34 days
Booleroo	% Incidence	6	14	94	99
	% Severity	0	0.2	2.2	6.5
Jamestown	% Incidence	0	2	28	95
	% Severity	0	0.01	0.3	1.9
Quambatook	% Incidence	0	0	7	83
	% Severity	0	0	0.07	3.2
Inverleigh	% Incidence	0	0	16	93
	% Severity	0	0	0.11	2.9

Influence of fungicide rate (mean of fungicide products – four site mean)

Stem rust control assessed over the four trial sites revealed that using high rates was essential for the control of the disease, even if the fungicide had been applied prophylactically (before infection was visible in the crop). There was a significant advantage to the high rate of fungicide (87% control) over the intermediate rate (76% control), which in turn was superior to the low rate (61% control).

Influence of fungicide product and rate on stem rust control – four site mean

At the high rate of fungicide, the formulated mixtures azoxystrobin/cyproconazole (Amistar Xtra[®]), propiconazole/cyproconazole (Tilt Xtra[®]) and prothioconazole/tebuconazole (Prosaro[®]) gave significantly better disease control (92 to 93% control) than propiconazole (for example Tilt[®]) at 500 millilitres per hectare (75% control). At the intermediate rate, a rate which it must be stressed is below the label rate

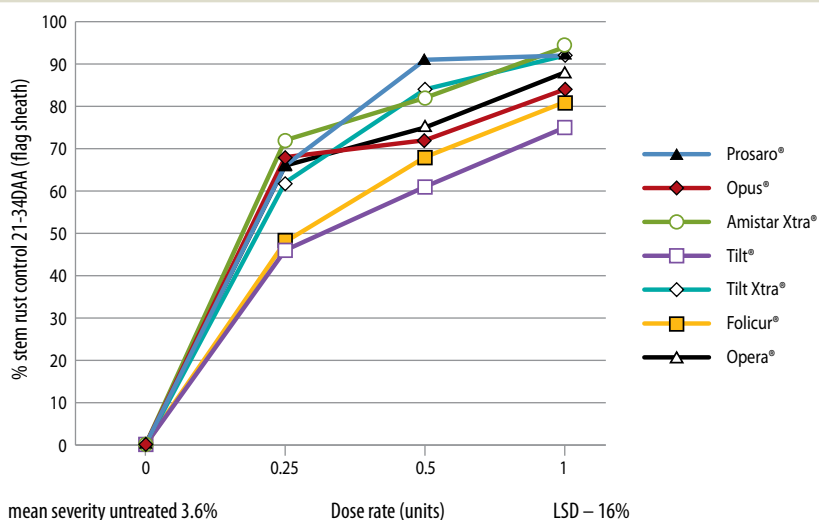
for most of the products, the spread of performance was greater with Prosaro[®] performing significantly better than single active ingredients epoxiconazole (Opus[®]), tebuconazole (Folicur[®]) and propiconazole (Tilt[®]). At the lowest rate of active ingredient disease control ranged from 46 to 71% control, tebuconazole (Folicur[®]) propiconazole (Tilt[®]) being statistically inferior to all other fungicides except propiconazole/cyproconazole (Tilt Xtra[®]).

Was it economic to spray for stem rust in these trials?

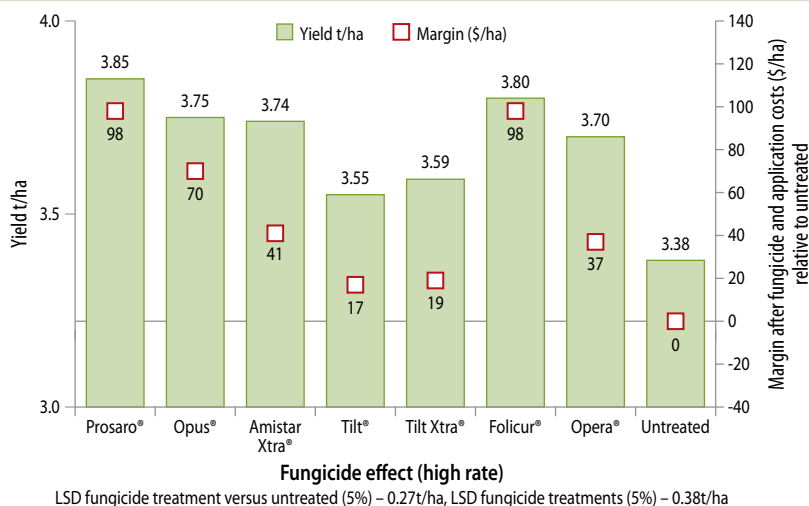
Three trials were taken to harvest in 2010.

At Booleroo in SA yield responses were very small, the only treatments to significantly out-yield the untreated were at intermediate or high rates of application. There was no significant difference in yield between the fungicide treatments (yields ranging from 4.0 to 4.29 tonnes/ha with an untreated yield

of 4.14t/ha). At Quambatook in Victoria all full rate fungicides applied gave significantly higher yields than the untreated, except propiconazole (Tilt®) and propiconazole/cyproconazole (Tilt Xtra®). The significant yield increases ranged from 0.29 to 0.45t/ha and all gave rise to economic yield increases; however, it was lower-cost fungicide products such as Folicur®, Prosaro® and Opus® that gave the greater margins in this trial.



Influence of fungicide product and rate on stem rust infection in wheat, expressed as % control of stem rust (severity of disease on the leaf sheath relative to the untreated at 0% control) – four site mean 2010.



Influence of full-rate fungicide application for the control of stem rust on the yield (t/ha) and margin after fungicide and application cost (\$/ha) – Quambatook, Victoria, crop variety Yipti[®].

Note: grain price \$317/t; 2.5% wheel damage was subtracted from the treated yield.

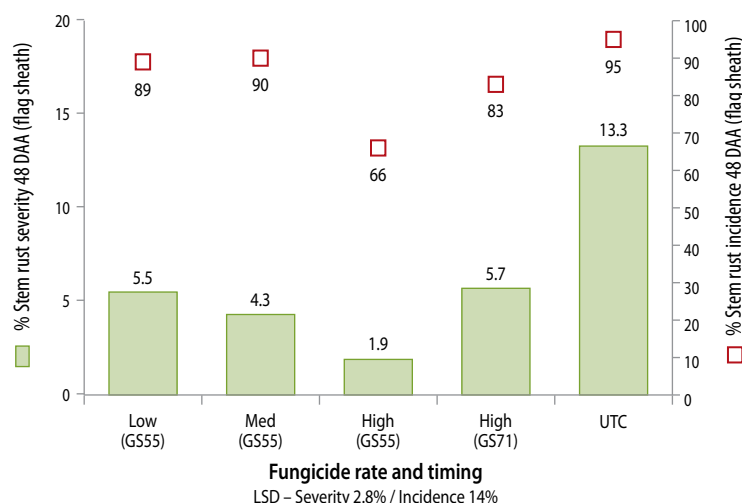
How important is fungicide timing for stem rust control?

Due to the late nature of infection during 2010, fungicide timing pre and post-infection could only be evaluated in the longer season environment in southern Victoria, on the feed cultivar LongReach Beaufort[†]. The trial (Trial 4 – Inverleigh) compared fungicide application pre and post-infection. Application of the same seven fungicides (as outlined earlier) were made at the high rate at 50% ear emergence (GS55) pre visible infection, and then again 16 days later at early grain fill-watery ripe stage (GS71).

Comparisons of stem rust control between the two timings illustrated that when the plant structure to be protected is already infected with stem rust the ability of the fungicide to control the disease is reduced. At GS71, when the second fungicide timing was applied, the flag leaf sheath was already infected (16% flag sheaths infected), in comparison to the earlier application at ear emergence when no infection was noted. As a consequence the stem rust control achieved with high rates applied late (GS71) was significantly inferior to the same rates used earlier (GS55) and was no better for stem rust control than the low and intermediate fungicide applications.

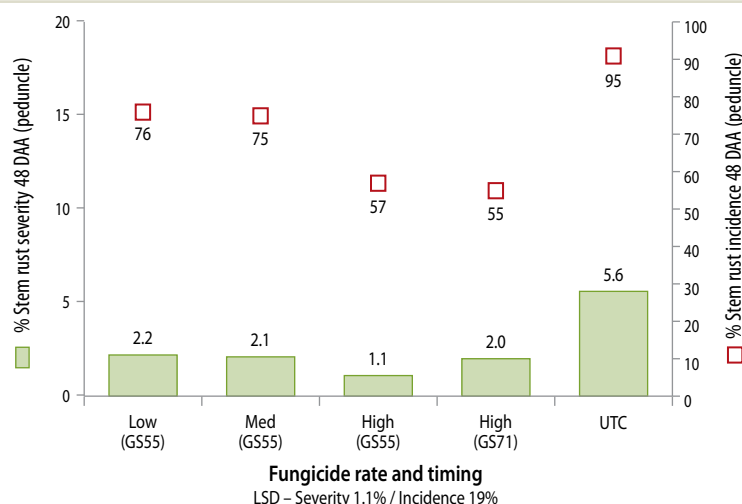
In contrast, the peduncle (the true stem beneath the ear) was not fully exposed to the fungicide at the ear emergence timing (GS55) (since it was still inside the sheath) and the later application timing, at grain fill (GS71), was applied with no visible infection in the peduncle. In this case there was no significant difference in stem rust control between the two timings for the protection of this part of the plant, though the trend was for the earlier spray to be more effective.

Pre-stem rust infection applications at 50% ear emergence (GS55) gave better control of the disease on the **flag leaf sheath** than post-infection applications made 16 days later at GS71.



Influence of fungicide timing at 50% ear emergence (GS55) v watery ripe (GS71) and rate of application on stem rust (% incidence and severity) **on the flag leaf sheath** 48 days after fungicide application at GS55 and 32 days after fungicide application at GS71 (mean of seven fungicide products) – cv Beaufort[†], Inverleigh (HRZ), Victoria.

In contrast, since the peduncle was not exposed at the time of the pre-infection spray, there was no significant difference in control of stem rust on this part of the plant when pre and post-fungicide application were compared.

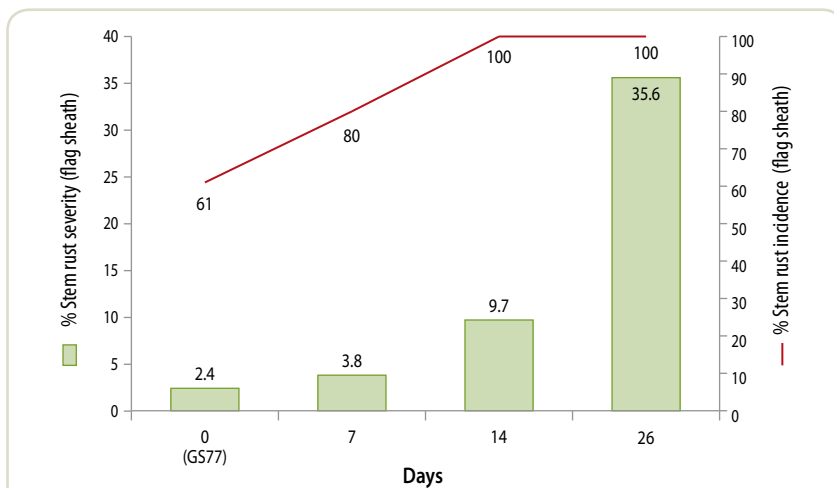


Influence of fungicide timing at 50% ear emergence (GS55) versus watery ripe (GS71) and rate on stem rust (% incidence and severity) **on the peduncle** 48 days after fungicide application at GS55 and 32 days after fungicide application at GS71 (mean of seven fungicide products) – cv Beaufort[†], Inverleigh (HRZ), Victoria.

What is the value of fungicide application post infection at the late milk stage of grain fill?

In an additional trial (Trial 5), set up at Corack in the Victorian Mallee, 60% of stems showed infection when the fungicides were applied at the late milky ripe stage (GS77). In this trial fungicide application was made at a later growth stage and at a higher level of initial infection than in the four previous trials. The disease increased very rapidly. At physiological maturity (GS89–90) 35% of the flag leaf sheath area was infected by the disease and 31% of the peduncle. Though the same treatment trends were exhibited on the peduncle, the difference between products and rates was only significant on leaf sheaths when assessed 26 days after application.

In this trial fungicide control was relatively poor with full rate products only giving 41 to 69% control of the disease. There were no significant yield differences and fungicide application was ineffective at creating a profitable return, although there was a trend to higher rates and some products (Prosaro®) providing better control.



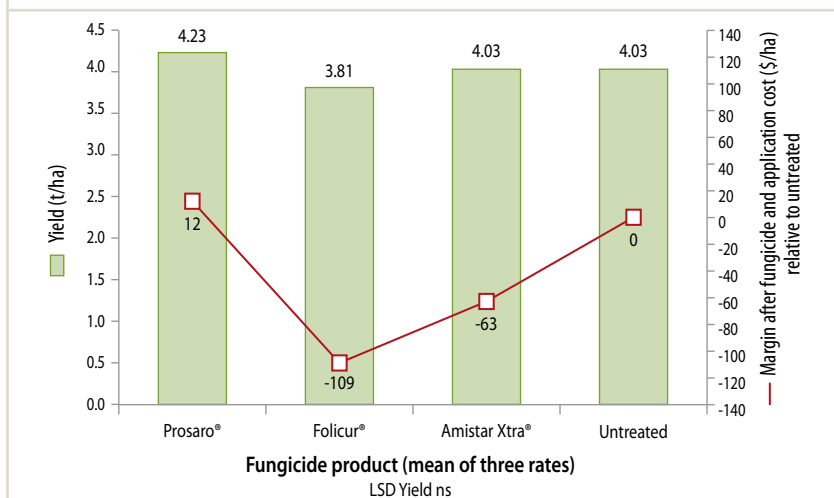
Stem rust development (% incidence and severity) on the flag sheath of the **untreated crop** zero, seven, 14 and 26 days following trial treatment application at GS77 – Corack, Victoria.

Fungicide treatment	% Stem rust infection on flag leaf sheath					
	Low Rate		Mid Rate		High Rate	
	% Severity	% Control	% Severity	% Control	% Severity	% Control
Prosaro®	18	50	17	53	11	69
Folicur®	28	22	22	39	21	42
Amistar Xtra®	17	53	20	44	17	53
Mean	21	42	20	44	16	56

LSD (Treatment comparisons at same rate) – 9%, LSD (Treatment comparisons at all rates) – 9%, Untreated – 36% infection.

Influence of fungicide product on disease severity (% of assessed leaf area with stem rust necrosis) and % control of stem rust on the flag sheath at the three application rates tested 26 days after application (26 DAA) – GS89–90 (physiological maturity) – Trial 5 Corack, (Mallee) Victoria, 2010.

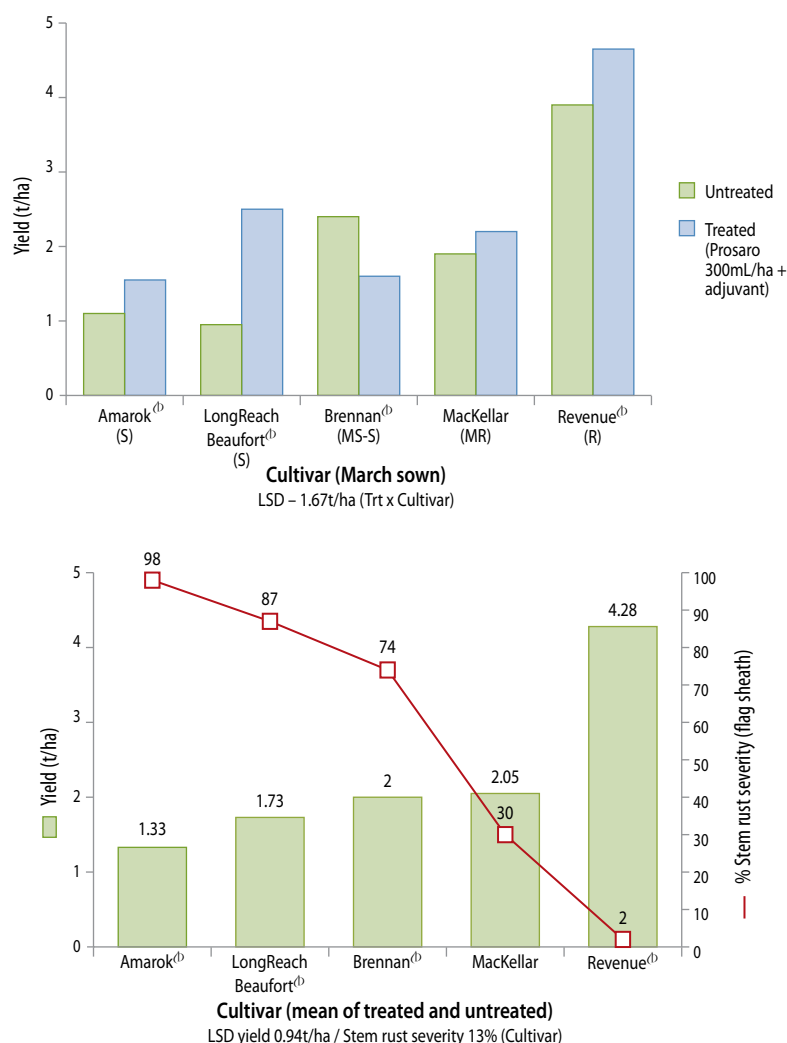
Applications of fungicides made at the late milky stage (GS77) when the crop already had 60% stem infection were uneconomic.



Influence of fungicide application at late milky ripe (GS77) for the control of stem rust on the yield (t/ha) and margin after fungicide and application cost (\$/ha) – (Trial 5) Corack, Victoria, cv Yipti¹.

What is the role of cultivar resistance in the control of stem rust?

Cultivar resistance is crucial for the control of this disease. Information presented in this booklet shows that stem rust can be controlled with foliar fungicides, but the effectiveness of these products is limited once infection becomes established. In trials in Gippsland (Victoria) (trial 6) where stem rust in early November was well established on the stems of susceptible cultivars (100% infection incidence), Revenue's^{db} genetic resistance to stem rust was far superior to the effect of foliar fungicide applied late, both in terms of disease development and yield. Foliar fungicide (Prosaro® 300mL/ha) applied late at the early dough stage (GS82) gave no significant improvement in yield or disease control. There was a strong relationship between cultivar resistance to stem rust and yield; with susceptible cultivars such as Amarok^{db} and Beaufort^{db} displaying the highest level of stem rust and lowest yields whilst the resistant cultivar Revenue^{db} had the lowest levels of stem rust and delivered the highest yields.



Influence of cultivar resistance and fungicide application (Prosaro®) on yield and stem rust severity measured on the flag sheath 18 days after fungicide application at early dough (GS82) and assessed at mid dough – physiological maturity (GS85–90) – Bairnsdale, Gippsland, Victoria, 2010.

Disease thresholds for spraying

This material is sourced from the Department of Primary Industries, Victoria, based on Western Australian data and modified with results of the 2010 eastern states studies.

Crop Growth Stage	% Stems infected	Resistance rating	
		MS-S	MR-MS
Before ear emergence (GS51–59)	1–5	Spray	Monitor
	>5	Spray	Spray
Ear emergence to late milky ripe stage (GS59–77)	>5	Spray	Monitor
	>50	Spray	Spray

Guidelines for Stem Rust Management with Foliar Fungicides

1. Disease control

- Fungicides can be used successfully to control stem rust in wheat (*Puccinia graminis f.sp. tritici*) but timing of application in relation to disease development is crucial.
- In susceptible cultivars fungicide application must be made at a very early stage of disease development, preferably prophylactically.
- Fungicide activity is limited where disease is established in the stem at application; in these cases cultivar resistance was far more effective in the defence against this disease than fungicide application.
- Control of stem rust with fungicides is very rate sensitive, particularly with single active ingredient products such as tebuconazole (Folicur), epoxiconazole (Opus®) and propiconazole (Tilt®), which show a sharp fall-off in activity when label rates for stem rust are reduced. It is therefore important to use full label rates.
- The formulated mixtures (which in most cases apply more total active ingredient and are more expensive) still show reduced activity at lower dose rates but the fall-off in activity is less pronounced.
- Propiconazole (Tilt®) gave significantly poorer stem rust control than the other fungicides tested at full label rates.
- Prothioconazole, the partner triazole to tebuconazole, in Prosaro® was particularly effective on stem rust, making Prosaro® one of the most cost-effective fungicides for control of this disease.
- Though formulations including strobilurin gave good control of the disease at high rates, the lower cost of high (label) rate applications of tebuconazole (Folicur® 290 millilitres per hectare), epoxiconazole (Opus® 500mL/ha) and tebuconazole/prothioconazole (Prosaro® 150mL plus adjuvant and 300mL/ha rate) gave these products better cost benefit ratios (in those trials harvested to date).

2. Yield data

- Stem rust control measures implemented at GS77 (late milk) or later when the crop was already infected were not economic.
- The data collected in these trials questions the effectiveness of fungicides applied at very late grain filling growth stages (GS77 onwards) when infection is already established on more than 50% of stems.
- The correlation between stem rust scores and resultant yields was not strong. However, there was a clear trend for treatments with higher rates of fungicides to out-yield lower rates at the Quambatook and Inverleigh trials. At Booleroo, where yield responses were very small the only treatments to significantly out-yield the untreated were intermediate or high-rate treatments.
- At Inverleigh, where full rate fungicide applications were applied pre and post-infection, there was a trend for better disease control and yield advantage with the earlier prophylactic treatment than the post-infection treatments, though the yield difference was not statistically significant.
- At Inverleigh, comparing the mean of both fungicide timings (GS55 and GS71), prothioconazole/tebuconazole was the highest yielding treatment, although the difference was not significant.
- At Quambatook, all treatments with products applied at full rate significantly out-yielded the untreated except propiconazole and the mixture of propiconazole and cyproconazole.
- Under high disease pressure in Gippsland, late fungicide application (GS80–85) gave poor yield responses and were not statistically significant.
- In contrast there was a good correlation ($R^2 = 0.65$) between stem rust severity at physiological maturity and yield when cultivars of differing resistance to stem rust were compared.
- Overall the trial work conducted illustrates:
 - the value of fungicide application pre-infection with susceptible cultivars;
 - little economic value applying fungicides at late milk GS77 or later when the crop has established infection (higher than 50% disease incidence); and
 - pre-infection fungicide applications applied at 50% ear emergence (GS55) gave more effective disease control than later watery ripe (GS71) applications applied post-infection (despite the lack of fungicide coverage on the peduncle with the earlier timing). Yield differences were not statistically significant.

Stripe rust control in wheat

Why is growth stage important in making fungicide decisions?

Up to five years ago it would be common to make decisions on fungicide applications for stripe rust based on thresholds of infection—these thresholds varied from 1 to 5% plants infected. The problem that soon became apparent to growers and advisers was that in the paddock it was difficult to calculate whether you had reached this disease threshold, not least because of the sporadic nature of the initial foci of the disease. In addition, by the time growers realised that the threshold had been reached and the spray operation had been carried out, the crops were often badly infected. Since fungicides work better as protectants than as curatives, fungicide application to crops badly infected with stripe rust resulted in poor control.

Trial work on stripe rust control (GRDC project SFS00006 – 2002–04) quickly established that foliar fungicide applications, based on

growth stages and applied between second node (GS32) and flag leaf emergence (GS39) or at both timings, gave good control of stripe rust disease. These growth stage-based timings also gave growers the opportunity to pre-plan disease management strategies with susceptible cultivars.

Why do these growth-stage timings work for stripe rust control?

The primary reason that growth-stage timing works for stripe rust control is that the growth stages between GS32 and GS39 coincide with the emergence of the top three leaves of the crop canopy in wheat, meaning that fungicides are applied to leaves shortly after they have emerged and before tissue becomes heavily infected. However, it is also important to understand that foliar fungicide applied at first or second node (GS31–32) does not protect the flag leaf or the leaf beneath it (flag-1) as they have not

emerged at this growth stage. Equally, a foliar fungicide applied at flag leaf (GS39) may protect the flag leaf but may be too late to protect flag-2, which emerged two to three weeks earlier and may have been infected.

Yield loss to disease at different growth stages of disease onset

While growth stage timings of fungicides can ensure that the top three leaves of the plant are adequately protected, it is the growth stage at which symptoms first appear that dictates the level of economic response to a fungicide. For the construction of the Rustman model, a simple relationship (derived from trial results) linked expected yield losses to the onset of stripe rust infection at particular growth stages. This simple chart (see below), while complicated by the presence of adult plant resistance (APR) in some cultivars, remains a useful guide to potential yield loss in susceptible cultivars at different growth stages.

Expected yield losses (%) based on different growth stages of disease onset (stripe rust)

Disease Onset Growth Stage		Stripe rust reaction			
		Susceptible	Moderately susceptible	Moderately resistant	Resistant
GS31	First node	85	75	55	25
GS39	Flag leaf	75	45	15	5
GS45	Booting	65	25	7	2
GS49	first awns	50	10	3	1
GS55	Mid Heading	40	5	2	0
GS65	Mid Flower	12	2	1	0

Source: ICAN Cereal Foliar Disease Workshops for Advisers (G. Murray NSW DPI – July 2004).

This guide to yield loss is based on the premise that yield loss to stripe rust is dependent on:

1. the extent of stripe rust that develops by early grain development;
2. the temperature during grain fill – the stated responses in the table above assume average temperatures, if hotter the yield loss (due to disease) is less than expected; and
3. some cultivars (for example EGA Gregory[®]) rated as resistant (R) to stripe rust, may be infected at GS30 but, with the current pathotypes, have not shown yield losses as great as 25%, because adult plant resistance (APR) in the plant switches on ensuring that the disease does not develop. It is unlikely that a cultivar could be rated as resistant if it were subject to yield losses of 25% from an early infection. For this reason the table remains a useful guide for losses at particular growth stages for more susceptible cultivars, but not for the resistant ones.

Bearing aside the complication with APR, the data illustrates that the earlier the disease infects the crop, irrespective of variety resistance rating, the greater the expected loss.



Influence of disease onset on optimum fungicide spray timings for very susceptible cultivars

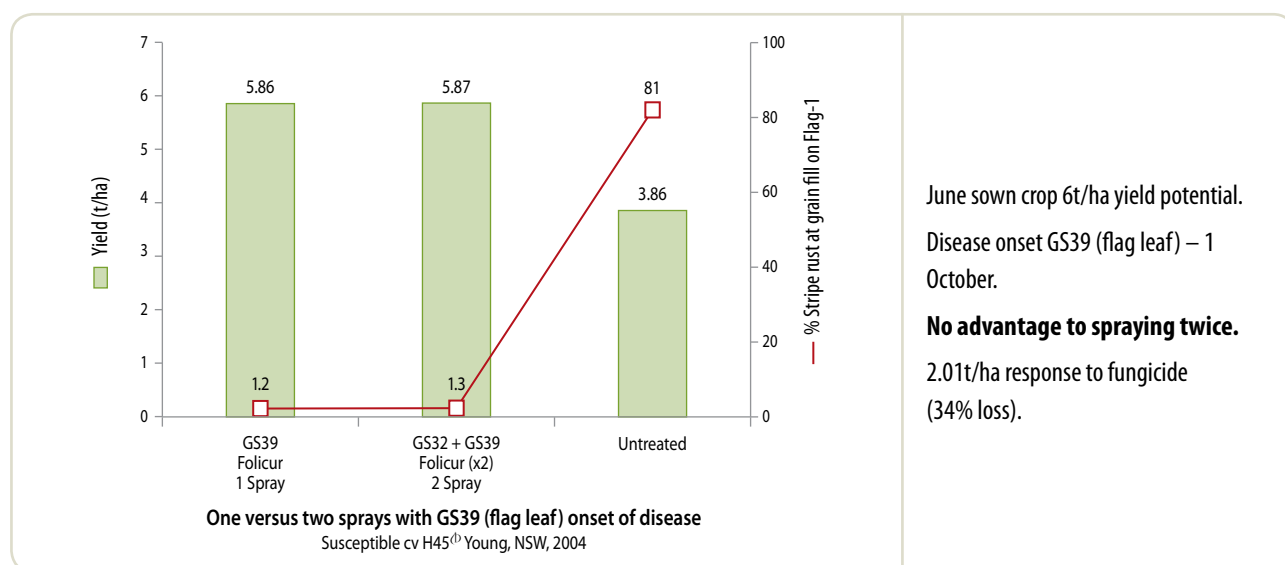
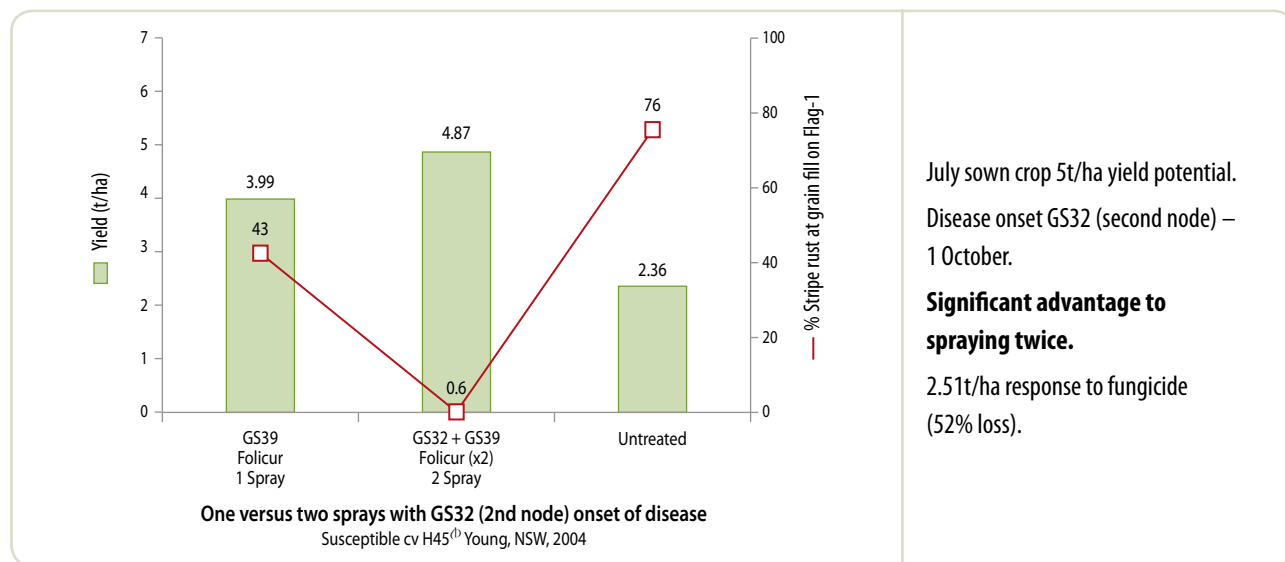
The growth stage at which infection first occurs not only influences the expected return from using foliar fungicides, but also influences the timing of fungicide application in order to ensure the greatest return.

What difference does it make to fungicide strategy if stripe rust infects the crop at GS32 (second node) versus GS39 (flag leaf emergence on the main stem)?

This scenario occurred in research work in Young, NSW with the very susceptible cultivar H45^{db} in 2004 (GRDC project SFS0006). Stripe rust came into the district at the beginning of October. One research trial had been established in early June, the other in early July. The earlier sown trial was infected at flag leaf emergence (GS39) while the later sown trial was infected at second node (GS32). So if you had one unit of fungicide, in this case 145mL/ha Folicur®, how would you use it?

1. Would you spray both crops at flag leaf (GS39) because this is the most cost effective timing in most fungicide trials?
2. Would you split the fungicide active between two timings, the first applied at GS32 the other applied at GS39?
3. Or would you treat the two crops using a different strategy?

Influence of stripe rust infection on disease management strategy applied on the basis of growth stage.



The answer to these questions are: where stripe rust infection occurred at second node GS32 the two-spray program was optimal, but with a later flag leaf infection there was no advantage to applying fungicide twice. As fungicides are insurance inputs, the most consistent program over the two trials (in terms of disease control and yield response) was a fungicide applied at both second node GS32 and at flag leaf GS39.

But would the result be the same if a cultivar had a low level of adult plant resistance rather than a very susceptible rating for stripe rust?

The cultivar Wyalkatchem[®] is rated susceptible for stripe rust resistance but is acknowledged as having a low level of adult plant resistance (APR). In order to look at the interaction between cultivar resistance and environment this cultivar (in 2008 and 2009) and Derrimut[®] in 2010 (moderately susceptible rating to stripe rust) were sown at two sowing dates in the long-season southern-Victorian high-rainfall zone (HRZ) environment. The questions to be answered were:

- Would later sowing exhibit greater disease resistance than earlier sowings, given that later sowings develop later in the season when it is usually warmer and therefore less conducive to stripe rust infection and fungicide response? Might it also encourage greater APR if the switches for APR genes were linked to temperature, a feature of APR expression in some cultivars?

Or

- Would stripe rust onset be the same for all crops in the district, later sown crops being infected at earlier growth stages and therefore giving greater response to fungicide?

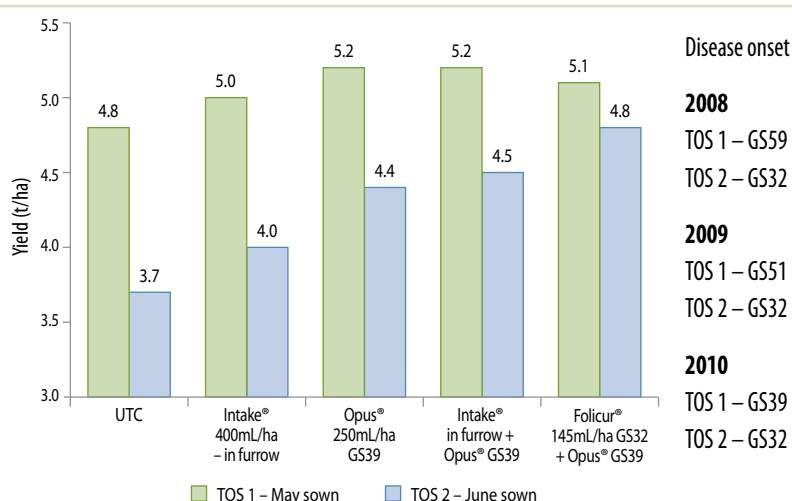
Three years of data generated at Inverleigh in southern Victoria from 2008–10, revealed that Wyalkatchem/Derrimut[®] gave greater responses to fungicides when sown later (June) as opposed to early sowing (May), despite having lower yield potential. Over

the three years, stripe rust infection came into the district (and trial) at similar times of the year. This resulted in the earlier sowings first showing infection at more advanced growth stages (relative to the later sowings), which was then less damaging to yield than that experienced with later sowings. In contrast, later sowings first showed infection at a similar calendar date, but at earlier growth stages.

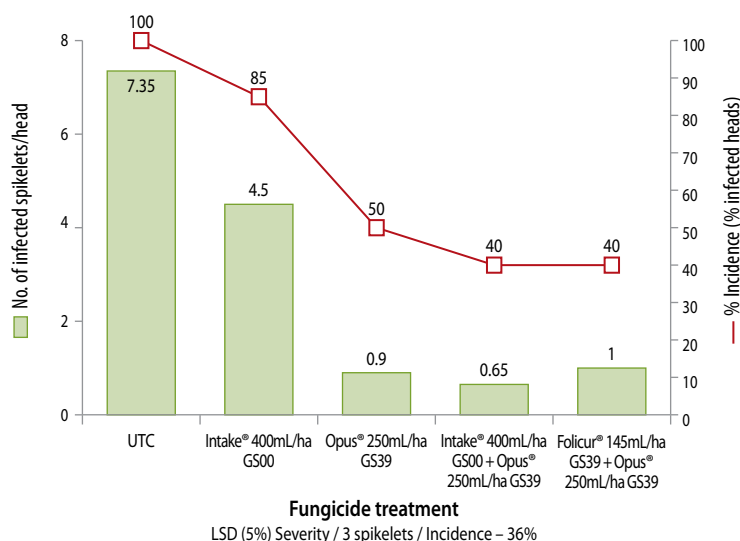
Do fungicides applied to the foliage protect the head from stripe rust infection?

None of the fungicide treatments directly applied fungicide to the head, but treatments that were effective at reducing stripe rust in the foliage were also effective at reducing head infection. Earlier (May) sowings had stripe rust infection occurring at later growth stages and as a consequence had less head infection.

Later (June) sowings of susceptible cultivars gave greater yield responses to fungicide application, as stripe rust infection occurred at earlier growth stages, relative to the earlier (May) sowings. Two fungicide applications had a larger yield than one spray with later sowing but not with the early sowing.



Influence of sowing date on fungicide response to stripe rust control in Wyalkatchem[®] – Inverleigh, southern Victoria, 2008–10 (three-year yield mean).



Influence of fungicide treatment for control of disease in the foliage and its subsequent effect on infection in the head – June sown Derrimut[®], Inverleigh, southern Victoria, 2010.



What is adult plant resistance?

Adult Plant Resistance as the name suggests, does not protect the cultivar from rust infection until it has reached the “adult” phase of development – the plant is in the stem elongation phase pseudo stem erect to ear emergence, GS30-GS59. This resistance is frequently conferred by more than one gene and rarely offers complete protection. The exact genetic make-up and environmental stimuli to switch on these different gene combinations within cultivars is complicated and not well understood, though it is known that some cultivar APR is temperature sensitive. This was observed in 2005 when lower than normal temperatures at flag leaf emergence resulted in later expression of APR and greater necrosis of the crop canopy, particularly those leaves under the flag leaf. The expression of APR can vary between different cultivars and in the same cultivar between different regions and seasons.

What do I look for as signals that APR is working in my crop?

With stripe rust, APR has been activated when the infection on the leaf increasingly appears to be less active with yellow stripes appearing on the leaf showing less postulation in the stripe. Very often infection can appear very active on lower leaves whilst on the flag leaf there may be yellow streaking or flecking but little evidence of stripe rust postulation.



Can stripe rust infection in the head be prevented with the use of fungicide?

Yes, only if fungicide is applied to the head before infection is evident. In order to do this, fungicide should be applied at early head emergence (GS59) when it is exposed to viable spores for the first time. It is not possible to control stripe rust infection that is already present in the head when the fungicide is applied. If a particular variety only has APR, it may be susceptible in early growth stages (prior to GS20). A treatment applied at seeding may effectively cover that period of vulnerability. Early applications, when adopted widely, help protect all crops in the area. This should reduce the need for later applications by all growers. This is particularly in the case where varieties have a suitable level of APR. In cultivars expressing APR at the MR-MS level or better, there may be no need, in most grain growing regions, to apply later fungicides to protect the top two leaves. In long-season districts with severe rust pressure, varieties may need an MR level of APR resistance to avoid the need for these later sprays.



Resistance Ratings

Resistance ratings are revised and issued annually by the Australian Cereal Rust Control Program (ACRCP). The ACRCP group monitors rust populations to maintain awareness of pathotype distribution and to detect and report new and emerging pathotypes. Refer to the most recent Cereal Rust Report at www.rustbust.com.au

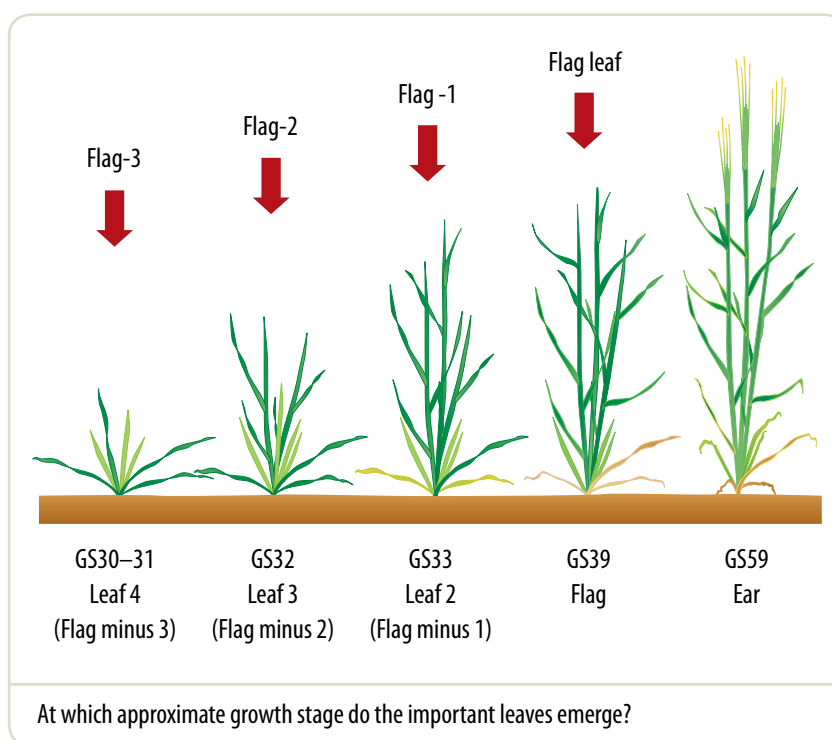
Seedling and adult plant resistance.

Zadoks growth stages	GS00-GS09	GS10-GS19	GS20-GS29	GS30-GS39	GS40-GS49	GS50-GS59	GS60-GS69	GS70-GS79	GS80-GS89	GS90-GS99
Development phase	Germination	Seedling growth	Tillering	Stem elongation	Booting	Ear emergence	Flowering	Milk	Dough	Ripening
Adult plant resistance: Often switches on around tillering to node formation Can be earlier or later, depending on the gene(s) involved Level of protection can vary with environment and inoculum load										
Seedling resistance	Resistant	Resistant	Resistant	Resistant	Resistant	Resistant	Resistant	Resistant	Resistant	Resistant
Adult plant resistance	Susceptible	Susceptible	Susceptible	+/- Resistant	Resistant	Resistant	Resistant	Resistant	Resistant	Resistant
Adult plant resistance	Susceptible	Susceptible	Susceptible	Susceptible	+/- Resistant	Resistant	Resistant	Resistant	Resistant	Resistant
Adult plant resistance	Susceptible	Susceptible	Susceptible	Susceptible	Susceptible	+/- Resistant	Resistant	Resistant	Resistant	Resistant

SOURCE: THE UNIVERSITY OF SYDNEY

Guidelines for using fungicides when cultivars exhibit adult plant resistance to stripe rust

In project trials later sowing of cultivars with weak APR such as Wyalkatchem[®], did not result in more APR expression but instead gave greater response to fungicide, since earlier infection (relative to growth stage at later sowing dates) resulted in more time for the disease to cause damage. However, cultivars with greater resistance may express APR more strongly, the level of resistance conferred by the cultivar depends on those genes present and the environmental stimuli for expression. The question then arises that if the crop protects itself from disease at later growth stages (ear emergence – APR generally fully activated) can this trait be used to avoid fungicide application?



i) Can I make use of APR to avoid using in-crop foliar fungicide?

Yes, but in some circumstances it may still be necessary to apply a fungicide, despite the APR. **Since the expression of APR may vary from season to season depending on the environmental conditions and from cultivar to cultivar it is useful to have some general guidelines as to when APR can be relied upon.** In most cases the principal guideline for spray action is likely to be the level of disease inoculum that the crop has been exposed to and the level of the infection that has built up in the canopy.

How do I know which leaf layer is infected if the flag leaf has not yet emerged?

Knowing which leaves are infected in a crop canopy is essential in order to make the best decisions with foliar fungicides. This is the case irrespective of whether the cultivar has APR or not. In general the leaves produced prior to GS31 (first node) contribute relatively little to yield. However, from GS31 onwards leaves that become infected in the canopy become relatively more important. While there are differences in yield contribution from the later formed leaves dependent on whether the crop is grown in the Mallee or the HRZ, the top three (flag, flag-1 and flag-

2) contribute most to green leaf area and are thus the key leaves to be protected.

ii) Under what infection conditions should in-crop fungicides be applied in relation to cultivars with known APR?

1. Pre-stem elongation infection during tillering (before GS30)

In varieties with resistant, moderately resistant or intermediate ratings (R, MR, MR-MS) it is easy to overreact to disease at this stage. While low rates of foliar fungicides can be tank mixed with herbicides at the tillering growth stages (GS20–29), **the impact of these foliar fungicides is not as great as those same sprays applied during stem elongation (GS30–39). Therefore with a variety with known resistance it is better to defer expenditure on fungicides until stem elongation.** This is principally because the leaves that are protected at tillering are less important to yield and it is difficult to protect the plant with foliar fungicides due to the high number of new leaves yet to emerge (remembering that foliar fungicides have limited systemic activity and primarily protect what they cover). In many ways seed treatments and in-furrow treatments are more suited to give

control of the disease during tillering because the fungicide is translocated from the roots, rather than applied to the leaves.

2. Stripe rust infection from stem elongation onwards (GS30 onwards)

Monitor the wheat crop closely from the start of stem elongation (GS30 onwards). If, in the period up to flag leaf, particularly at GS32 and GS33, stripe rust is present on the newest emerging leaf or the leaf below (ultimately the two leaves under the flag leaf) then a foliar fungicide should be applied in order to protect green leaf area in these yield-supporting leaves. Note this may be before the flag leaf has fully emerged.

With cultivars expressing APR there may be no need to apply a later flag leaf fungicide – as the later growth stage (flag leaf emergence – ear emergence) APR should be able to protect the cultivar.

Where varieties have little or no APR (susceptible ratings) for stripe rust, fungicide timed at GS32 and GS33 would frequently need to be followed up with a fungicide applied to protect the flag leaf. This follow up is best timed at flag leaf emergence (GS39) if the first spray was applied at GS32, or no later than ear emergence (GS59) if the first

spray was applied at third node GS33. Note that in drier environments the need for a second spray may be reduced purely due to environmental conditions (hot and dry), even in susceptible cultivars.

3. *Stripe rust infection at flag leaf – booting (GS39–45)*

From flag leaf through to booting the same guidelines could be used. Where active stripe

rust infects the top leaves of the canopy consider applying a foliar fungicide as, even though the cultivar may possess APR. There is a danger that green leaf area will be lost while waiting for this resistance to be activated in the top leaves of the canopy. At flag leaf, fungicide decisions can take far greater account of the seasonal prospects and overall yield potential than is the case with infections prior to the flag leaf stage.

KEY POINTS

Guidelines for stripe rust management with foliar fungicides

- For stripe-rust-susceptible cultivars, foliar fungicides applied on the basis of growth stage offer greater opportunities to protect the crop canopy than basing decisions on disease thresholds.
- Growth stage-based applications give greater opportunities to pre-plan fungicide strategy for larger acreages and simplify management decisions.
- Stripe rust infection occurring at earlier growth stages (pre-flag leaf emergence) gives rise to greater yield loss and the need to consider two fungicide applications for stripe rust control.
- Research with very susceptible (VS), susceptible (S) and moderately susceptible (MS) cultivars has shown that later sowings can give greater yield responses to fungicides than earlier sowings due to the initial infection occurring at an earlier growth stage.
- Where stripe rust was controlled in the foliage, the level of head infection was reduced.
- Where susceptible cultivars are grown in drier regions and/or where adult plant resistance (APR) is effective, the need for a second spray at flag leaf/booting can be reduced, provided the first fungicide was not applied too early (i.e. before second node – GS32).
- Varieties with stripe rust resistance based on APR genes may require backup from fungicide application early in the stem elongation period (GS30–45) in order to protect the crop from stripe rust.
- A simple guideline is an early fungicide application is required if stripe rust infection becomes evident on the two leaves below flag leaf in the period up to booting. Remember these important leaves emerge from GS31–32 (first to second node) onwards.
- In cultivars with defined APR, fungicide application may be required earlier than flag leaf emergence since the level of resistance is more effective at the later growth stages (GS45–59).



Barley disease management

Disease management guidelines for susceptible barley cultivars grown in the high rainfall zone (HRZ)

Up-front versus in-crop disease control under leaf rust and powdery mildew pressure

Over the five years of this project and the previous project (SFS00015), a single foliar fungicide applied at GS33 (third node on the main stem) had given yield increases significantly greater than Impact®/Intake® (Intake Combi® at 250 grams per kilogram) applied in-furrow at seeding.

However, using two fungicides together (such as Impact®/Intake® in-furrow followed by a foliar fungicide at GS33) resulted in a consistent yield increase over and above the performance of either of the two used alone. The increased benefit of Impact/Intake® followed by a single fungicide at GS33 was also matched by an application of two foliar fungicides applied at GS31 (first node on the main stem) and GS49 (first awns emerging).

Though powdery mildew that is resistant to azole demethylation inhibitors (DMI) fungicides (for example tebuconazole) was only confirmed in 2010, it is likely that these results were influenced by resistant strains of the disease.

N.B. Please note the high-rainfall zone (HRZ) results in this section have been generated in Western Australian crops where disease (leaf rust, powdery mildew and spot form of net blotch (SFNB) were present for the whole or part of the season. It should also be noted that the results in 2009–10 are likely to have been influenced by powdery mildew populations that were resistant to azole DMI (Group 3) fungicides, however, this was not confirmed with resistance testing.

The location of the trials on the south coast of WA at South Stirling and Munglinup and the widespread nature of resistance in those regions, mean it is likely there was powdery mildew resistance. In addition, trial performance of Impact®/Intake® and the

single spray of Opus® were not as effective in the two seasons (2009 and 2010) as they had been in 2005 and 2006. However, it needs to be pointed out that the response to all fungicides has been lower in the last two seasons.

Five year mean yield (2005, 2006, 2008–10) and economic response (tonnes per hectare, % and \$/ha) over the untreated using different fungicide strategies in Baudin⁽¹⁾ (Powdery mildew and leaf rust were the primary disease pressure).

Treatment	Response over untreated (5 year mean)		Value at \$250/t \$/ha	Margin over untreated \$/ha
	t/ha	%		
Impact® (400mL/ha) in-furrow	0.0	0	0	-11
Impact® + 1 Spray (GS33) Opus® 250mL/ha	0.40	17.3	100	73
2 Spray (GS31) + (GS49)	0.48	19	119	91
1 Spray (GS33) Opus® 250mL/ha	0.23	9.2	59	36

Notes: All figures are relative to an untreated control, for example Impact® lost \$11/ha relative to the untreated over the five years.

2 spray – GS31 Tilt® 250 millilitres/ha followed by GS49 Opus® 250mL/ha.

Margins based on wheeling damage at 2.5% for application at GS33 or after. Application cost at \$8/ha. Impact®/Intake® at \$10/ha, Opus® \$10/ha and Tilt® \$5/ha.

Impact®/Intake® is only registered for powdery mildew control not leaf rust.

Opus® is registered for leaf rust control in barley but not powdery mildew.

Two year mean yield and economic response (at \$250/t) for 2005 and 2006 versus 2009 and 2010 in cv Baudin⁽¹⁾.

Treatment	Response over untreated t/ha		Margin over untreated \$/ha	
	2005–06	2009–10	2005–06	2009–10
Impact® (400mL/ha) in-furrow	0.12	– 0.18	20	– 54
Impact® + 1 Spray (GS33) Opus® 250mL/ha	0.65	0.18	133	17
2 Spray (GS31) + (GS49)	0.72	0.37	148	62
1 Spray (GS33) Opus® 250mL/ha	0.41	0.09	85	5

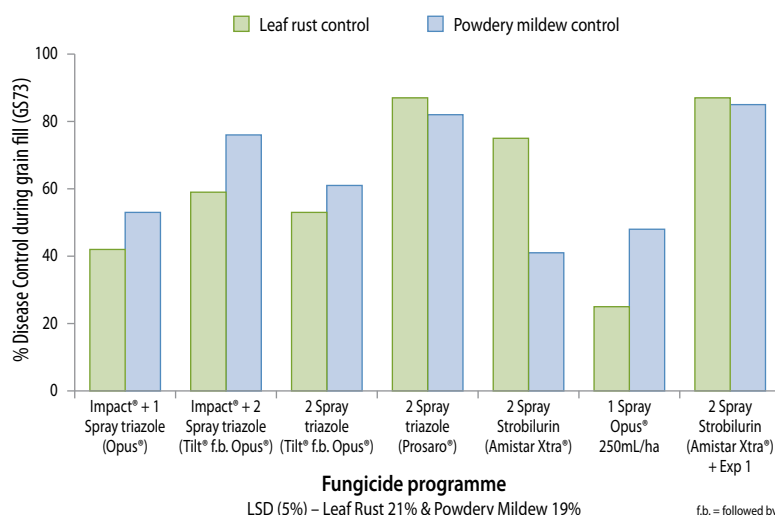
Performance of two-spray foliar programs under high disease pressure

Project work continued by asking the question:

Would the profitability of two foliar sprays be enhanced with the use of newer fungicide active ingredients such as the strobilurin/triazole mixture Amistar Xtra® (azoxystrobin and cyproconazole) and Opera® (pyraclostrobin and epoxiconazole) or the triazole mixture Prosaro® (prothioconazole and tebuconazole)?

Work conducted under high disease pressure in southern WA has helped to clarify the answers to these questions, though at the same time there is an indication that results are being influenced by powdery mildew resistance, which has been confirmed in this region. Where disease pressure is high (leaf rust and powdery mildew) using newer fungicide chemistry in two-spray programs applied during stem elongation has led to greater profitability. The newer azole fungicides such as Prosaro® and mixtures of azole with strobilurin (Amistar Xtra®) have been particularly effective on leaf rust and, to 2010, Prosaro® was also a good powdery mildew protectant. Thus despite the slightly higher cost, these two-spray programs have been more cost-effective than other options tested, when growing susceptible cultivars in a region with a high risk of disease.

Both Australian and overseas data show prothioconazole (the new azole in Prosaro®) has a good activity against wet weather diseases such as scald in barley. Results also served to illustrate that the slightly more leaf-rust-resistant cultivar Vlamingh⁽¹⁾ gave a similar pattern of response to the fungicide strategies tested, although it did not show the economic response to the strobilurin program based on Amistar Xtra®, a feature related to the greater importance of leaf rust control in Baudin⁽¹⁾ compared to Vlamingh⁽¹⁾.

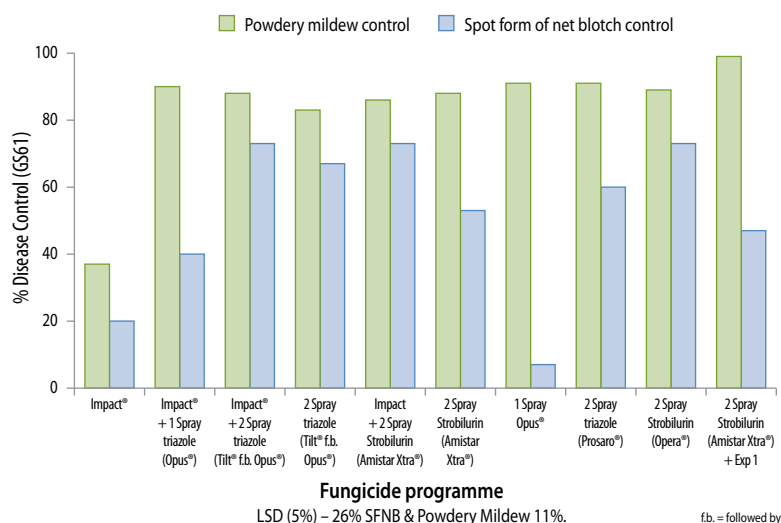


% Disease control (leaf rust 10% infection on flag-1) and powdery mildew 13% infection on flag-2) in Baudin⁽¹⁾ – Munglinup, southern-coastal WA, 2009.

Notes: 'Exp 1' – experimental mildewicide – active ingredient with different mode of action to triazoles and strobilurins (not approved for use in Australian cereal crops).

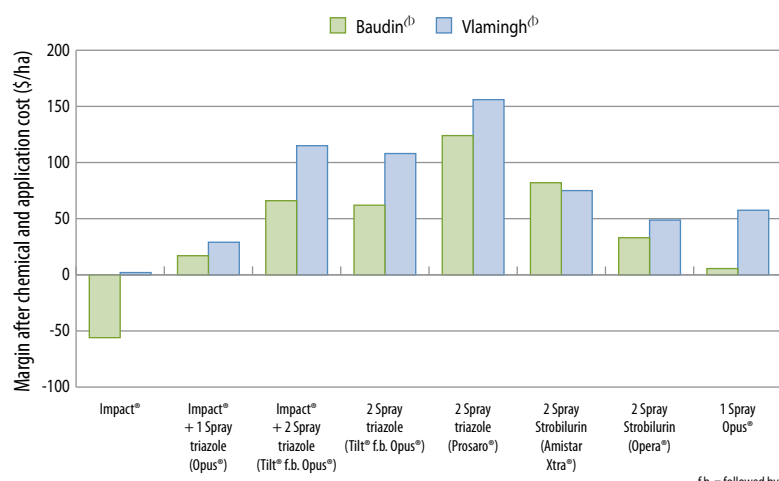
Two-spray programs based on Amistar Xtra® 200mL/ha applied GS31 and GS49, Prosaro® 150mL/ha + Hasten applied GS31 and GS49 and Tilt® 250mL/ha at GS31 followed by Opus® 250mL/ha at GS49.

The use of these products in these trials does not always constitute a registered use of the product for control of the specified diseases. **N.B. Please check the registered product label before use of the product.**



% Disease control SFNB 10% infection on flag – Vlamingh⁽¹⁾ and powdery mildew 30% infection on F-2 in Baudin⁽¹⁾ – Munglinup, southern-coastal WA, 2010.

Two-spray programs based on Amistar Xtra® 200mL/ha applied twice at GS31 and GS49, Prosaro® 150mL/ha + Hasten applied twice at GS31 and GS49, Opera® 500mL/ha applied twice at GS31 and GS49 and Tilt® 250mL/ha at GS31 followed by Opus® 250mL/ha at GS49.



Economics of fungicide application in malting barley in southern-coastal WA (Munglinup) – two-year mean 2009 and 2010 (mean untreated yield Baudin⁽¹⁾ 3.02t/ha Vlamingh⁽¹⁾ 3.21t/ha).

N.B. Opera[®] was trialled at 300mL/ha x 2 in 2009 and at 500mL/ha in 2010.



Powdery mildew on wheat.

KEY POINTS

Mildew and leaf rust control in high-rainfall zone environments

Management strategies for barley mildew should not just be based on agrichemicals

If possible reduce reliance on fungicides for control of disease by implementing cultural methods for disease control, for example:

- control green bridge barley volunteers heavily infected with mildew as these will act as an infection source for the new crop;
- reduce the acreage of barley-on-barley in the farming system to reduce exposure to powdery mildew and other diseases;
- review and reduce the acreage of very susceptible and susceptible barley in the farm portfolio; and
- avoid thick crop canopies which increase the humidity and create more favourable conditions for mildew.

What agrichemical strategies have been most effective over the last two years?

In FAR project trials, using the cultivars Baudin⁽¹⁾ and Vlamingh⁽¹⁾ the most cost-effective fungicide programs were based on applying two foliar fungicides at early stem elongation (GS30–31) with a second dose three to four weeks later at first awns emerging (GS49). The trials conducted in southern Western Australia revealed that two sprays based on Prosaro[®] and Amistar Xtra[®] were particularly cost-effective, though at 200 millilitres per hectare, Amistar Xtra[®] is not recommended (on the label) for mildew situations.

- Apply fungicides by growth stage in mildew-susceptible cultivars to ensure that fungicides are applied before disease becomes established in the top four leaves of the canopy.
- Applying fungicides to clean leaves at these key growth stages allows rate adjustment so that dose rate can be appropriate for both the risk and economics of the situation.
- Reduced rates are not expected to create higher resistance risk compared to high rates, unless they are being applied as multiple low dose sequences. Use fungicides on the important leaves before infection is established.
- Where flutriafol in-furrow (Impact[®]/Intake[®]) has declined in effectiveness against powdery mildew consider switching to Jockey[®] seed treatment (fluquinconazole), the performance of which in Department of Agriculture and Food, WA trials (up to 2010) appeared to be unaffected by resistance at this time.
- Applying a seed treatment followed by two newer generation fungicide mixtures such as Prosaro[®] or Amistar Xtra[®] or an alternation of the two (Prosaro[®] first followed by Amistar Xtra[®]) is the most comprehensive protection one could put in place at present, if powdery mildew resistance is prevalent in the region.



Barley powdery mildew resistance to triazole fungicides

What is happening in the paddock?

Growers in southern Western Australia have been reporting reduced control of powdery mildew from fungicide application in barley. It is important for growers to remember that **barley mildew does not cross infect wheat, so resistant mildew in barley does not mean that mildew found in wheat is fungicide resistant at this stage.**

What has been found?

In 2010 strains of powdery mildew resistant to triazole fungicides were isolated from barley crops in south-western WA, predominantly the south-coastal and western areas of the Great Southern region. The resistance to fungicide was confirmed by the Australian Centre for Necrotrophic Fungal Pathogens at Curtin University on mildew isolates collected in 2009 and 2010. Mutations were also found in eastern Australia in 2012, however limited infection had occurred.

What fungicides were affected in 2013?

Not all triazole fungicides in the demethylation inhibitors (DMI) fungicide family are affected.

Triazoles such as propiconazole, tebuconazole and flutriafol, are less effective in those regions where resistant powdery mildew is present. Newer triazole fungicides such as epoxiconazole (Opus®) and prothioconazole (Prosaro®) do not appear to be affected by resistance at this stage, likewise the strobilurins do not seem affected, however, note that the strobilurins are at high risk of being affected by resistance. There are also a number of triazole products that do not appear to have been affected in the field (2012), but their status with regard to resistance remains unknown; these include the triazole seed treatment fluquinconazole that underpins the seed treatment Jockey® and cyproconazole the triazole component of Amistar Xtra®. If cyproconazole is compromised by this resistance then the strobilurin component of Amistar Xtra® (azoxystrobin) would be severely compromised since azoxystrobin has little curative activity against this disease. Evidence from GRDC-funded trials in the FAR lead project (2009–10) suggests that prothioconazole is effective against powdery mildew (in the regions where resistance is widespread).

Which fungicides were compromised in 2013 in barley in WA and at risk in the Eastern States?

Group	Fungicide Active Ingredient	Product Name Examples	WA Status	Eastern States Status	Notes for Eastern States
Group 3 – DMI	Epoxiconazole	Opus®	OK	OK	
	Flutriafol	Titan Flutriafol	Compromised	High Risk	Danger of import from WA and of selection in situ
	Propiconazole	Tilt®	OK	OK	
	Propiconazole + Cyproconazole	Tilt®Xtra	OK	OK	
	Propiconazole + Tebuconazole	Cogito®	OK	OK	
	Tebuconazole	Folicur®	Compromised	High Risk	Danger of import from WA and of selection in situ
	Tebuconazole + Prothioconazole	Prosaro®	OK	OK	
	Tebuconazole + Flutriafol	Impact® Topguard®	Compromised	High Risk	Danger of import from WA and of selection in situ
	Triadimefon	Novaguard Triadimefon	Compromised	High Risk	Danger of import from WA and of selection in situ
	Flutriafol ^{F+F}	Impact®	Compromised	High Risk	Danger of import from WA and of selection in situ
	Triadimefon ^{F+F}	Titan Triadimefon	Compromised	High Risk	Danger of import from WA and of selection in situ. Only registered in NSW, VIC and SA
	Fluquinconazole ^S	Jockey®	OK	OK	
	Flutriafol + Cypermethrin ^S	Vibrant®	Compromised	High Risk	Danger of import from WA and of selection in situ
	Triadimenol + Cypermethrin ^S	Battalion® C	Compromised	High Risk	Danger of import from WA and of selection in situ
	Triadimenol + Imidacloprid	4Framers Imid-Triadimenol	Compromised	High Risk	Danger of import from WA and of selection in situ
	Triticonazole + Cypermethrin ^S	4 Farmers Triadimefon 500 WP	Unsure	Unsure	Almost certainly OK
Group 3+11 – (DMI + QoI)	Tebuconazole + Azoxystrobin	Custodia®	Compromised	OK	OK unless resistance to Azoxystrobin or Tebuconazole is found
	Cyproconazole + Azoxystrobin	Amistar Xtra®	OK	OK	OK unless resistance to Azoxystrobin or Cyproconazole is found
	Epoxiconazole + Azoxystrobin	Radial®	OK	OK	OK unless resistance to Azoxystrobin or Epoxiconazole is found
	Epoxiconazole + Pyraclostrobin	Opera®	OK	OK	OK unless resistance to Pyraclostrobin or Epoxiconazole is found
Group 5 – Amines	Spiroxamine*	Prosper®	OK	OK	Only registered in WA

According to the latest research information the following applies:

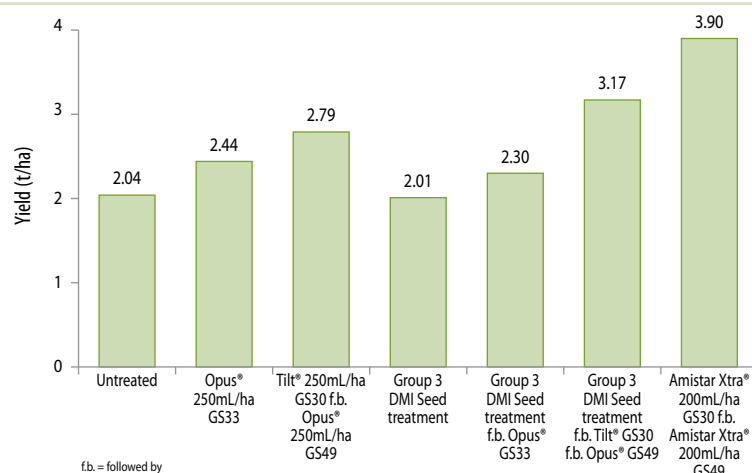
Green – OK; Dark green – OK when used once a season; Red – Compromised/High risk; Blue – Unsure.

^{F+F} Applied as foliar and in-furrow. ^SApplied as seed dressing. * APVMA permit (PER14012) expires on 31 March 2016.

Source: Oliver et al. (2014).

Two-spray foliar programs performance under high-leaf-rust pressure in South Australia

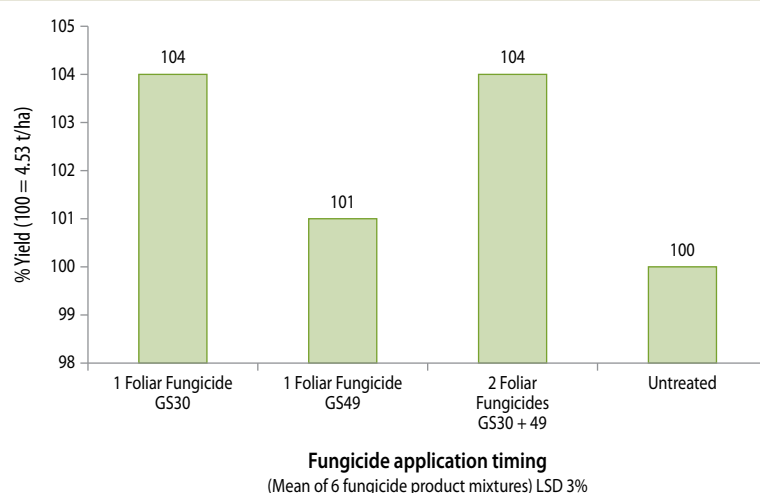
Similar results from two-spray programs have been observed against leaf rust in the HRZ of South Australia in three cultivars (Baudin^{db}, Gairdner Plus^{db} and Gairdner^{db}) as that noted against leaf rust in southern WA. Trials conducted near Naracoorte in 2007 illustrated the excellent performance of Amistar Xtra[®] applied twice at the 200mL/ha rate for leaf rust control in barley. This treatment produced the highest yields in all three cultivars. The trial work served to illustrate the strength of the strobilurin/azole combination for the control of leaf rust in barley.



Influence of fungicide strategy in the presence of leaf rust – Naracoorte, SA (mean yields of three cultivars (Baudin^{db}, Gairdner Plus^{db} and Gairdner^{db})).
GRDC project SFS00015 2007 – Group 3 DMI seed treatment.

Disease management guidelines for susceptible barley cultivars grown under lower rainfall

In research on disease control of spot form of net blotch (SFNB) in this project (and previous projects) there have rarely been yield responses in lower-rainfall regions. In the highest disease pressure scenarios (barley followed by barley in Victorian Wimmera) the best result was a 9% yield increase (70% disease control) from the use of a high-rate triazole and strobilurin mixture. This work showed that, as SFNB develops at earlier growth stages than leaf rust, better control was achieved from early fungicide application at the start of stem elongation (GS30–31). Fungicide application at first awns (GS49) did not significantly increase yield.



Influence of foliar fungicide timing (mean of six product mixtures) on % yield response in the presence of spot form of net blotch – cv Gairdner^{db}, Wimmera, Victoria, GRDC project SFS00006.

KEY POINTS

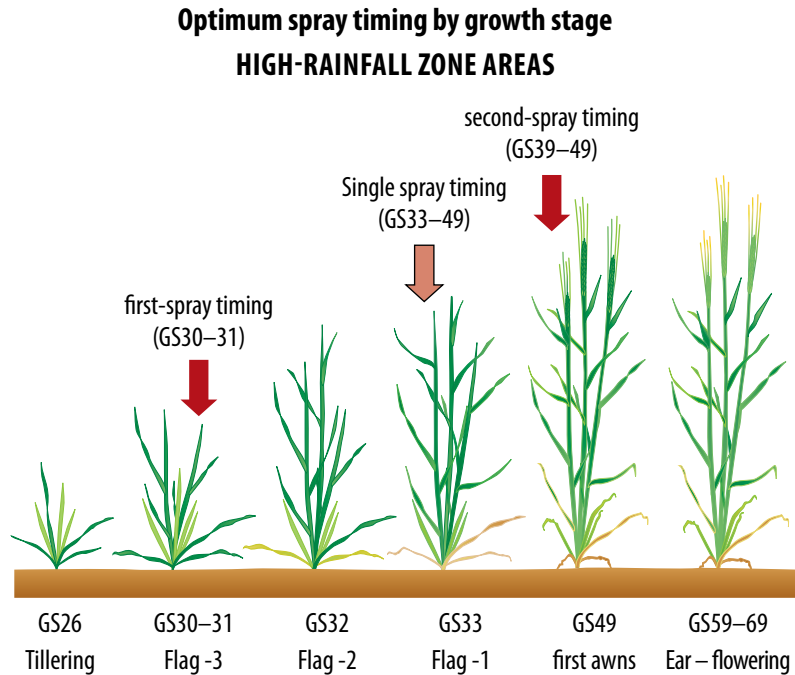
Barley disease control in low-rainfall environments

- Under higher spring rainfall the importance of fungicide input for control of all foliar diseases increases.
- The value of foliar fungicides in lower-rainfall regions is marginal.
- With susceptible cultivars cultural control is an important means of reducing overall inoculum in the region and individual paddock (remember that in-furrow and seed treatments may not be as effective at reducing powdery mildew if resistant strains are present in the region – currently only Western Australia affected 2013).
- Overall, the cost of foliar fungicides can be substantially reduced by using:
 - more resistant cultivars; and
 - by adopting widespread use of upfront fungicide measures.
- In-furrow and seed treatment measures have less impact on green leaf retention than foliar fungicides applied at stem elongation.
- Use of fungicides to control spot form of net blotch does not give as large a yield response as has been found with fungicide to control leaf rust, mildew and scald.
- There is little evidence to suggest that fungicides substantially improve malting barley quality such as screenings and retentions unless fungicides create yield benefits.

Foliar fungicide timings for barley disease control in high and low-rainfall areas based on growth stage

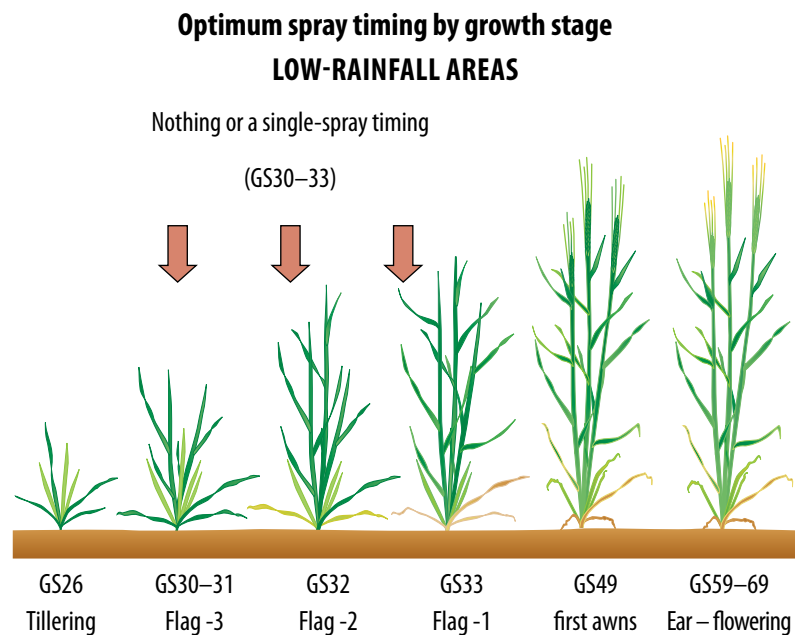
i) High-rainfall areas

It is less easy to adopt a single spray timing in barley, particularly when it is grown in higher-rainfall areas, since susceptible crops can suffer from wet weather disease early in the season (for example scald) and then from diseases such as leaf rust later in the season. Frequently this requires two foliar fungicide applications with three to four weeks between applications. Where a single spray is adopted, it is important to consider protection of flag-1, which is more important in barley than the flag leaf, hence timings coinciding with GS33 (third node).



ii) Low-rainfall areas

Under low-rainfall environments with generally lower yield potential it is difficult to justify the use of fungicides based on results to date, particularly where spot form of net blotch has been the principal disease. It is earlier fungicides that tend to be more important in lower-rainfall areas, since disease tends to naturally subside later in the season as the lower rainfall restricts both disease and yield potential. In many cases no foliar fungicide may be required, however, where scald or net blotch is dominant there may be benefits to considering a GS30-31 spray application.





3. Advancing Canopy Management

Canopy management in wheat – row spacing interactions

There are a number of reasons why growers might wish to pursue wider row spacing in cereals, for example, residue flow, inter-row weed control and disease control; however in all trials covering a wide range of rainfall scenarios conducted on wheat, increasing row width reduced yield in trials conducted between 2007 and 2010. This yield reduction in wheat was particularly significant when row width exceeded 30 centimetres (12 inches). At row widths of 30cm (12 inches) the reduction in wheat yield compared to narrower 20–22.5cm (8–9 inches) row spacing was dependent on overall yield potential.

- At yields of 2–3 tonnes per hectare the yield reduction has mainly been negligible.
- At yields of 5t/ha the yield reduction has been 5–7%, averaging about 6%.

Integrating new technologies with canopy management – use of crop sensors

If little or no nitrogen has been applied to the crop by the start of stem elongation, Normalised Difference Vegetative Index (NDVI) values (captured by proximal or remote sensors) could be a useful spatial indicator of fertility (soil nitrogen) in the paddock. This is provided N-rich strips or calibration strips are used to verify that any differences in biomass and chlorophyll content are due to nitrogen rather than other nutritional, pest or soil water factors.

To employ crop sensors at growth stages when they both accurately visualise the crop canopy N supply and allow sufficient time for N top dressing to be applied is:

GS24 (Late Tillering) ←————→ GS33 (third node)

This growth stage range gives the greatest visualisation of the crop canopy with crop sensors but ensures that N doses for yield can still be optimised.

Can delayed nitrogen application work with barley?

In Western Australia delaying nitrogen application until early stem elongation (GS30–31) on soils with low soil nitrogen reserves confined to the top 30cm, resulted in malting barley crops with significantly lower yields compared to nitrogen strategies placing 50–100% of the N dose at sowing. In these crops where nitrogen was delayed, tiller numbers were noted to fall below 400 tillers per square metre by the time the crop reached GS30–31. Conversely in the eastern states on heavier soils where tillers numbers are high in the spring (over 500 tillers/m²) overall response to nitrogen was lower, but stem elongation nitrogen was more likely to be successful for increasing yield.

Management of long season wheat

With irrigated long season wheat (sown March/April) grown under Tasmanian conditions lodging could be controlled by grazing the crop prior to GS30. In ungrazed plots, the rank order of effect (order of importance) in terms of preventing lodging was:

cultivar > plant population > PGR application > N timing.

Influence of row spacing on wheat yield in high and low-rainfall zones

Is the effect on yield different if I farm in a higher-rainfall environment (for example southern Victoria) compared to a lower-rainfall situation?

A series of canopy management trials showed that, in all cases, moving row spacing wider reduced grain yield. Across the set of trials, using 30 centimetre row spacing incurred a yield penalty of 6% (5 tonnes per hectare yield potential) compared to 17–22cm rows; and there was a trend for yield reduction to be greater in higher-rainfall environments and when row spacing increased beyond 30cm.

Effect of wheat row spacing on grain yield									
Zone	Low to medium-rainfall zone					High-rainfall zone			
Site	Hart, SA	Hart, SA	Hart, SA	Bungeet, Vic*	Coreen, NSW*	Mininera, Vic	Mininera, Vic	Inverleigh, Vic	Bungeet, Vic*
Year	2007	2008	2009	2009	2009	2007	2008	2009	2010
Cultivar	Gladius ^(b)	Correll ^(b) Wyalkatchem ^(b)	Gladius ^(b)	Bolac ^(b)	Gladius ^(b)	Bolac ^(b) / Kellalac ^(b) Beaufort ^(b)	Bolac ^(b)	Bolac ^(b)	LongReach Lincoln ^(b)
Row spacing (cm)	17.5 or 35	22.5 or 45	22.5 or 35	22.5 or 37.5	22.5 or 37.5	20 or 30	20 or 30	20 or 30	22.5 or 37.5
Growing-season rainfall (GSR)	273	204	322	286	234	457	392	427	586
Narrow row spacing (t/ha)	2.20	1.52	2.14	2.22	2.63	5.32	4.94	2.14	3.13
Wide row spacing (t/ha)	2.13	1.28	2.08	1.85	2.29	4.99	4.65	2.08	2.62
Disadv. of wider rows (t/ha)	0.07	0.22	0.06	0.37	0.34	0.33	0.29	0.06	0.51
Disadv. of wider rows (%)	3.2	15.8	2.6	16.5	12.9	6.2	5.9	2.6	16.3

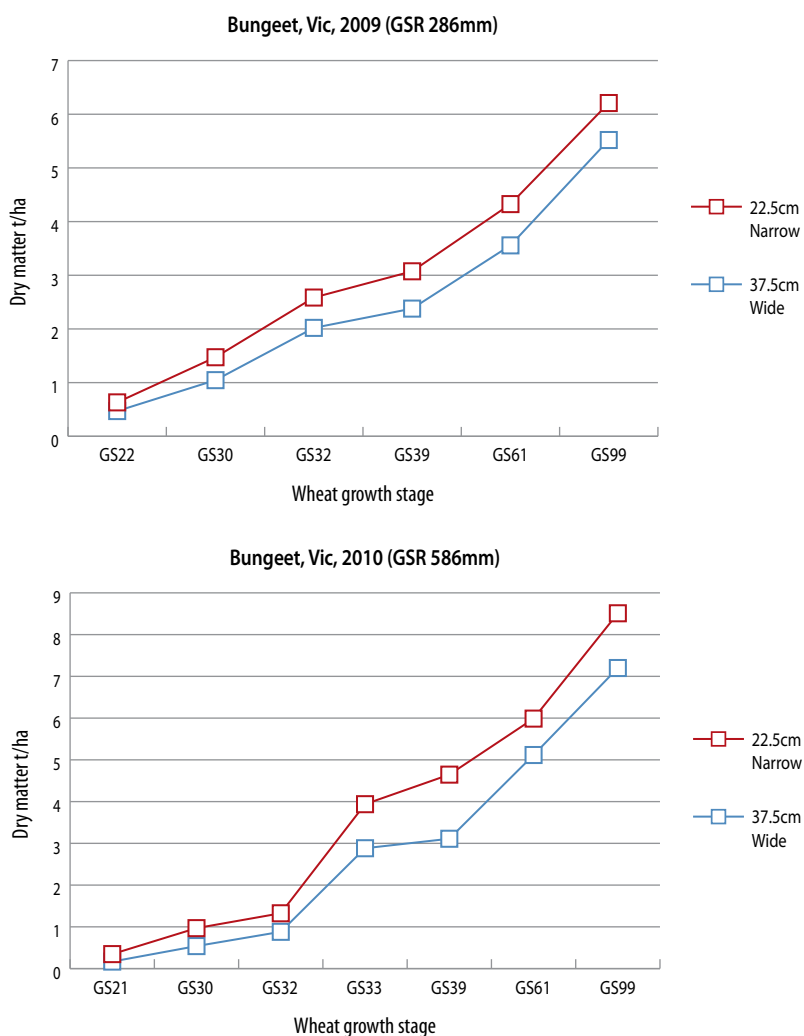
* Bungeet, Victoria and Coreen, NSW data courtesy of Riverine Plains group and the GRDC Water Use Efficiency project.

So what is happening when we adopt wider row spacing?

There are several effects that have been observed in the project trials examining row spacing.

- Using the same plant population and moving to wider rows reduces the plant to plant spacing within the row, this reduces % plant establishment relative to narrow row spacing (for reasons that are still not clearly understood).
- The same plant populations in wider rows produce lower dry matter per unit area at harvest, the greater the increase in row width, the larger the decrease in dry matter.
- Unlike initial differences in dry matter due to plant population (in the same row spacing) the difference between narrow and wide rows does not compensate by harvest.
- Lower dry matters at harvest with wider row spacing can lead to greater harvest indices (proportion of the plant harvested for grain) than equivalent narrow row spacing. However, this increase in harvest index is not sufficient to compensate for the overall reduction in dry matter and grain yield associated with wider rows.
- Canopy closure in wider rows is slower and therefore readings from crop sensors such as Greenseeker® are significantly affected by row spacing.

Wider rows lead to lower dry matter production per unit area in low and high-rainfall scenarios.



Bungeet, Victoria data courtesy of Riverine Plains group and the GRDC Water Use Efficiency project.

Wheat row widths – Coreen, NSW



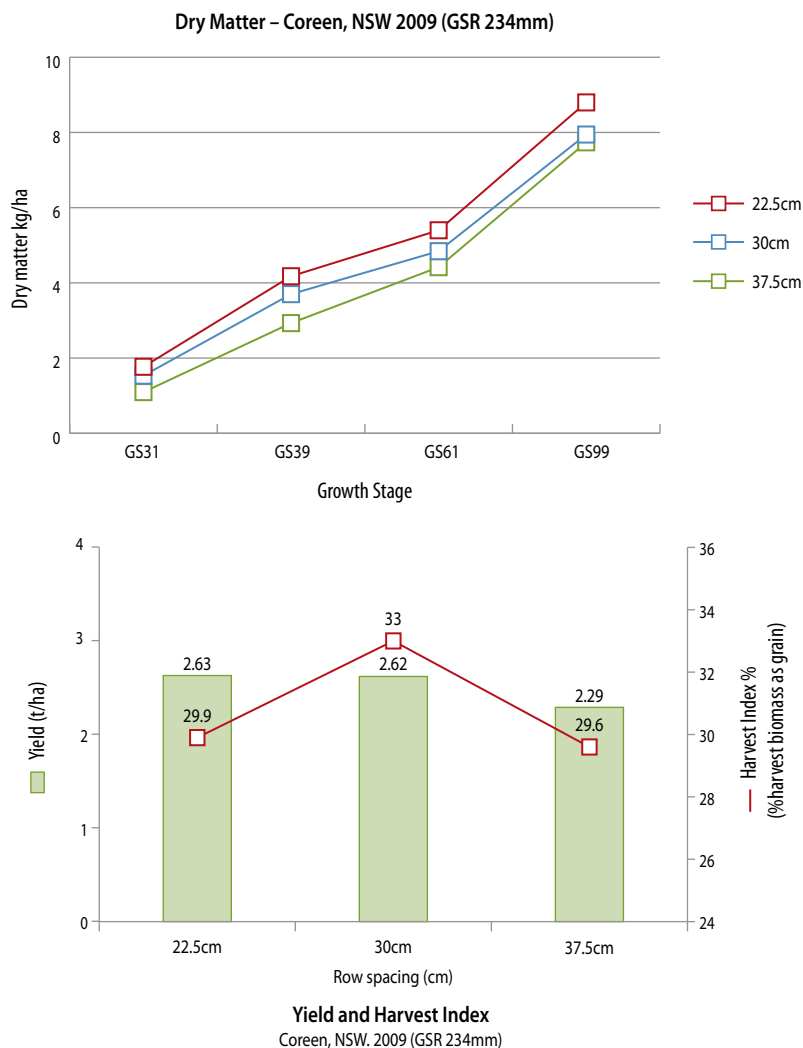
22.5cm (9 inch)

30cm (12 inch)

37.5cm (15 inch)



Wider the rows the greater the reduction in dry matter and yield – Coreen, NSW, 2009.



Coreen, NSW data courtesy of Riverine Plains Group and the GRDC Water Use Efficiency project.

But can we manage the canopy differently to improve the yield performance of wider rows?

There are many reasons why growers may chose row spacing's wider than 17–22cm and project trials have examined the influence of cultivar, plant population and nitrogen to identify interactions between plant population and wide row spacing that might improve the performance of wider rows.

Increasing plant population in wider row spacing was expected to boost yield, but the reverse appears to be the case, particularly where target plant populations are higher than 100 plants per square metre. As row width increases for a given plant population the intra row plant spacing (plant to plant spacing within the row) decreases.

Increasing plant population with wider rows (35–45cm), when plant populations have been at or over 100 plants/m², have not resulted in a significant yield increase at the four sites where it was evaluated. At these four sites increasing plant population reduced plant-to-plant distance in the wide rows down to an average of 2cm, while with narrow rows the same increase in plant population reduced plant-to-plant spacing to an average of 3.3cm.

Canola row widths – Coreen, NSW



22.5cm (9 inch)

30cm (12 inch)

37.5cm (15 inch)



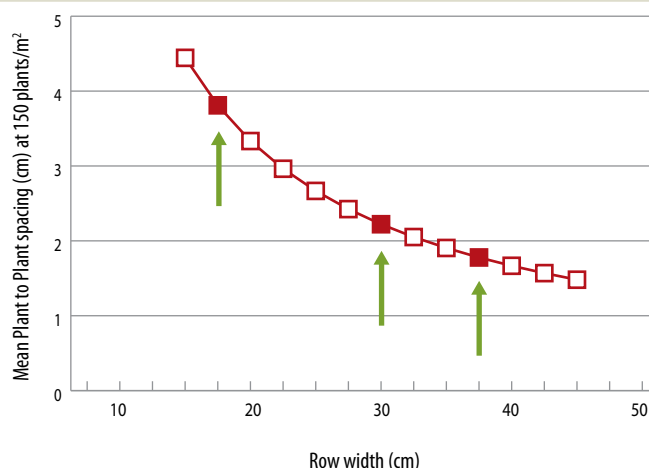
At one site (Bungeet in 2009) yield increases were observed when plant population was increased in wide rows. The plant population in those wide rows (37.5cm) was increased from 50 to 95 plants/m². In this case increasing plant population reduced plant to plant spacing from 5.4 to 2.8cm.

The trials illustrated that as a general rule of thumb, increasing plant population such that plant to plant distance in the row fell below 2.5cm had either neutral or negative impact on yield. Project and non-project data indicated that increasing seeding rates with wider rows may create canopies that are too thick within the row even though there is a natural compensation that reduces the number of establishing plants per square metre when wider rows are adopted.

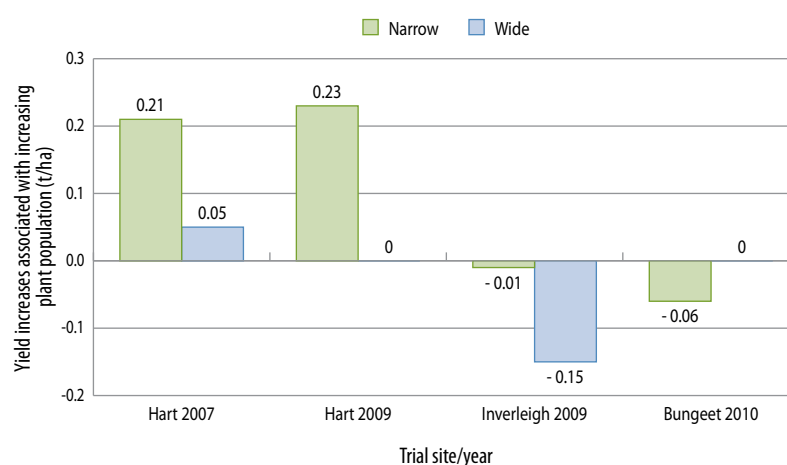


Growers using wide row spacing should have a well-planned weed management and herbicide resistance program in place. Row spacing and crop competition is an important factor for integrated weed management.

As row spacing gets wider for a given population plant to plant spacing in the row gets smaller.



At 150 plants/m² 17.5cm row spacing gives approximately 4cm plant to plant spacing and approximately 2cm plant to plant at 37.5cm.



Yield effect of increasing plant population in wide and narrow rows in trials where initial populations exceeded 100 plants/m².

Row Spacing (cm)	Plant to plant spacing within the row (cm) at different target plant populations and row spacings					
	75	100	125	150	175	200
17.5	7.6	5.7	4.6	3.8	3.3	2.9
20.0	6.7	5.0	4.0	3.3	2.9	2.5
22.5	5.9	4.4	3.6	3.0	2.5	2.2
25.0	5.3	4.0	3.2	2.7	2.3	2.0
27.5	4.8	3.6	2.9	2.4	2.1	1.8
30.0	4.4	3.3	2.7	2.2	1.9	1.7
32.5	4.1	3.1	2.5	2.1	1.8	1.5
35.0	3.8	2.9	2.3	1.9	1.6	1.4
37.5	3.6	2.7	2.1	1.8	1.5	1.3
40.0	3.3	2.5	2.0	1.7	1.4	1.3
42.5	3.1	2.4	1.9	1.6	1.3	1.2
45.0	3.0	2.2	1.8	1.5	1.3	1.1

- Plant population and row space combinations with plant to plant spacing in the row of greater than 2.5cm.
- Plant population and row space combinations with plant to plant spacing in the row of 2.5cm or less.

Does wider row spacing produce more water use efficient canopies?

The answer to this question is both yes and no! Evidence from the trials would indicate that though less dry matter is produced with wider row spacing (in project trials), on some occasions a greater proportion of that dry matter is turned into grain (higher harvest index), relative to narrower row spacing. However, this increase in transpiration efficiency (kilogram of grain produced for every millimetre of water used) is not great enough to compensate for the overall lack of dry matter. In addition by applying a fixed relationship between dry matter production and soil water used of 55kg dry matter/ha.mm, it can be deduced that wider rows lose more water through either increased soil evaporation or greater drainage. Therefore wider rows may on occasions be more efficient at converting water used by the plant into grain, but sustain greater water losses due to soil evaporation, drainage, or unused water.

Does rotation position of the wheat influence the impact of wider row spacing?

Most of the data in the project trials was conducted on wheat grown after a break crop, however in a comparison made at Coreen, NSW in 2010 there was some evidence to suggest that the yield reduction associated with wider row spacing was greater in wheat after the break crop than wheat following wheat. In two wheat trials at the same location (30m apart, sown at the same time and treated with the same inputs) yield reduction in the wider rows compared to narrow rows was only 4% (ns) where wheat followed wheat but was 12% (significant) where wheat followed canola. The results have not been seen previously in wheat on wheat trials conducted as part of the trial program, therefore it cannot be assumed to be a consistent effect. Both these trials illustrated significantly lower dry matter production with wider row spacing but harvest index in the wheat on wheat trial illustrated that the biomass of the narrow row spacing was not partitioned into grain as successfully as it was with wider row spacing. It is possible some differences in the row spacing response for wheat at different points in the rotation relate to the incidence of soil-borne disease and the avoidance from disease when planting in wider rows.

Inverleigh, Victoria, 2009 – wider row spaced canopies, lower dry matter, better harvest index (HI), greater water losses through evaporation and drainage – overall lower yield.

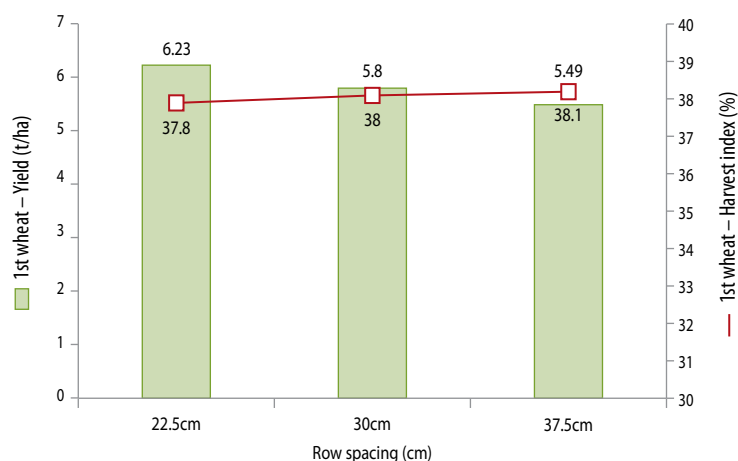
Treatment Row Spacing	Plant Pop.	GSR (Apr–Nov)	Biomass kg/ha	Yield kg/ha	H.I. %	WUE ¹ kg/mm	Trans ² mm	Unused Water ³ mm	T.E. ⁴ kg/mm
20cm	Low (86 plants/m ²)	427	10767	3196	30	7.5	196	231	16.3
20cm	High (109 plants/m ²)	427	10333	3189	31	7.5	188	239	17.0
30cm	Low (86 plants/m ²)	427	8895	3061	34	7.2	162	265	18.9
30cm	High (109 plants/m ²)	427	8218	2913	35	6.8	149	278	19.5

¹ Water use efficiency based on 427mm (Apr–Nov) including stored water with no soil evaporation term included.

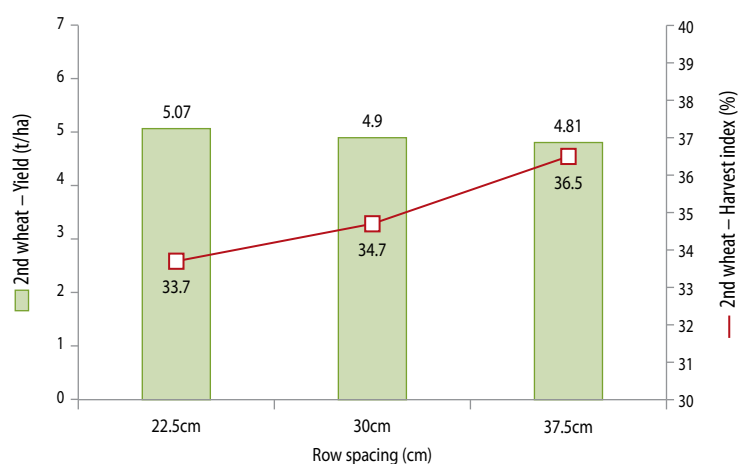
² Transpiration through the plant assumed to be constant based on a maximum 55kg biomass/ha.mm transpired. ³ Difference between water transpired (water used by the plant) through the plant and GSR (mm).

⁴ Transpiration efficiency for grain production based on kg/ha grain produced per mm of water used by the plant.

Two 2010 wheat trials (30m apart) in two different rotation positions showing different yield reductions due to row spacing cv Gladius^{db}.



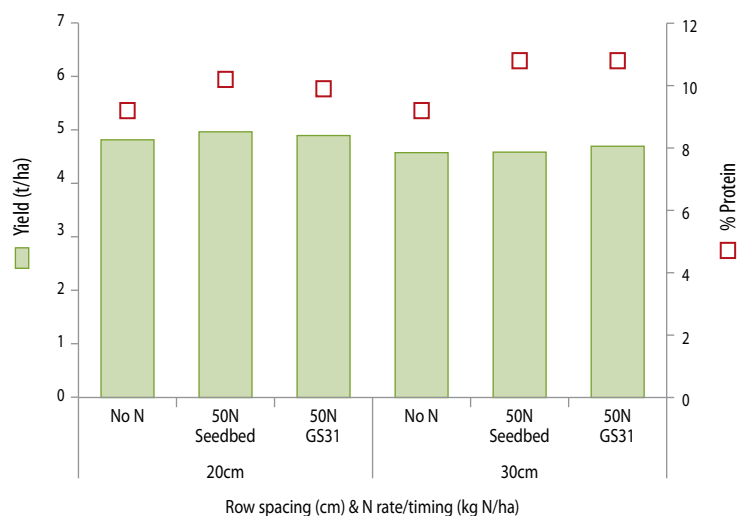
Wheat after canola – Coreen, NSW, 2010.



Wheat on wheat – Coreen, NSW, 2010. (Courtesy of Riverine Plains group)

Interaction with nitrogen timing – up-front versus in-crop nitrogen

Project trials with different N timing strategies at different row spacings in wheat indicate that the optimum N strategy does not change with row spacing.



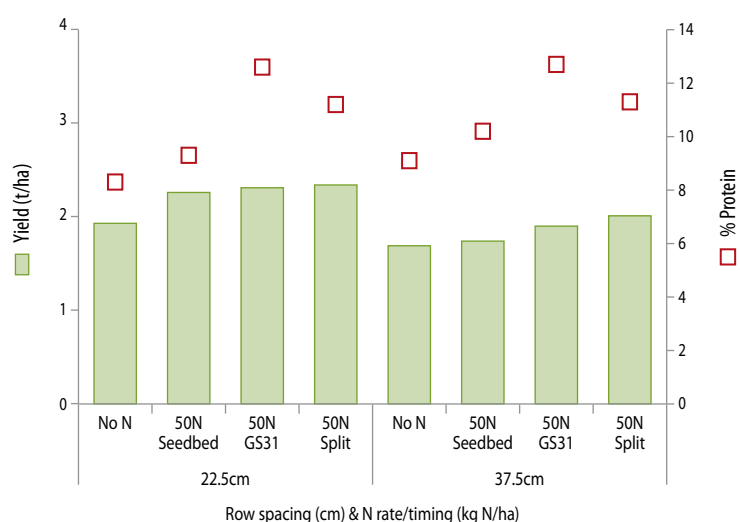
Mininera, Victoria – 2008.

GSR (Apr–Nov) – 392mm.

No response to applied N.

No significant interaction between row spacing and N rate and timing.

Significantly higher protein with 30cm row spacing.



Bungeet, Victoria – 2009.

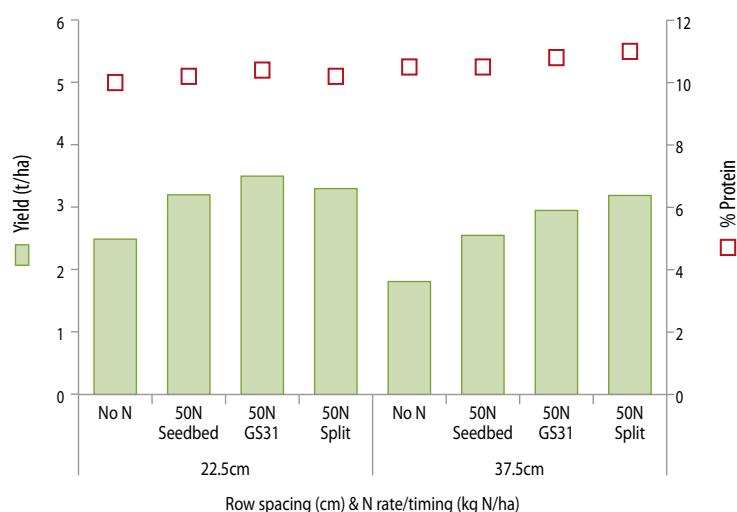
GSR (Apr–Nov) – 286mm.

Significant response to applied N.

No significant interaction between row spacing and N rate and timing.

Significantly higher protein with 37.5cm row spacing.

(Courtesy of Riverine Plains group)



Bungeet, Victoria – 2010.

GSR (Apr–Nov) – 586mm.

Significant response to applied N.

No significant interaction between row spacing and N rate and timing.

No significant difference in protein content between wide and narrow.

(Courtesy of Riverine Plains group)

i) Yields

- There are a number of reasons why growers might wish to pursue wider row spacing in cereals, for example, residue flow, inter-row weed and disease control. However, in all project trials (2007–10) on wheat covering a wide range of rainfall scenarios, increasing row width reduced yield.
- The yield reduction in wheat was particularly significant when row width exceeded 30 centimetres.
- Crop row spacing is an important factor for weed competition.
- At row widths of 30cm the reduction in wheat yield compared to narrower 20–22.5cm row spacing was dependent on overall yield potential.
 - At yields of 2–3 tonnes per hectare the yield reduction was negligible.
 - At yields of 5 t/ha the yield reduction was between 5–7%, averaging about 6%.
- Data from a single site suggests that rotation position may influence the yield response in wider row spacing in wheat. In wheat, wheat-on-wheat suffered less yield reduction with wider rows than an equivalent trial at the same site which was in wheat after canola.

ii) Plant spacing

- Increasing row width decreases the plant-to-plant spacing within the row, leading to more competition within the row and reduced seedling establishment (for reasons that are not clearly understood).
- Increasing plant populations when using wider rows can be counterproductive with regard to yield, particularly where plant populations exceed 100 plants per square metre as a starting point.
- Limited data indicates that increasing seeding rates such that the average plant to plant spacing in the row drops below 2.5 cm are either negative or neutral in terms of grain yield.
- Planting seed in a band (as opposed to a row) will increase plant to plant spacing but may increase weed germination and moisture loss through greater soil disturbance.

iii) Dry Matter

- Wider row (30cm and over) spacing reduced harvest dry matter relative to narrower rows (22.5cm and under), with differences growing steadily (kilograms per hectare) from crop emergence to harvest, by which time differences were in the order of 1–3t/ha depending on row width and growing season rainfall.
- The reduction in dry matter in wide rows was also significant at flowering (GS60–69), frequently 1t/ha reduction when row spacing increased 10cm or more over a 20cm row spacing base. This could be important when considering harvesting for hay rather than grain.

iv) Grain quality

- The most noticeable effect of row width on grain quality was on protein, wider rows reduced yield and increased grain protein.
- Differences in grain quality were typically small in terms of test weights and screenings, with very small benefits to wider rows over narrow rows on some occasions.

v) Nitrogen management

- Nitrogen management did not interact with row spacing, optimum N regimes for narrow row spacing (22.5cm or less) were the same as for wider row spacing (30cm or more). The greater nitrogen efficiency observed with stem elongation applied nitrogen was more important with narrow row spacing since higher yields lead to a tendency for lower protein.

Integrating new technologies with canopy management – use of crop sensors

Nick Poole (Foundation for Arable Research) and Peter Hooper (Hart Fieldsite Group Inc., Clare, South Australia).

For most growers canopy management has been the adoption of delayed nitrogen. Based on trial results, growers have had greater confidence to delay expenditure on inputs such as nitrogen and fungicides in order to respond effectively to seasonal climatic conditions. The approach has been valuable not only for taking account of drier spring conditions but also in making greater use of crop models such as Yield Prophet®.

Why crop sensors?

There are a number of ways of estimating nitrogen requirement for a crop, for example soil nitrogen testing and budgeting. Tractor mounted crop sensors may have a number of potential advantage in better N management (assuming crop sensor readouts can be correlated to the nitrogen content of the plant); these include:

- an immediate result for canopy nitrogen status;
- an indication of nitrogen status across the whole paddock;

- an objective measure of crop response to applied nitrogen i.e nitrogen rich strips;
- a better indication of nitrogen supply to the plant than soil testing, since the plant can be an indicator of available N on a spatial basis;
- an easier link to variable rate fertiliser;
- forming the basis of a change map where the grower could use the sensor to record the degree of change or growth following an earlier nitrogen application; and
- management of other inputs that could be linked to crop canopy size and N status such as plant growth regulators applied to reduce lodging risk, and disease control linked to canopy density.

What do crop sensors measure?

Ask the majority of growers how they make decisions on crop input and they will tell you it is based on experience and the visual appearance of the crop. Over the past three seasons, GRDC project SF500017 has been examining the role of crop reflectance

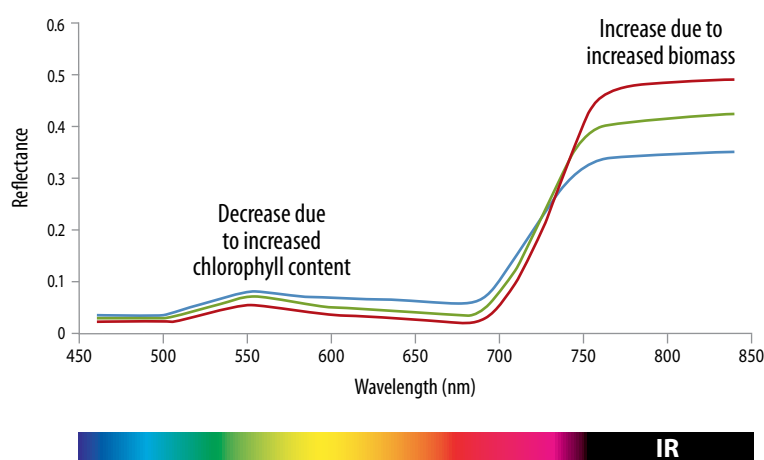
sensors such as the Crop Circle™ and GreenSeeker® in canopy management trials, in order to assess whether we can use them to visualise canopy size and nitrogen status.

So what do they measure?

Mounted on the tractor or on the boom the current active light source (ALS) sensors such as Crop Spec®, Greenseeker® and Crop Circle®, measure the amount of reflectance at specific wavelengths of light, particularly in the red and near-infrared wavebands. Since light reflected from the crop diminishes with distance from the crop, reflectance values from the specific wavelengths are expressed as ratios so that differences in distance from the target is negated. These reflectance values from different wavelengths can be made into a plethora of vegetative indices the most common of which is Normalised Difference Vegetative Index (NDVI).

As nitrogen application increases there is an increase in biomass and increased NIR reflectance (move from blue line to red line at 760nm–800nm+) but increased chlorophyll content reduces visible red reflectance (move from blue line to red line at 650nm).

$NDVI = \frac{\text{reflectance NIR} - \text{reflectance Red}}{\text{reflectance NIR} + \text{reflectance Red}}$



Typical reflectance spectra for a crop (Reusch, 2008).

$NDVI =$

$$\frac{(\rho_{NIR} - \rho_{VIS})}{(\rho_{NIR} + \rho_{VIS})}$$

Where ρ is crop reflectance at that wavelength of light.

E.g.

NIR – Near infrared – $\rho = 0.3$

VIS – visible red $\rho = 0.05$

$$(0.3 - 0.05) = 0.25$$

$$(0.3 + 0.05) = 0.35$$

$$= NDVI \text{ of } 0.71$$

What affects crop reflectance and the resultant vegetative indices?

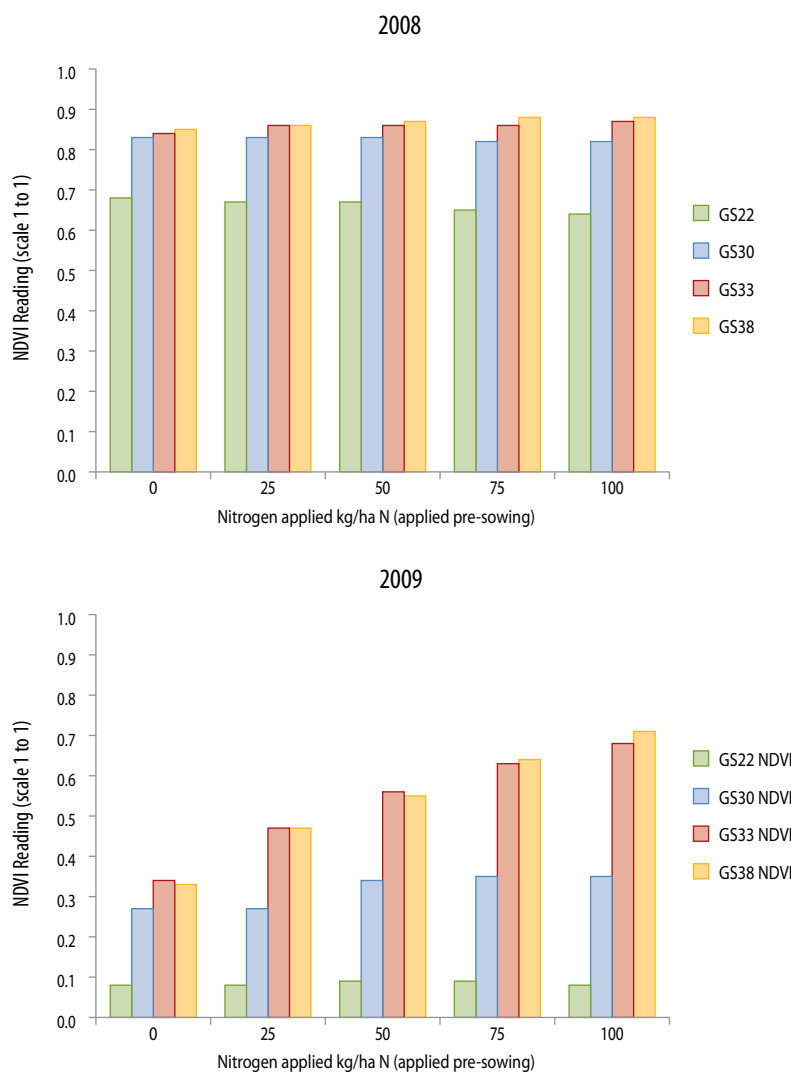
Chlorophyll content

The chlorophyll content of the crop canopy is linked to nitrogen concentration. As nitrogen increases, the leaf gets greener and the reflectance in the visible red range is reduced. Plants absorb light in the red zone of the spectra.

Crop biomass

As the biomass and ground cover of the crop increases so does the near-infrared reflectance, therefore as the crop grows with adequate water and nitrogen supply biomass and chlorophyll content increase; as a consequence NDVI increases (by virtue of greater reflectance in NIR and lower reflectance in visible red).

NDVI values change with both growth stage and soil nitrogen status. This was shown in trials conducted in 2008 and 2009 in the Wimmera. Where wheat followed lentils and had an autumn soil nitrogen level of 253 kilograms of nitrogen per hectare, NDVI values exceeded 0.8 at GS30. However, in 2009 in a neighbouring paddock the wheat followed oaten hay with only 60kg N/ha in the zero to 100 centimetre profile and NDVI values at the same growth stage were less than 0.4.



A comparison of NDVI values recorded from a wheat crop fertilised with five rates of nitrogen (0, 25, 50, 75 and 100kg N/ha) following lentils in 2008 and oaten hay in 2009 – cv Derrimut, Lubeck, Victoria (Wimmera clay).

Contrasting the NDVI data for three years with and without nitrogen allows one to build up an excellent profile of site fertility and seasonal conditions.

2008 – (Soil N at sowing – 253kg N/ha following lentils)

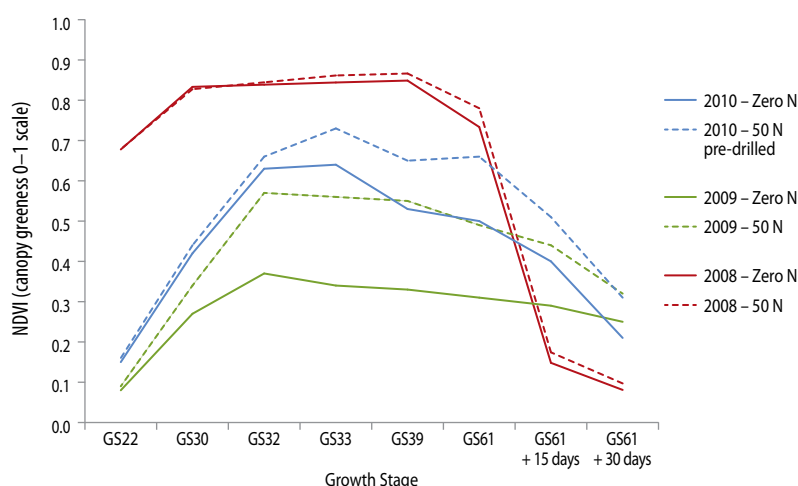
- NDVIs were above 0.8 at GS30, correlating with the high degree of fertility. There was no indication that plots receiving pre-drilled N had higher NDVI at this growth stage.
- NDVI remained high until flowering, with little indication that those plots receiving N exhibited a greater NDVI.
- At flowering, severe drought resulted in a rapid decline in NDVI.
- There was a negative response to applied N in the trial.

2009 – (Soil N at sowing – 60kg N/ha following oaten hay)

- By contrast, 2009 NDVIs never reached 0.4 in the unfertilised crop, while large increases occurred where N was pre-drilled, for example, 0.2 in NDVI from an application of 50N by the time crop reached GS32.
- The softer finish was mirrored by higher NDVIs at the end of grain fill than had been the case in 2008.
- There was a 25% yield increase from the application of N (50kg N/ha).

2010 – (Soil N at sowing – 153 kg N/ha following wheat hay)

- Intermediate fertility was reflected by higher NDVI than recorded in 2009, and later separation of the NDVI lines from N-treated and untreated crops.
- The extremely long season led to very high yield potential: 5.8t/ha yield with no N applied.
- There was an 18% yield increase with the addition of 50kg N/ha.



A comparison of NDVI values recorded from a wheat crop fertilised with 50kg N/ha and with no N applied following lentils in 2008, oaten hay in 2009 and wheat hay in 2010 – cv Derrimut, Lubeck, Victoria (Wimmera clay).

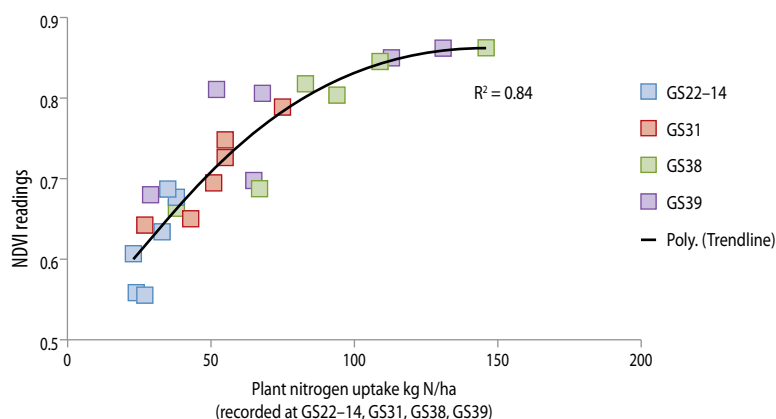
Whilst NDVI clearly relates to applied nitrogen, it is the relationship with nitrogen in the plant that ultimately determines the reflectance signal (i.e. whether the N is taken into the plant). Work conducted as part of the project has shown that NDVI gives a good relationship with the nitrogen content of the plant biomass, though the correlation becomes weaker at NDVI levels above 0.8 (due to saturation of greenness). Good relationships between NDVI and plant nitrogen uptake have been recorded from late tillering up to flag leaf emergence (GS39).

KEY POINTS

If little or no nitrogen has been applied to the crop by the start of stem elongation NDVI values could be a useful spatial indicator of fertility (soil nitrogen) in the paddock, (provided N rich strips or calibration strips are used to verify that any differences in biomass and chlorophyll content are due to nitrogen rather than other nutritional factors or disease or waterlogging).

In project trials NDVI readings collected from late tillering – flag leaf emergence (GS24–39) correlate strongly to nitrogen uptake (kg N/ha in the plant biomass) in wheat.

Correlation between NDVI and Plant Nitrogen uptake in Wyalkatchem[Ⓓ].



Crop reflectance index (NDVI) in relation to plant nitrogen uptake assessed at different growth stages from tillering until flag leaf emergence (GS22–GS39) – cv Wyalkatchem[Ⓓ] Tarlee, SA 2008.

So can we relate our rate of N input to NDVI values?

The answer is yes. There are already parts of the world where growers are applying nitrogen on the basis of crop reflectance; however, there are a number of complicating factors.

Many growers are currently using crop sensors to map crops and apply a predetermined amount of nitrogen at variable rates. Absolute NDVI values are influenced by a range of factors other than nitrogen and these could distort NDVI values from one paddock to the next. These factors include:

- different cultivars and row spacing;
- soil nutrition imbalances, for example pH, other nutrient deficiencies other than nitrogen;
- weed patches;
- disease; and
- waterlogging.

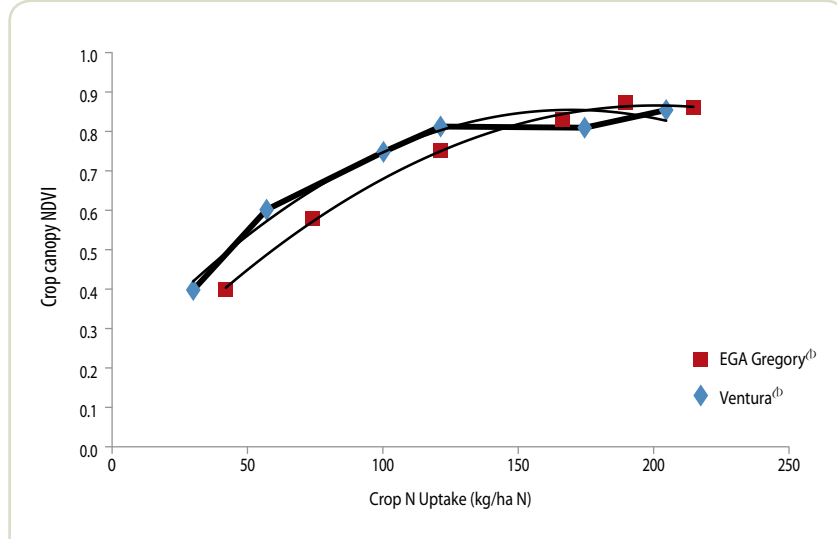
This means that to use crop reflectance to vary nitrogen application across a paddock, specific calibration strips must be used.

These complicating factors have led to the use of paddock N-rich strips or N ramps (where more than one rate of N has been applied at sowing as a test strip), which give the grower a gauge as to how much nitrogen is being supplied from the paddock, but also confidence that the difference in the crop canopy NDVI is due to nitrogen uptake.

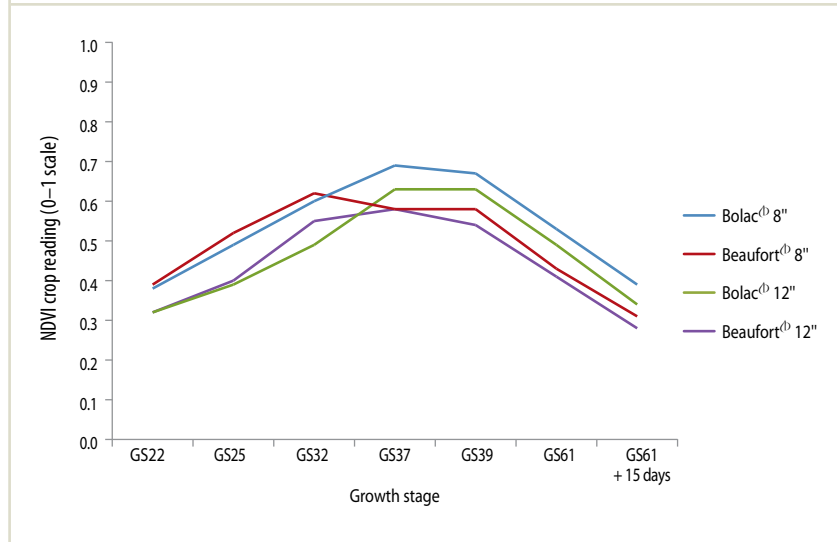
NDVI Response Index and the N-rich Strip

There are websites available (Oklahoma State University being an example) that offer algorithms (NDVI values that can be matched to suggested N applications). These algorithms are also built into some of the software packages supporting the sale of crop sensors. Gradually more algorithms are being developed for Australian conditions by growers and advisers working with crop sensors, and by researchers.

A simple calculation that has been applied to the canopy management trials over the last



Difference in the relationship between crop canopy NDVI and crop N uptake using two different wheat cultivars EGA Gregory^{db} and Ventura^{db} – Gowrie, NSW, 2008.



Influence of row spacing (200mm versus 300mm) and cultivar on NDVI with no nitrogen applied – cv Bolac^{db} and LongReach Beaufort^{db}, Victoria, 2008.

three seasons, which relates to Oklahoma State University methodology, is to calculate the NDVI response index using trial plots (as N-rich strips) which have been treated with 50kg N/ha at sowing in the autumn. In early spring (GS30–31), by crop sensing both the N-rich strip plots and no N plots, an index of predicted N response can be made from the comparison of the NDVI values. More than 12 trials carried out in a range of climatic zones, using differing cultivars, sowing dates and row spacing, compared the predicted N response (calculated from the response index (i.e. the difference between the N-rich strip and no nitrogen plots) with the actual N response as a percentage yield increase over

the untreated. The Oklahoma State University methodology calculates the N dose to be applied based on multiplying the predicted N response index (based on NDVI difference between N-rich strip NDVI/Paddock NDVI) by the predicted yield for that site with no nitrogen applied. The yield potential for the crop with no nitrogen applied is estimated at GS30 from the results of numerous of trials conducted in that region where NDVI at GS30 is divided by the number of growing degree days (GDD) greater than 0°C since planting, referred to as the INSEY units (in season estimate of yield).

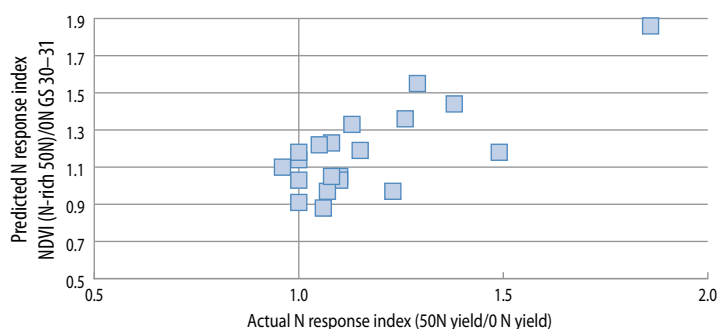
In Australian project trials, estimates of yield without nitrogen fertiliser applied have been based on crop models such as APSIM/Yield Prophet, since there were insufficient trial data with variable yields to build an estimate of yield at GS30 using NDVI.

NDVI values and subsequent response to N in wheat

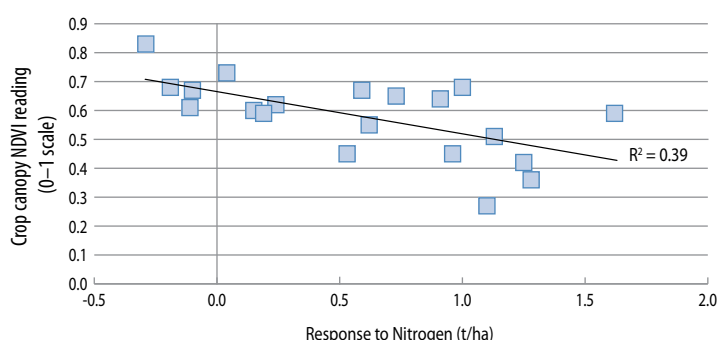
Based on the research data collected in these trials it has been difficult to predict yield purely from NDVI at GS30–31. However one simple question that has been asked is “has there been an absolute NDVI value recorded at the start of stem elongation GS30–31 above which no response to applied nitrogen can be observed?”

Data from canopy management trials collected over the last three seasons (12 trials – 20 data sets) has been plotted to answer this question, remembering that at these sites, wheat cultivar, row spacing, soil type and climatic conditions have all been vastly different.

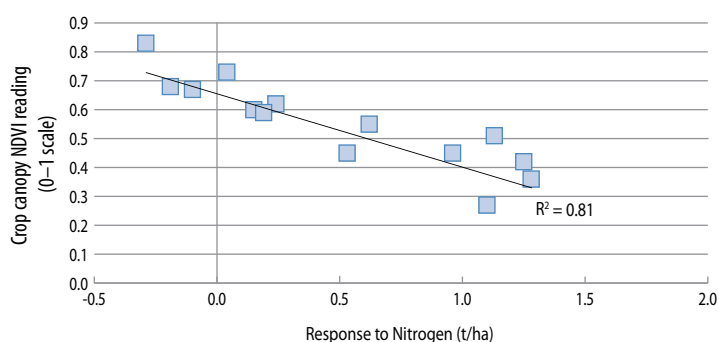
With the exception of one site (five data points – Tarlee, South Australia, 2008–10) the data showed that when NDVI exceeded 0.7 assessed at GS30–32 (start of spring) no subsequent yield response to applied nitrogen was recorded at those sites. At Tarlee there was a high NDVI yet excellent responses to applied nitrogen in all three seasons. Subsequent experimentation illustrated that wet winters encouraged green moss growth on the surface of the soil which may have increased the NDVI readings (possibly by as much as 0.1), making the NDVI readings for the unfertilised plots artificially high. If the correlation was determined using all data from the three years with the exception of Tarlee, the correlation R^2 exceeded 0.8.



Yield response to applied nitrogen (50 kg N/ha) in comparison to the NDVI response index (The NDVI of 50kg N/ha N-rich strip versus the unfertilized paddock situation – 20 site/cultivar/population/row spacing combinations 2008–2010 seasons).



NDVI value recorded at GS30–GS31 in wheat at 20 data set combinations of site/cultivar/population/row spacing combinations and the subsequent response to applied nitrogen 2008–10 seasons.



NDVI value recorded at GS30–GS31 in wheat at 15 data set combinations of site/cultivar/population/row spacing combinations (excluding Tarlee) and the subsequent response to applied nitrogen 2008–2010 seasons.

Steps to turn NDVI readings into N dose (based on Oklahoma State University methodology):

1. calculate predicted yield in the absence of N applied (based on INSEY (in-season estimated yield graph));
2. multiply predicted N response (based on NDVI N-rich strip/NDVI Paddock) by untreated yield in t/ha to obtain yield with N applied; and
3. nitrogen dose applied = Grain N content with N applied minus Grain N content of zero N in kg N/ha/fertilizer allowing for an efficiency factor (50% typical figure for Australian conditions).

Crop Reflectance Calibration Strips

In many cases the grower still makes the choice on the overall N dose to be applied and crop reflectance values (and calculated indices) are used to determine variable rate N distribution based on the variation in NDVI recorded on a pass through the paddock. This pass through the paddock is used to calibrate the sensors to the amount of variation in that paddock. The extent of variation recorded in a pass through the paddock, is the basis of a calibration strip which then sets the range of nitrogen rates for application. For example, if we assume 50kg N/ha is determined to be the set rate and NDVI variation runs at 20% above and below the mean in the calibration

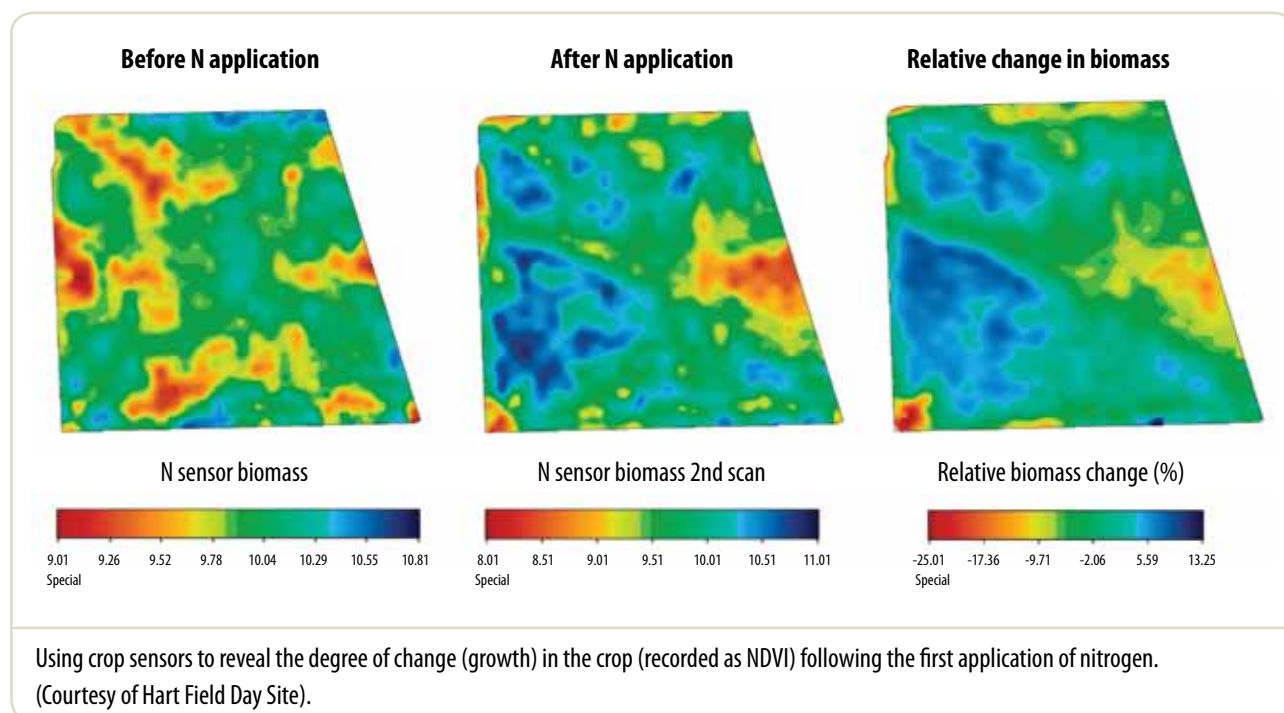
strip, this then dictates the extent of variable rate application (– 20% and +20% giving 40 to 60kg N/ha).

What is a change map?

Moving forward an approach that may be suited to higher yielding regions (where nitrogen applications are split – see later section) is using the crop sensors to record the degree of change (or growth response) in a crop following a first nitrogen application. Recorded on a spatial basis this NDVI change map or crop reflectance change map becomes the basis of a second N application. The theory being that more N is applied to the areas showing greatest

change. However, work conducted by the Riverine Plains group has challenged this approach suggesting that more N applied to areas of greatest change could be counterproductive.

The issue then becomes determining how late such a N application could be applied. In canopy management studies conducted so far, the target growth stage for such a second dose would be difficult to delay beyond third node to flag leaf emergence (GS33-39). After this stage the opportunities for creating yield from N application become limited, though effects on protein would still be possible.



KEY POINTS

- Crop sensors are useful tools for measuring and mapping variability in crop growth.
- Crop sensors can be used to assess crop nutritional status and crop canopy size.
- How this information is used is dependent on the growth stage, crop situation and the causes of the variability.
- It is easier to determine the extent of the nitrogen dose variation using NDVI variation than it is to determine the absolute rate of nitrogen application.

Warning – crop sensor reflectance readings are influenced by:

- **water, dew and frost on the leaves;**
- **incorrect operating height above the crop;**
- **green biomass such as moss or weeds in the crop;**
- **the need to adjust indices to take account of soil background; and**
- **large crop canopies with complete ground cover can saturate crop reflectance readings.**

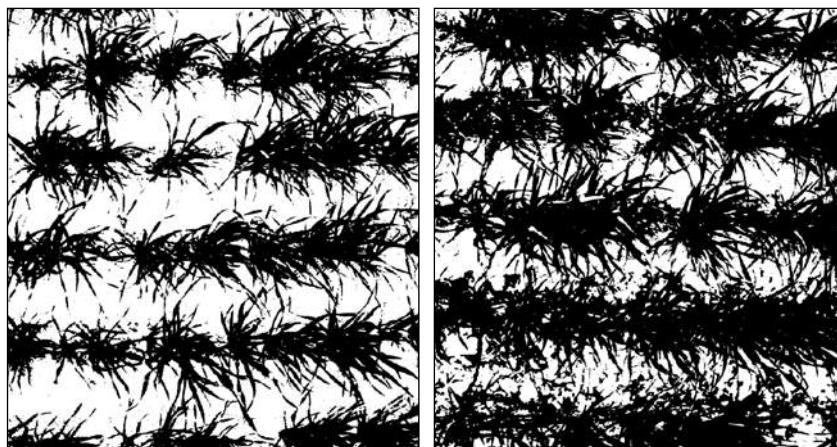
Digital photos for measuring canopy cover

Using early crop growth as a guide to paddock nitrogen fertility is a well-understood and utilised gauge. It is easier and simpler to measure surrogates for nitrogen concentration in the crop tissue compared to multiple soil tests. This can be done through plant nitrogen concentration tests, chlorophyll content, shoot density and colour charts to name a few.

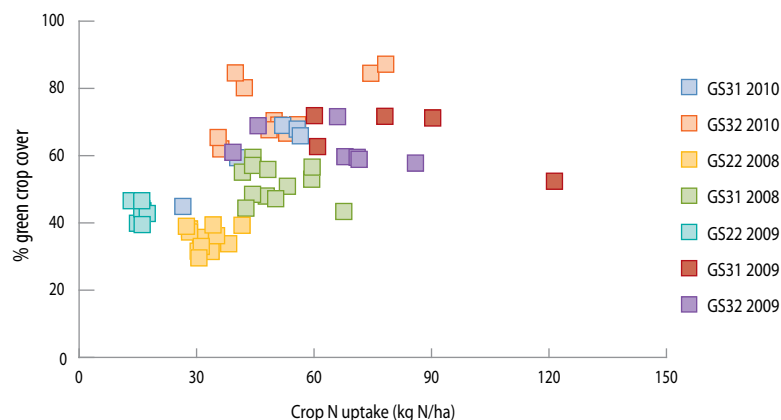
With the introduction of crop sensors, and aerial and satellite photographs, an objective value of crop growth can be produced. It has allowed for more crops and treatments to be measured and also has the ability to account for spatial variation.

A simple digital camera or mobile phone camera can also provide a useful measure of early crop growth. It measures the intensity of reflectance in the red, green and blue bands and so could act as an inexpensive alternative to multispectral sensors for measuring crop nitrogen.

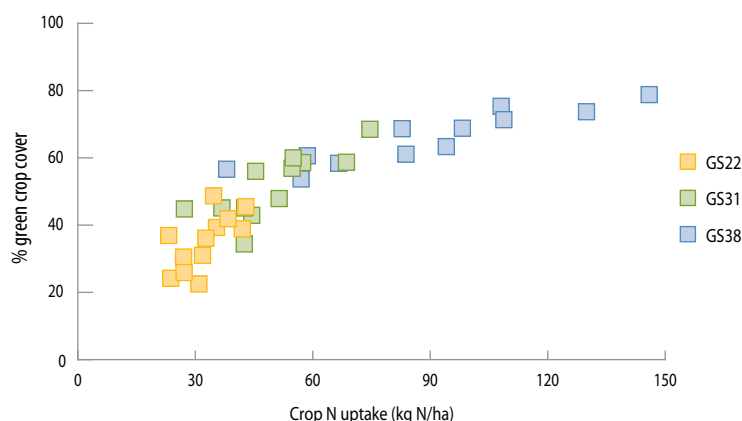
- One such camera system has been developed by John Angus (CSIRO Plant Industry, Canberra) and is able to estimate canopy cover from digital camera images. The program can be downloaded at http://plantindustry.csiro.au/canopy_cover
- In the UK, BASF and Agricultural Development and Advisory Service (ADAS) have developed the 'oilseed rape GAI tool' for managing the canopy of oilseed rape (canola) during early crop growth. An application has been developed for the iPhone or pictures can be uploaded to www.totaloilseedcare.co.uk
- Yara, a Norway-based fertiliser company, are also close to releasing a smartphone application that will generate figures for crop nitrogen content for both canola and cereals.



Example of processed digital images collected at GS31, where black represents green canopy and white background soil and stubble. The image on the left has 44% cover and the image on the right 66% cover.



Crop nitrogen uptake against % green crop cover (measured with a digital camera) for wheat with different crop densities, crop nitrogen rates, averaged over three replicates at Tarlee in 2008 and 2010.



Crop nitrogen uptake against % green crop cover (measured with a digital camera) for wheat at two crop densities and three rates of nitrogen, averaged over three replicates, measured at three timings, at Tarlee in 2008. $R^2 = 81\%$.

Work conducted by the Hart Field Site Group between 2008 and 2010 has demonstrated the relationship between green crop cover and crop nitrogen content. The relationship becomes less reliable after GS33 and is strengthened by using more than one photo. Importantly the relationship between green cover and NDVI, or crop sensor output, has also been very good.

While this tool offers much toward measuring the size of a young crop canopy, it only captures a small area of a crop so needs to be used carefully, replicated photos would improve this. There are a number of factors

that need to be considered in making the measurement, and there is also the necessity to ensure that the area captured is representative of the crop. Factors could include one or more of:

- crop growth stage and sowing time;
- crop variety;
- time of day or position of sun during image capture;
- wind blowing or bending the crop during the photo; and
- the presence of dew or moisture on the leaves.

KEY POINTS

- Digital cameras can provide a cheap and simple method of crop canopy measurement.
- This method is limited to early crop growth and there are many limitations to consider.
- A sequence of photos taken in the same location over time will give an idea of crop development.

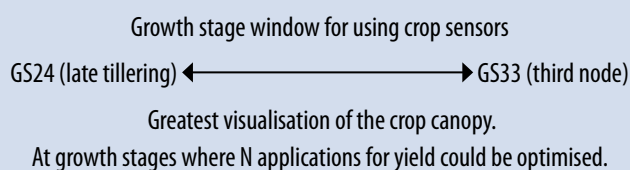
Which nitrogen strategy would allow us the greatest opportunity to employ the potential of crop sensors?

If the majority of nitrogen has been applied at sowing then there will be less value in crop reflectance data as an aid to nitrogen decision making as there is less opportunity to manage nitrogen application. To get the greatest benefit from crop sensors nitrogen applications should be made in the window where the sensors allow the greatest visualisation of the crop canopy thus maximising the opportunity to respond to differences in nitrogen supply.

- In early tillering (GS21) wheat crops are small and have not had time to express the benefit of different levels of soil nitrogen, therefore crop reflectance readings such as NDVI are less likely to visualise differences in soil nitrogen available to the crop.

KEY POINTS

It is critical to use crop sensors at growth stages when they both accurately visualise the crop canopy N supply and allow sufficient time for N top dressing to be applied:



- In project trials, crop reflectance readings taken over the emergence of the flag leaf (GS37–39) have given good correlations to nitrogen uptake. However, at this stage it would be too late in most situations to apply the main application of nitrogen, since there would be insufficient time for the crop to compensate for the loss of tillers with an increase in grain size and grain number.

Any strategy is also likely to be influenced by the amount of N applied, for example in lower-rainfall region, where yield potential dictates total N doses of little more than 20 to 40kg N/ha, it is likely that N would be applied as a single dose in the GS24–33 window. In higher-rainfall scenarios, with greater yield potential and potentially higher N requirement, it might be possible to use split nitrogen dressing during the GS24–33 growth stage window as an alternative to a single application.

Lower Rainfall: 2 to 3t/ha yield potential	Higher Rainfall: 3 to 6t/ha yield potential
Typical N doses applied – 0 to 40kg N/ha.	Typical N doses applied – 50 to 100kg N/ha.
N supply – soil N relatively more important in supplying total crop need.	More dependent on applied N – thus more N demand driven.
Single N application GS30–31 applied based on spatial reflectance data where: <ul style="list-style-type: none"> • high NDVI indicates high soil N availability; and • low NDVI indicates low soil N availability. 	Single application GS30–31 or split application where two N dressings are applied.
Using N-rich/Calibration strip to verify that low NDVI is linked to nitrogen not some other nutritional or soil related factor.	Split dressing: first application (late tillering or pseudo stem erect (GS26–30) based on spatial reflectance data (50 to 70% of total dose).
	Second N application to be applied at third node – early flag emergence (GS33–37) on the basis of spatial growth response to the first dose (i.e. to the parts of the paddock with the greatest response – greatest change in NDVI over the period from GS30–33), 30 to 50% of total N application.

Split applications of in-crop nitrogen during stem elongation – could they be used with crop sensors under Australian conditions?

Though split applications involve greater application costs and more passes through the paddock, they would allow the grower greater flexibility to take account of weather conditions during spring and an opportunity to assess the response to the first N application on a spatial basis using the crop reflectance readings from the crop sensors.

But how effective is a split nitrogen application (applied in a window between GS24–37) going to be in comparison to a single application at GS31 or a seedbed application under Australian conditions?

In five project trials where split N applications were compared to single N doses in the 2008–10 seasons, results revealed only small differences in yield compared with the other N timing strategies. In seasons with a very harsh finish the split held a benefit over other N timing strategies possibly as a result of

restricted N uptake under dry conditions and/or less opportunity to create an overly large canopy through increased tillering. In seasons with higher yield potential and lower soil N reserves, yields were slightly lower but the differences were not significant in any of the trials. The biggest difficulty is the timing of N to ensure uptake at later stem elongation (third node/early flag leaf emergence). For this reason it would be sensible to make the first N application at late tillering/early stem elongation the slightly larger application (in trials, N applications were always split 50:50).

KEY POINTS

In commercial situations the benefit of planning a split application of in-crop N is that a second N dose can be omitted if climatic conditions and soil water supply has reduced the expected yield potential. It also means crop reflectance sensors could be used to assess growth changes on a spatial basis (crop reflectance changes, for example NDVI) in light of the application of the first N dose (the so-called Change Map).

Caution: Splitting nitrogen during stem elongation will not be successful with later sown crops (early June onwards) or where the nitrogen applications are applied after the start of flag leaf emergence.

Influence of splitting the in-crop nitrogen dose at stem elongation in wheat – Mean of five trials 2008–10.

Site	Soil N kg N/ha		Yield % of No N (t/ha)				Split (GS30–33/39)
	0–90/100 cm	Cultivar	No N	Seedbed N	GS31 N		
Lubeck, 2008	253	Derrimut [Ⓛ]	100 (3.23)	87 (2.83)	87 (2.83)		91 (2.94)
Lubeck, 2008	145	Derrimut [Ⓛ]	100 (2.81)	n/a	105 (2.95)		106 (2.98)
Lubeck, 2009	60	Derrimut [Ⓛ]	100 (3.26)	125 (4.09)	125 (4.09)		126 (4.11)
Tarlee, 2010	103	Mace [Ⓛ]	100 (3.1)	152 (4.70)	153 (4.75)		148 (4.60)
Lubeck, 2010	153	Derrimut [Ⓛ]	100 (5.79)	127 (7.33)	128 (7.43)		126 (7.29)
Mean (5 sites)			100	n/a	119.6		119.4

Why is canopy manipulation in barley different to wheat?

There are a number of factors that growers and advisers need to take into account when considering canopy management in barley as opposed to wheat.

i) Nitrogen use efficiency

In project trials in wheat, nitrogen applied during stem elongation (G30–39) increased protein levels in resultant grain with equal or better yields. This led to an increase in nitrogen use efficiency and in seasons with little spring rain gives the option to omit applied nitrogen altogether. However, in malting barley an increase in grain protein may be detrimental to hitting the target window for protein. Conversely, if nitrogen applied at stem elongation is more efficient then it might still be used in malting barley but at a lower nitrogen rate to take account of the increased nitrogen use efficiency.

ii) Less ability to compensate from lower shoot numbers

When N-application is delayed from planting to stem elongation, it results in lower shoot numbers at the start of stem elongation (GS30–31). In wheat this results in the plant compensating with more viable grains per ear and in some cases larger grains.

- With barley there is less ability to compensate for lower shoot numbers since the crop is constrained with two rows of grain (since four rows of grain abort at an early stage, except in six-row barley). There are less potential grain sites per head than in the equivalent situation with wheat. As a result barley is more dependent on shoot number and grain size to increase yield than in wheat.

iii) Lower fertility rotation positions

Unlike wheat, barley is frequently grown following other cereals, such as wheat, this is an inherently less fertile rotation position than following break crops such as pulses and oilseeds. Though this is an advantage for lower protein specification malting barley, it

makes the crop relatively more dependent on nitrogen supplied at planting, since the soil nitrogen reserve is likely to be lower.

iv) Greater tillering capacity

The time taken for barley leaves to emerge (phyllochron) is usually shorter than that of wheat. As a consequence, during the tillering phase, the rate of leaf emergence determines the rate of tiller emergence (since each leaf to emerge has its own tiller bud). Overall, the tillering capacity of barley tends to be greater than wheat.

v) Plant architecture

The barley canopy tends to be more competitive than wheat, with larger lower leaves in the crop canopy and smaller upper leaves (i.e. flag and flag-1) compared to wheat.

So is it possible to manipulate the barley crop canopy and improve yield by delaying nitrogen to stem elongation and increasing plant population?

Yes, but such a technique is likely to be most successful where the grower is growing feed barley or has high soil nitrogen reserves (in excess of 100kg/ha N 0–60cm). In these situations adding the N fertiliser early to the high level of soil N reserves would make the crop grow excess vegetation, increasing the number of tillers. Delaying N until stem elongation would both reduce lodging risk and early disease pressure.

In the project, results have indicated far more success with delayed N in trials conducted on more fertile soils in the eastern states than in the west.



First cereal barley trials – Influence of soil nitrogen reserve and soil type

Results from Western Australia

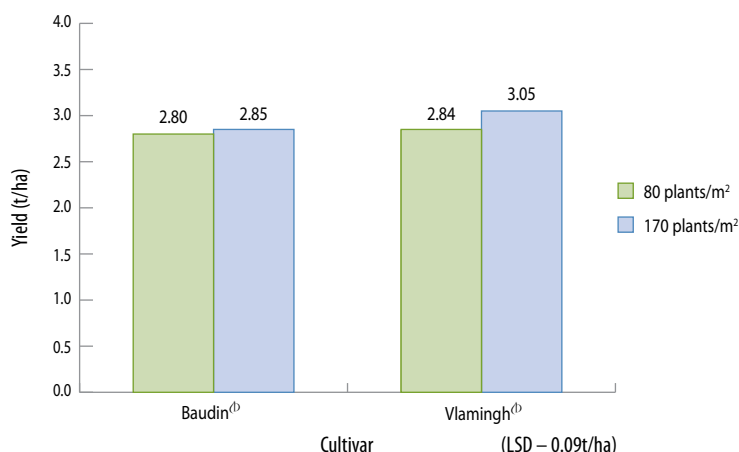
In the high-rainfall zone (HRZ) of Western Australia (WA Agzones five and six) manipulating the crop canopy in malting barley has had significant effects on grain quality, particularly with the popular cultivar Baudin[®]. These quality effects were often at odds with the canopy structure that created the highest yields. The trials on sandy gravel soils after canola with relatively low nitrogen reserves (less than 80kg N/ha) illustrated that there was no advantage to delaying nitrogen at sowing.

Manipulating the crop canopy with plant population – influence of variable spring rainfall

Comparing all barley project trials (seven in total), irrespective of location, increasing plant population from approximately 100 plants/m² to 150–200 plants/m² increased yield. In WA the differences have been small, but statistically significant at one site (Mount Barker).

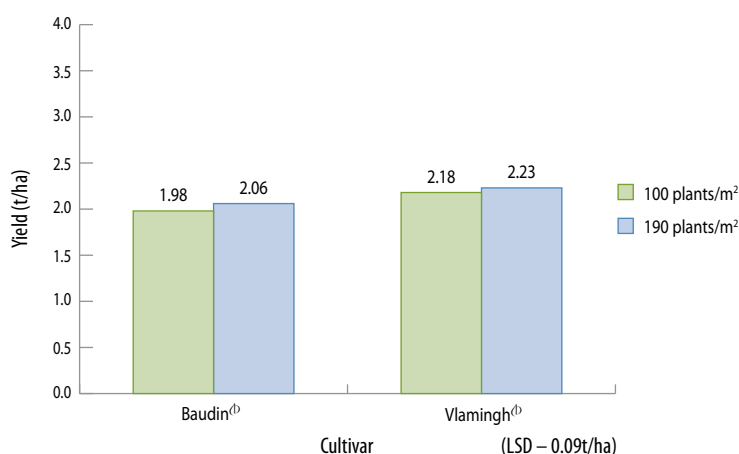
Baudin[®], with its greater propensity to tiller, has not shown the same yield increases from increasing plant population as were evident with Vlamingh[®]. The response of Baudin[®] to population increases being only 0.05t/ha over the two seasons, compared to 0.13t/ha with Vlamingh[®]. At the longer season site in southern Victoria the yield increases associated with manipulating plant population were very similar (3–4% – 0.18t/ha) but expressed at a higher yield level.

Mount Barker, WA, 2009



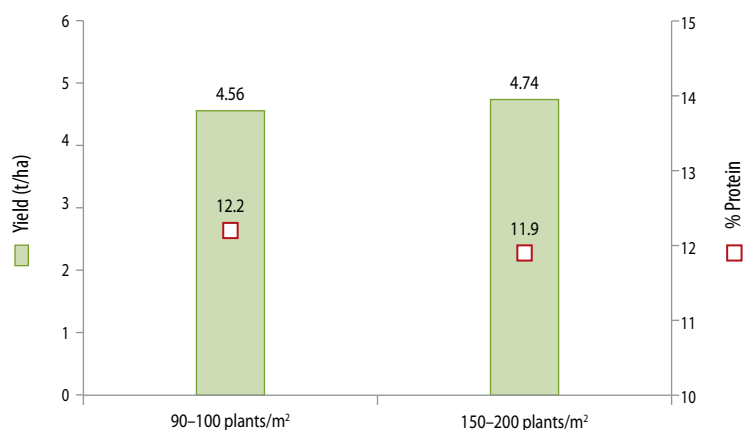
Influence of plant population on the yield of Baudin[®] and Vlamingh[®] at Mount Barker, WA, 2009.

Mount Barker, WA, 2010



Influence of plant population on the yield of Baudin[®] and Vlamingh[®] at Mount Barker, WA, 2010.

Inverleigh, Victoria, 2004–09



Influence of plant population on the yield and protein of barley at Inverleigh, Victoria, 2004–09.

- 2004 – cv Gairdner[®] (after wheat)
- 2006 – cv Gairdner Plus[®] (after peas)
- 2007 – cv Gairdner[®] (after canola)
- 2008 – cv Capstan[®] feed barley (after canola)
- 2009 – cv Capstan[®] feed barley (after canola).

This increase in yield with greater plant population has been associated with consistent positive and negative grain quality effects.

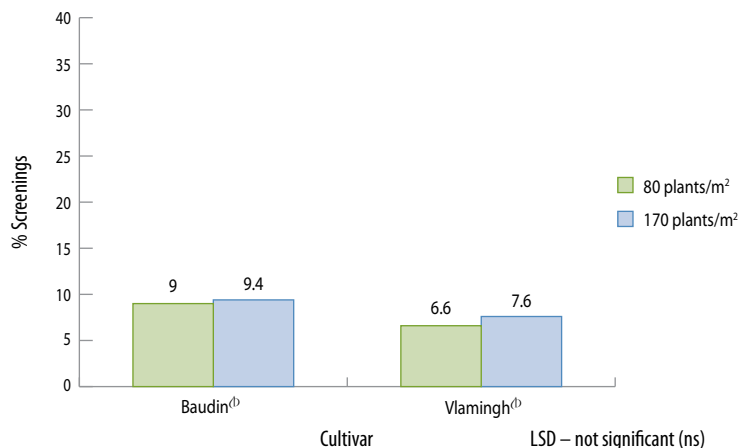
Positives

- A reduction in grain protein – an increase of approximately 80–100 plants/m² over and above a base population of 100 plants/m² reduced grain protein by up to 0.3% in WA and Victorian trials.

Negatives

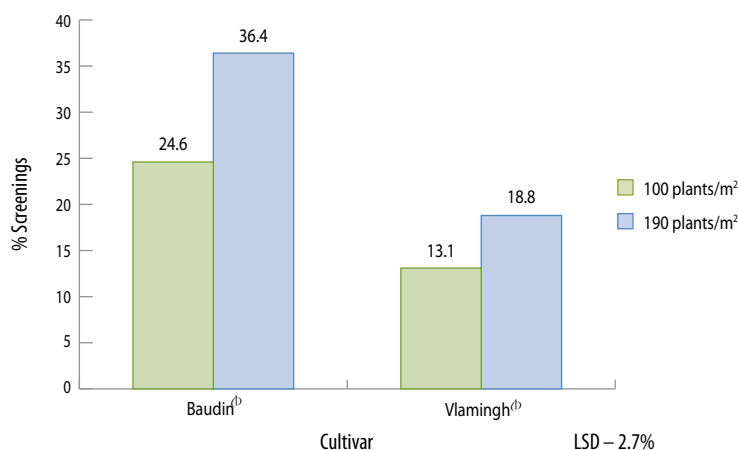
- In the same trials increasing plant population resulted in an increase in screenings, the severity of which was linked to the drought in the spring. In the 2009 season the differences were small and not significant, while in 2010 increasing population had significant effects.
- In both seasons Baudin[®] screenings were significantly higher than Vlamingh[®].
- The higher plant population was also associated with a small reduction in grain size and test weight.

2009 (Sept–Oct rainfall 105mm)



Influence of plant population on the % screenings of Baudin[®] and Vlamingh[®] at Mount Barker, WA, 2009.

2010 (Sept–Oct rainfall 64mm)



Influence of plant population on the % screenings of Baudin[®] and Vlamingh[®] at Mount Barker, WA, 2010.

Manipulating the crop canopy with nitrogen strategy – influence of different soil nitrogen reserves

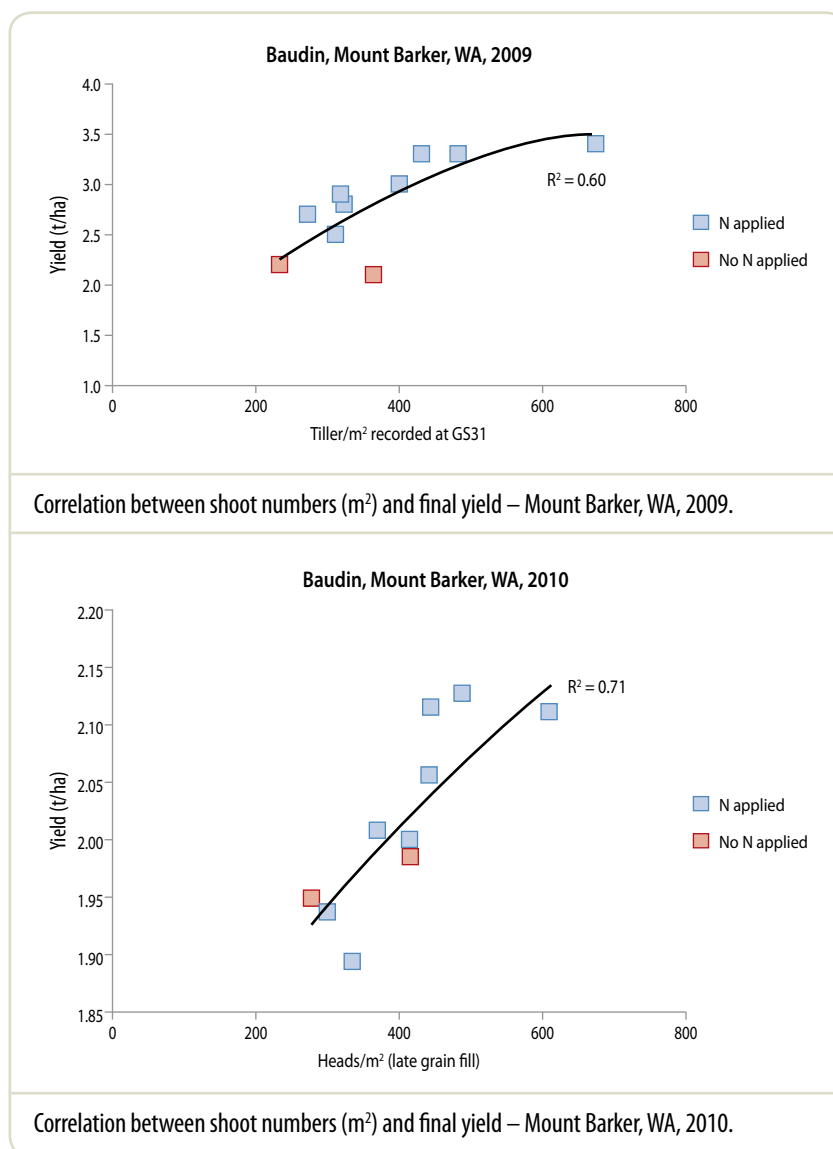
Low soil nitrogen reserves on Western Australian soils

In the 2009–10 WA trials, soil nitrogen reserves were lower than equivalent trials in the east with low to negligible reserves below 30cm depth. With soil nitrogen reserves lower than 80kg N/Ha on these WA soils, after canola, delaying all of the nitrogen until early stem elongation (GS30–31) resulted in significant yield losses in both years.

Under these circumstances delaying all the nitrogen until spring significantly reduced tiller number compared to N applied in the seedbed (IBS – incorporated by sowing). This effect was seen with all of the barley trials and is similar to wheat. However, when tiller numbers in no-nitrogen barley plots are down at 250–350 tillers/m² at GS31 there is insufficient time to compensate by applying N to increase thousand seed weight and prevent further tiller death. In WA trials with malting barley, delaying nitrogen until stem elongation led to a lower number of viable heads at harvest. In these WA barley trials there were good correlations between yield and final head number.

Correlations between grain yield and tiller and head number in lower fertility scenarios in WA malting barley

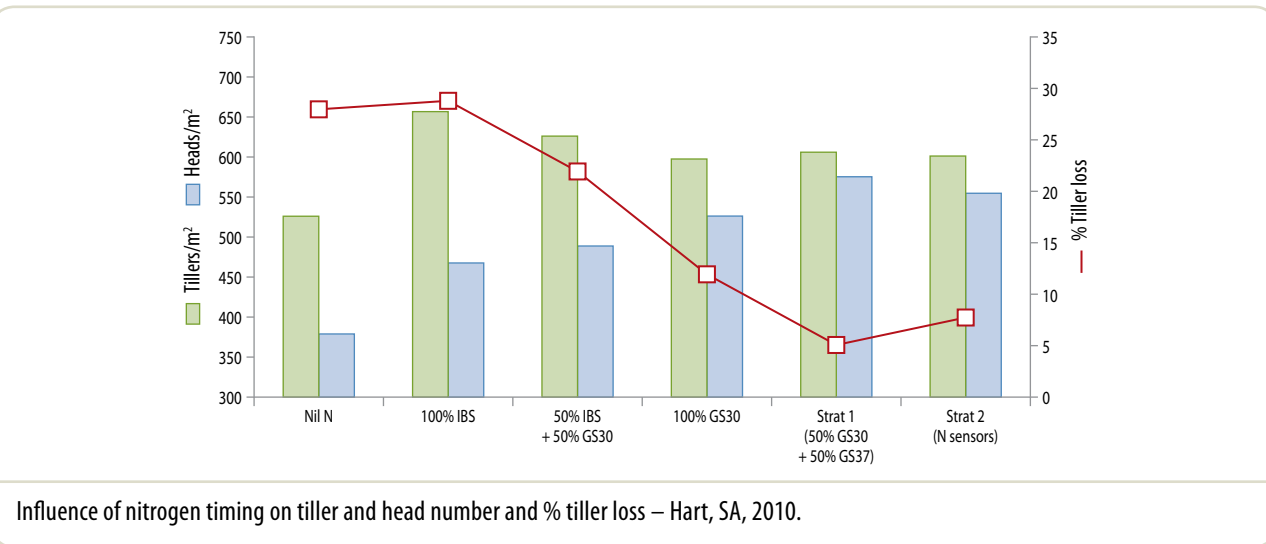
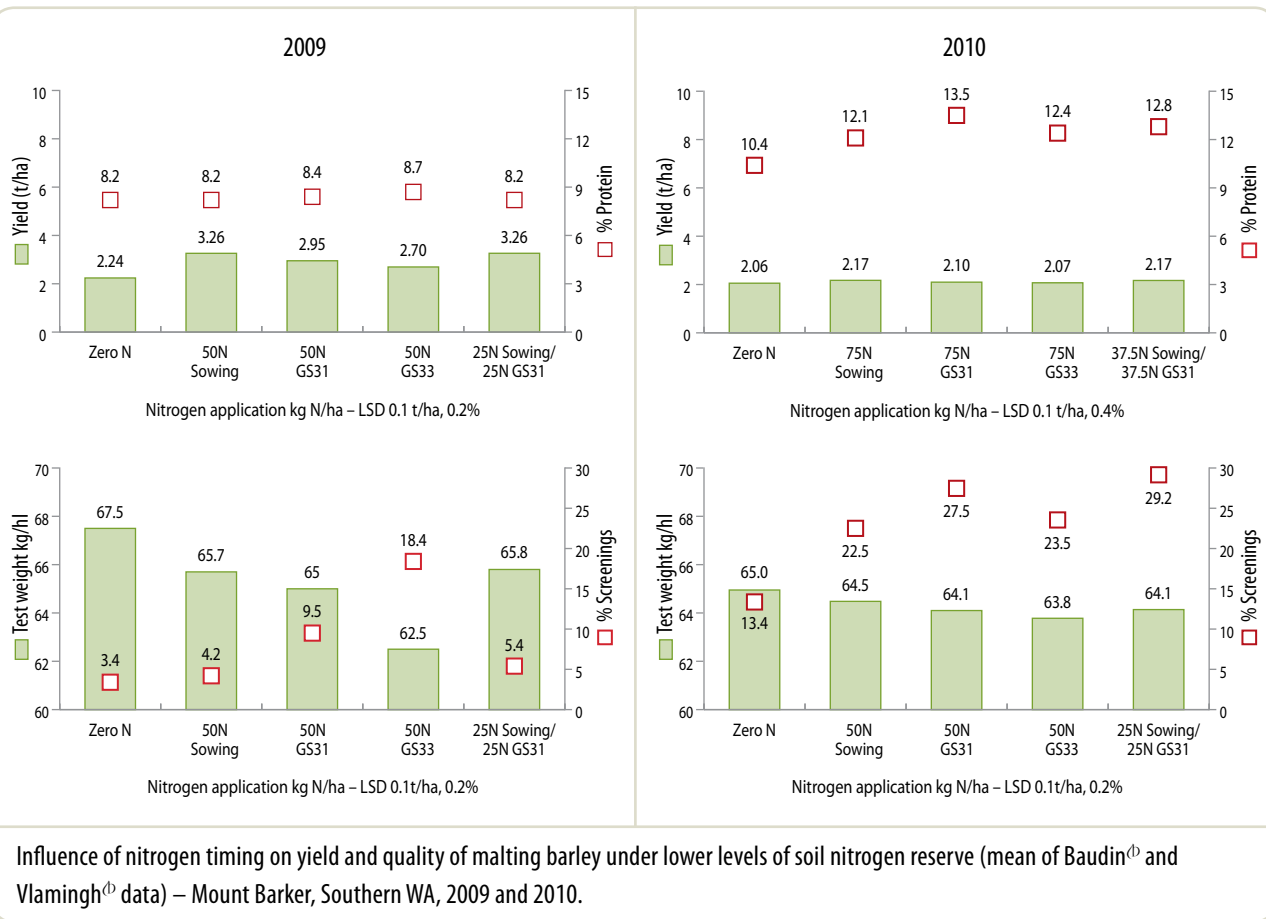
In WA malting barley trials it was not only yield that was reduced by delaying nitrogen but quality was also impaired. This was not just in the form of higher grain protein but also saw increased screenings particularly in 2010 when September and October were particularly dry.



Higher soil nitrogen reserves

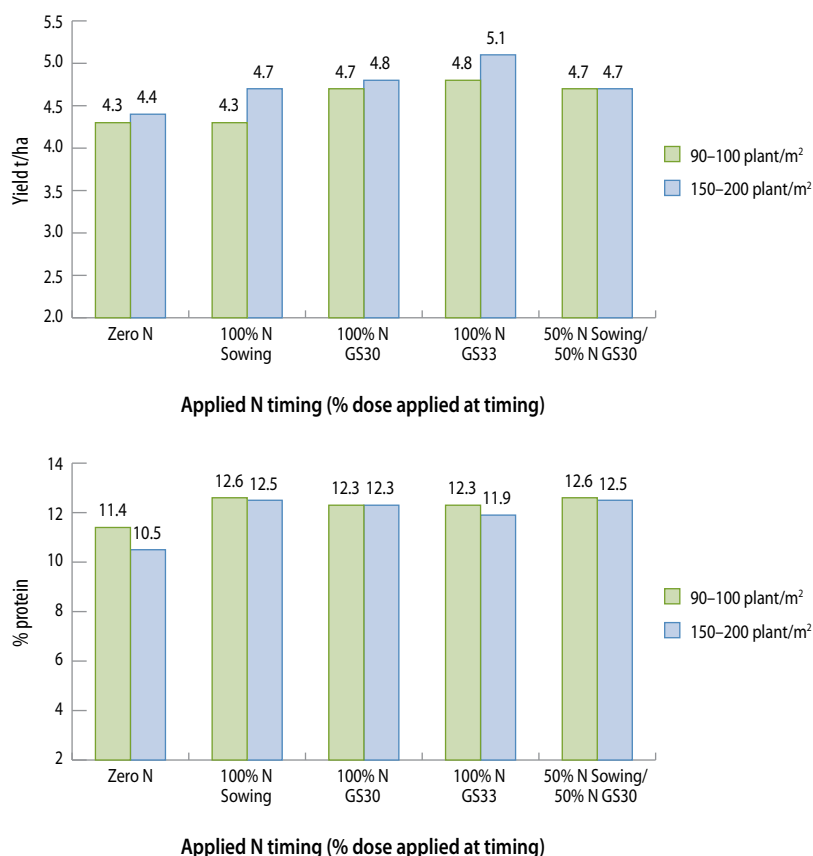
Reductions in tiller numbers at GS31, from holding back nitrogen, need not lead to lower head numbers or lower yields where soil nitrogen reserves are higher. These more fertile situations, often characterised by heavier soils than those in WA, have a greater propensity to produce tillers over winter. Where no nitrogen had been applied the crop canopy was still able to produce 500-plus

tillers. In these scenarios greater N input at sowing leads to excessive tiller population and a greater proportion of tillers die off without forming a head. For example at Hart in SA in 2010 there were clear indications that delaying nitrogen resulted in lower tiller numbers but no less heads, as tiller mortality was lower in these treatments.



In southern Victoria, with higher soil nitrogen reserves, results were similar to those obtained in SA – better yield responses occurred where nitrogen was applied at stem elongation. Results from trials with higher soil N reserves (100–200kg N/ha), carried out on both feed and malting barley, confirmed higher yield potential when nitrogen was applied at early stem elongation (GS30–31). Although protein levels with this N strategy have been over 12% when averaged over the five years, they were no greater than other nitrogen strategies based on applications at sowing. The higher fertility of these trials is strongly manifest in the relatively high yields and protein of the zero N plots and the lower overall response to nitrogen application.

In the trials in south-eastern Australia higher fertility gave higher tiller numbers than those experienced in WA, greater ground cover by GS31 and, as a consequence, high crop reflectance scores (NDVI) were recorded early in the season. In these trials untreated N plots produced over 550 tillers/m² (range 578 to 815) depending on plant population.



Influence of nitrogen timing and plant population on yield of barley under higher levels of soil nitrogen reserve – Inverleigh, southern Victoria HRZ, 2004–09 (mean of five trials).

Could the small response to nitrogen in southern Victorian trials be predicted from NDVI at GS30–31?

Using a crop that had received nitrogen at sowing, and comparing it to the zero N plots, it was possible to compare NDVI scores at GS30–31 to make an assessment of how responsive the site would be to applied nitrogen. Over three seasons at Inverleigh (2008–2010), nil nitrogen plots had relatively high NDVI (0.64–0.76) and high percentage ground cover with the crop canopy (indicating good nitrogen supply from the soil). However, the NDVI's recorded at GS30–31 in crops where at-sowing nitrogen had been applied still indicated a possible response to applied N when compared to the NDVI of the zero N plots, (NDVI response index over 1.05 (NDVI presow 75N divided by NDVI from the zero N plots) at GS30–31). It is generally recognised that a response index of over 1.05 will lead to an N response, however, over these three seasons the index never exceeded 1.10, indicating that any response to nitrogen would be small. Actual yield response to nitrogen was indeed small with relatively high yields in the zero nitrogen plots. In 2008 and 2009 the predicted response to nitrogen using NDVI based on at-sowing nitrogen and zero N was less than 1.1 but greater than 1.05. The actual yield response to applied N was less than 1.1 (less than a 10% yield increase from added nitrogen).

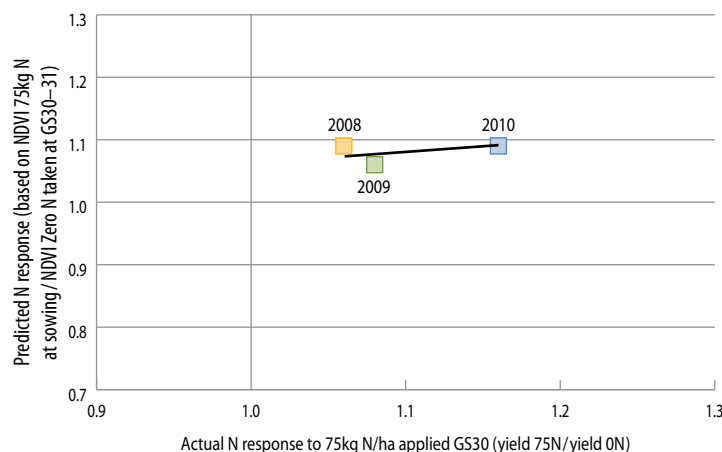
Could NDVI later in stem elongation give an indication of protein content at harvest?

If crop sensors could give an indication of likely grain protein content in barley during stem elongation it might provide an opportunity to adjust nitrogen application later (GS33–49). This may allow decisions to be made to manage a crop to fit the desired malting barley range or to manage a high protein crop for feed barley.

The results from southern Victoria showed no relationship between NDVI recorded at third node – flag leaf (GS33–39) and resultant grain protein. In all three years NDVI's were high, which accurately suggested little

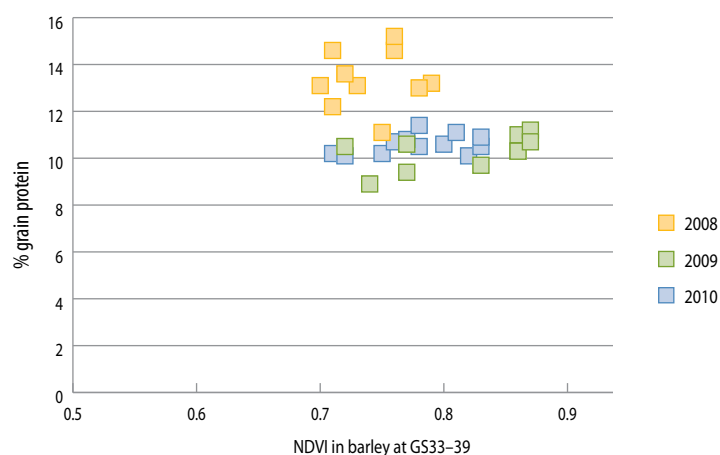
response (% yield increase) to nitrogen. However, NDVI was not strongly correlated to overall grain yield: similar NDVI values resulting in yields of between 4 and 8.5t/ha. In 2008 similar NDVI levels in the crop lead to yields that were half those observed in 2010.

Since yield did not correlate particularly well to NDVI between seasons it is perhaps not surprising that grain protein did not relate to NDVI. NDVI values recorded at GS33–39 in no nitrogen plots were similar (0.73–0.77), but protein levels varied from 9.4–13.1%.



Actual N response is the yield response to 75kg N/ha, for example 1.2 = 20% yield increase.

	2008		2009		2010	
	Zero N	75N GS30	Zero N	75N GS30	Zero N	90N GS30
NDVI GS30	0.66	–	0.76	–	0.75	–
NDVI Response Index (NDVI 75 N at sowing/NDVI 0N at GS30)	0.72/0.66 = 1.09	–	0.81/0.76 = 1.07	–	0.81/0.75 = 1.08	–
NDVI GS33–39	0.73	0.79	0.77	0.86	0.73	0.81
Yield t/ha	4.14	4.39	6.30	6.80	7.26	8.53
% Grain Protein	13.1	13.2	9.4	11	10.2	11.1



Barley NDVI at GS30–31 and resultant grain protein 2008–10 using different plant population and N strategies – Inverleigh, southern Victoria.



Zero N at GS31



Zero N at GS31

High fertility in no N plots in Inverleigh, Victoria.

By taking an NDVI figure from an untreated and fertilised area of the paddock, a nitrogen response index can be calculated.

KEY POINTS

For barley grown as a first cereal crop after the break crop, the resulting soil type, fertility and soil nitrogen reserves have a strong influence on strategies for manipulating the crop canopy:

i) Influence of plant population on yield & quality

- Whilst increasing plant populations from 100 to 150–200 plants per square metre has been associated with small yield increases in all trials, it comes at a cost of higher screenings, particularly with cultivars such as Baudin[®] in a dry spring.
- Plant populations of 100 plants/m², despite being slightly inferior on yield, gave better grain quality characteristics when grown with low soil nitrogen levels on soils with limited water holding capacity.

ii) Influence of nitrogen strategy under low soil nitrogen reserves (less than 80kg N/ha) in Western Australia and higher N reserves (greater than 100kg N/ha)

- Visual appearance (tiller density, greenness and ground cover) of an unfertilised crop in spring at the start of stem elongation can reveal a great deal about crop canopy status and how to manipulate it.
- If not already doing so, create some test strips in paddocks (with extra nitrogen or no nitrogen at seeding depending on what you are doing in the rest of the paddock i.e. the strip needs to be different to the rest of the paddock). These can be invaluable in helping you manage the crop canopy with or without crop sensors.
- In WA, May-sown barley crops with tiller numbers below 400 tiller/m² indicated crops have already lost yield potential through lack of nitrogen applied at sowing.
- Where soil nitrogen reserves are low and confined to the top 30 centimetres of the soil delaying nitrogen application until early stem elongation (GS30–31) in these barley crops will result in significant yield reductions compared to nitrogen strategies placing 50–100% of N at sowing.
- Conversely where tillers numbers are high in the spring (over 500 tillers/m²) it is likely that response to nitrogen will be lower and stem elongation nitrogen is likely to be a more successful strategy for increasing yield than seedbed nitrogen.
- Crop reflectance sensors assessing NDVI can be useful for quantifying the responsiveness of barley paddocks to N application using N-rich reference strips; however, they were not able to predict final grain yield and protein.

Early sown wheat management – grazed and ungrazed

Background

Some of the greatest advantages of manipulating the crop canopy in terms of leaf area are observed in early sown wheat, particularly where the use of true winter cultivars produce a longer tillering period. Project work over three years conducted in Australia's longest growing season environment in Tasmania, examined the influence of canopy management on long season feed (red) wheat yields in March-to-April-sown irrigated wheat.

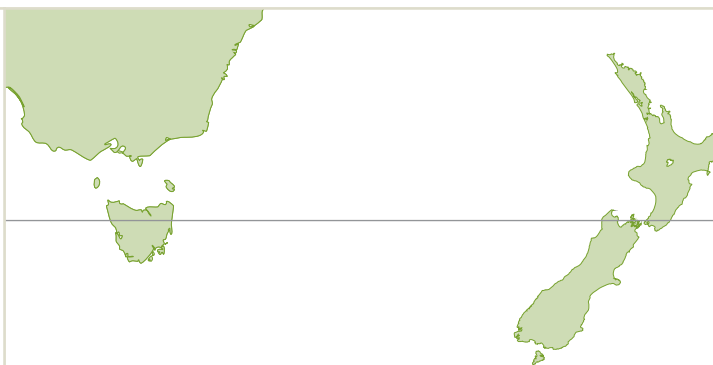
Key factors investigated were:

- the influence of grazing (sheep grazed/mechanical) and how it interacts with
 - plant population;**
 - nitrogen timing; and**
 - plant growth regulators.**

Site Details *(see panel opposite)*

Mackellar[Ⓢ] wheat in year one and Revenue[Ⓢ] in years two and three were sown between mid-March and mid-April in the three years of the project. Crops were subject to supplementary irrigation in 2008 and 2010. The winters in 2009 and 2010 were very wet, so much so that in 2009 it was not possible to graze with sheep prior to GS30, so plots were mechanically defoliated.

In all three years the trial was fertilised with 160kg N/ha.



Australia's longest growing season: Tasmania's latitude relative to New Zealand.

Trial Site Details

2008	Site:	Longford, Tasmania
	Sowing date:	11 March 2008
	Variety:	Mackellar
	Fungicides:	18 August, 16 October, 12 November
	GSR:	436mm (+165mm irrigation)
2009	Site:	Cressy, Tasmania
	Sowing date:	22 April 2009
	Variety:	Revenue
	Fungicides:	11 September, 20 October, 11 November
	GSR:	589mm (no irrigation)
2010	Site:	Nile, Tasmania
	Sowing date:	24 March 2010
	Variety:	Revenue
	Fungicides:	26 August, 22 September, 28 October, 11 November
	GSR:	594mm (+50mm irrigation)

What were the advantages and disadvantages of early sowing observed in the project trials?

The influence of early sowing (March/April) relative to surrounding crops sown in May was particularly apparent in the very wet winters when it was observed that the early sown crops appeared far more tolerant to high water tables and surface waterlogging. Though comparison to later sowing dates was not formally part of the project, there was some evidence to suggest that the earlier sown crop used more water prior to winter

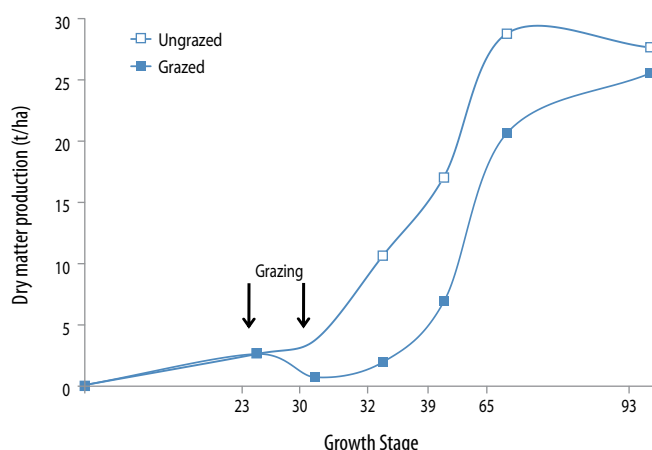
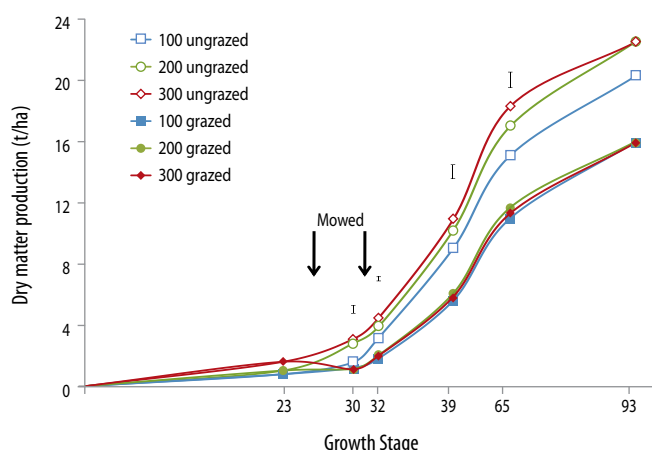
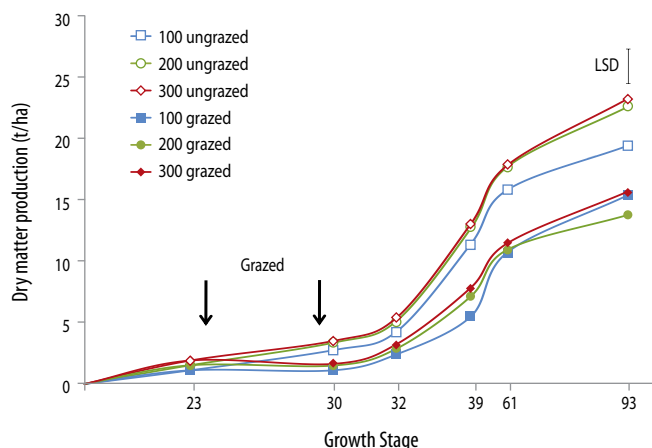
and in early spring and this alleviated the effects of the wet winter to a greater extent than May sown wheat in the region. The benefit of better tolerance to waterlogging came at the cost of increased frost risk, particularly in 2008 and greater lodging risk. **Cultivar straw strength plays a very important role in the success of early sowing.** Switching from Mackellar[Ⓢ] (lodging prone) in 2008 to the stiffer strawed cultivar SQP Revenue[Ⓢ] in 2009 increased the opportunity to manage the lodging in an ungrazed crop.

In addition to increased lodging pressure and frost risk, there was evidence that disease pressure was increased when wheat was sown in March/April, particularly in 2010, when, despite three fungicide applications, *Septoria tritici* was widespread in the trial.

What was the influence of grazing on dry matter over the three seasons of the trial?

The impacts of grazing were both positive and negative. In all three seasons the removal of dry matter, just prior to GS30 with grazing, retarded development pushing flowering five to 10 days later than in the ungrazed crop.

Dry matter



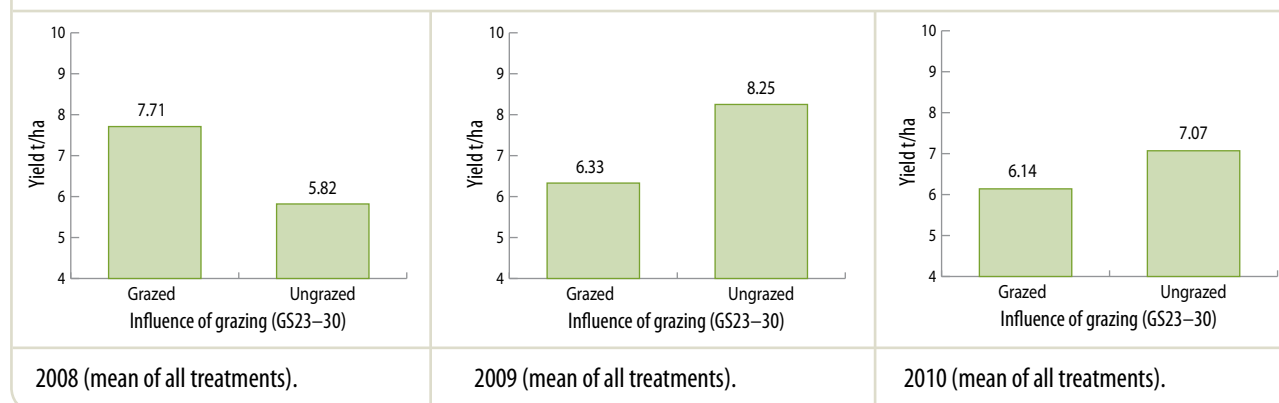
So was it possible to harness greater yield potential from these early sowing dates by grazing them?

In 2008 the slower development of the grazed crop increased grain site survival by avoiding key frost periods, which resulted in grain yields 1t/ha higher under a grazing regime. In addition, grazing significantly reduced lodging, though this was pronounced due to the poorer standing power of Mackellar^{db} for this sowing window. However, in 2009 and 2010 the grain yields of grazed crops were on average 1.9t/ha lower in 2009 and 0.95t/ha lower in 2010 than ungrazed.



Grain yields 2008–10 grazed versus ungrazed

The grazing was performed with sheep in 2008 and 2010, but mechanically mown in 2009.



Under what plant populations was grazing maximised?

Dry matter measurements at GS30 indicated that, over the three years of the project, there was between 0.5–3.0t/ha forage available for grazing depending on the plant population of wheat being grazed. Higher plant populations produced higher forage outputs, but showed a greater reduction grain yield in 2009 and 2010. In 2008 with the cultivar Mackellar^{db} frost affected the ungrazed crop leading to a 2t/ha advantage to grazing as well as a 3000kg dry matter yield. In addition, since grazing led to better lodging control this had much greater significance for yield with the weak strawed cultivar Mackellar^{db} than it did with SQP Revenue^{db} in 2009 and 2010.

Influence of grazing on dry matter production (kg/ha), grain yield (t/ha) and economics (\$/ha) – Midlands, Tasmania 2008–10.

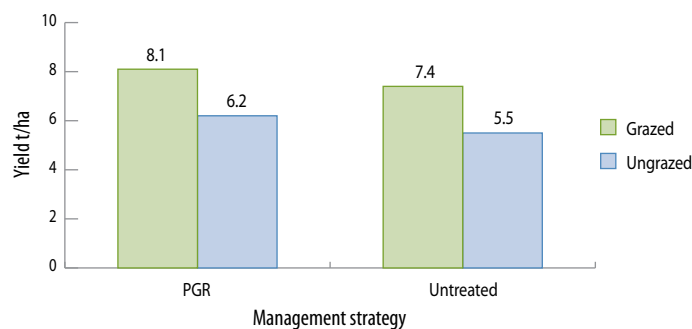
Effect of Grazing Plant Population (Plants/m ²)	2008	2009			2010		
	200	100	200	300	100	200	300
Dry Matter (DM) kg/ha GS30	3000	460	1660	2000	1640	1770	1880
Value (\$/ha)							
at \$0.15/kg DM	450	69	249	300	246	265.5	282
at \$0.2/kg DM	600	92	332	400	328	354	376
at \$0.25/kg DM	750	115	415	500	410	442.5	470
Grain Yield t/ha (loss)	+ 1.89*	0.21	2.1	2.43	0.33	1.39	1.08
Value (\$/ha)							
at \$200/t	378	42	420	486	66	278	216
at \$250/t	473	53	525	608	83	348	270
at \$300/t	567	63	630	729	99	417	324
at \$350/t	662	74	735	851	116	487	378

* + 1.89: Grazing increased yield in 2008.

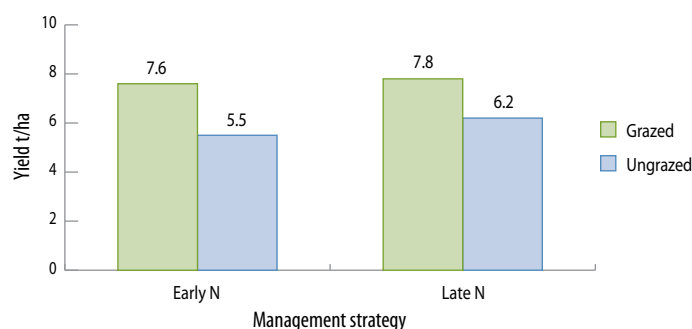
What agronomy strategies secured the maximum yield potential from the ungrazed crop?

The project evaluated three key components of canopy management in order to secure the yield potential of early sown irrigated wheat in a long season environment. Optimum plant population for the ungrazed crop over the three years was 200 plants/m². This population combined with later applied nitrogen (50:50 split between second node and flag leaf) reduced crop height and resultant lodging. However, this was not as effective for lodging control as combining later nitrogen with a sequence of plant growth regulators applied at pseudo stem erect (GS30) and second node (GS32), particularly in 2008. This result was achieved by reducing the crop canopy dry matter as well as height, all of which improved lodging control. This effect was particularly apparent with Mackellar^{db} in 2008 which lodged more severely than SQP Revenue^{db} in 2009 and 2010 (though SQP Revenue^{db} lodged late in 2010). In 2009 and 2010 the same trends in lodging response to treatments were apparent but at lower levels of lodging overall (combined with later lodging). In these two seasons 200 plants/m² combined with later N application and or PGR resulted in no significant yield advantages. Therefore adopting the correct plant population and cultivar was more important than either N timing or PGR application in terms of maximising yield production from early sown irrigated wheat in a long season environment.

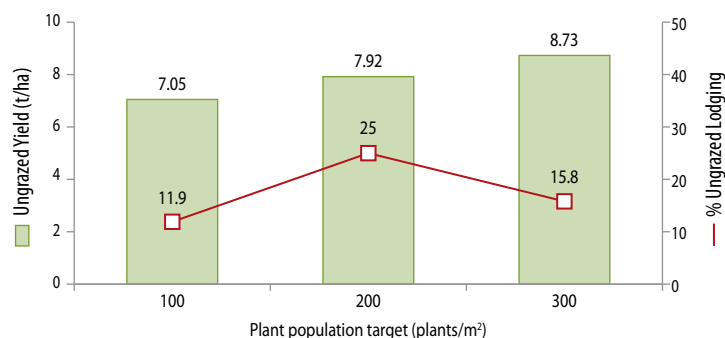
However, if the cultivar chosen was subject to greater lodging risk then lower plant population, followed by plant growth regulator application and later nitrogen timing were options which each individually, reduced lodging as well as combining to give even greater lodging prevention. In 2008 when lodging with Mackellar^{db} was severe, yield was maximised in an ungrazed crop by adopting later N timing and PGR application. Since there was also lodging in the grazed crop PGR application gave a benefit, although PGR's never gave a yield benefit in grazed crops of SQP Revenue^{db}, since they did not lodge.



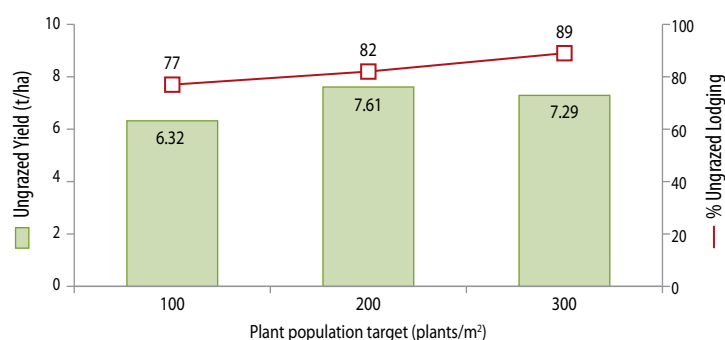
Influence of plant growth regulator sequence (Moddus® 0.1 l/ha + Cycocel® 1.25L/ha applied twice at GS30 and 32).



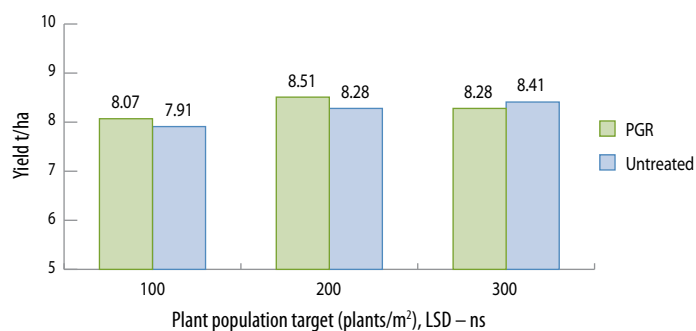
Nitrogen timing on yield in the weak strawed cultivar Mackellar^{db} 2008.



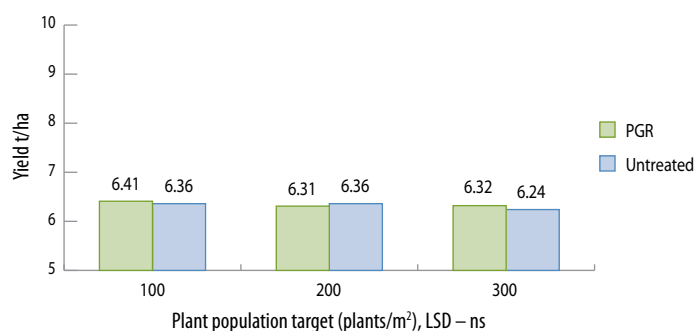
Influence of plant population on lodging and yield t/ha in the ungrazed crop (cv SQP Revenue^{db} in 2009).



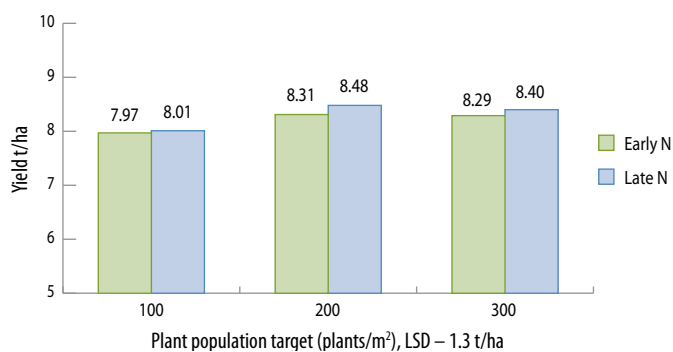
Influence of plant population on lodging and yield t/ha in the ungrazed crop (cv SQP Revenue^{db} in 2010).



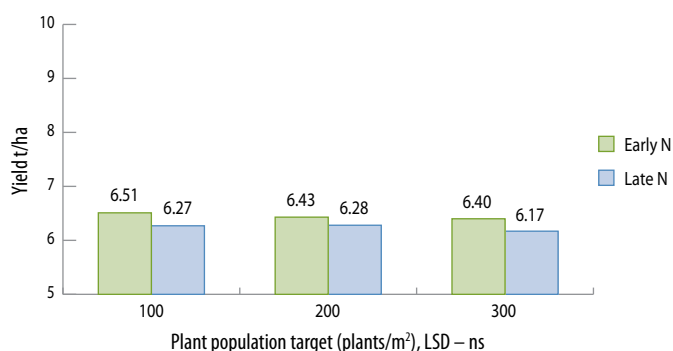
Influence of plant growth regulator sequence (Moddus® 0.1L/ha + Cycocel® 1.25L/ha applied twice at GS30 and 32) on yield in the **ungrazed** crop (cv SQP Revenue[®] in 2009).



Influence of plant growth regulator sequence (Moddus® 0.1L/ha + Cycocel® 1.25L/ha applied twice at GS30 and 32) on yield in the **grazed** crop (cv SQP Revenue[®] in 2009).



Influence of N timing (160kg N/ha – GS30:32 50:50 split compared to GS32:39) on yield in the **ungrazed** crop (cv SQP Revenue[®] 2009).



Influence of N timing (160kg N/ha – GS30:32 50:50 split compared to GS32:39) on yield in the **grazed** crop (cv SQP Revenue[®] 2009).

Thus the order of priority for lodging prevention is:

Cultivar > Grazing > Plant Population
= PGR application > N timing

Management of grazed crops to ensure maximum grain yield?

Following grazing there was no significant yield advantage to PGR application or moving nitrogen timing over the three years of the project. In 2009 using SQP Revenue[®] there was a trend for earlier applied nitrogen to out-yield later timed nitrogen (not significant), as it provided faster dry matter recovery. However, in 2008 and 2010 there was no difference in yield due to N timing. Most of the agronomy factors that influenced yield in the ungrazed crop, improved lodging control. The same factors did not have the same effect in grazed wheat since grazing prevented lodging.

NB: Use of a PGR in this guide does not constitute a recommendation. Always check label recommendations before use.

i) Early sowing (mid-March to mid-April)

- Some evidence that early sowing reduces some of the effects of waterlogging in a wet winter, as a bigger crop canopy uses more water in later autumn and early spring than a more traditional May-sown crop.
- However, this potential benefit comes at the price of increased lodging risk, frost risk and disease pressure.
- Cultivar selection is extremely important for very early sowing in this long-season environment. A stiff straw rating, good disease resistant and slower development are key attributes in order to exploit this sowing window, particularly where ungrazed.

ii) Grazing early sown wheat in the long season environment of Tasmania

- Grazing in the late tillering (GS23–30) phase broadens the range of cultivars that can be used for this early sowing window, since grazing reduces lodging pressure, disease pressure and delays development (for example, flowering).
- Following a wet winter grazing imposes excessive stress on the crop which can lead to large reductions in yield.
- Dry matter production for grazing was optimised with plant populations of 200–300 plants per square metre, with forage production averaging 1500 to 3000 kilograms per hectare of dry matter over the three years of the project, valued at \$225–450/ha at \$0.15/kg dry matter.
- Target plant populations of 100 plants/m² reduced forage dry matter removed during grazing down to 460–1640 kg/ha DM.
- Grazing also reduced tiller numbers particularly at the higher plant populations, where more apical growing points are likely to be removed, since greater competition between tillers leads to more erect growth habit as tillers compete for light.

iii) Effect of plant density on lodging control

- Lower plant populations, 100 plants/m² and lower, produce less dry matter during tillering and as a consequence reduce the competition for light between tillers. Reduction in competition between tillers at early stem elongation reduces the lower internode lengths which strengthens the lower internodes by reducing overall length. This reduces lodging in early sown wheat crops, particularly those that are ungrazed. The effect of plant population is particularly important with weak strawed cultivars (for example Mackellar[®] in project trials). Where lodging can be better controlled with cultivar straw strength (for example SQP Revenue[®]) there was evidence that low plant populations, 100 plants/m² or below, reduced dry matter and grain yield, relative to 200 plants/m². With grazed crops where lodging was effectively controlled by the physical removal of dry matter lower plant populations produced lower forage yields prior to GS30 (the target growth stage for finishing grazing).

iv) Influence of nitrogen timing on crop performance

- Moving nitrogen from a GS30/GS32 split to a GS32/39 split in early sown wheat led to approximately half the level of lodging and greater green leaf retention.
- Where crops are more lodging prone, by virtue of paddock history or cultivar, the delayed N timings reduced tiller number and dry matter, the key factors implicated in lodging risk.
- Where crops have been grazed, earlier N timing has increased tiller recovery and given faster dry matter recovery, but this has not been consistent. In 2008 using the weak strawed cultivar Mackellar[®] grazed crops still lodged, in these cases late N exhibited less lodging.



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Trial site locations for GRDC project SFS00017

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