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TRITICALE

SECTION 10

PLANT GROWTH REGULATORS AND CANOPY MANAGEMENT

PLANT GROWTH REGULATORS | CANOPY MANAGEMENT

Plant growth regulators and canopy management

Key messages

- In Australian cereal production, plant growth regulators (PGRs) are mostly used with the intention of producing a smaller plant that is resistant to lodging, or with the intention of reducing excessive growth in irrigated broadacre crops. They are not registered for use in triticale.
- Canopy management includes a range of tools to help manage crop growth and development with the aim of maintaining canopy size and duration to optimise photosynthetic capacity and grain production.
- Canopy management starts at seeding: sowing date, variety, plant population and row spacing are fundamental. There is more to it than delaying the application of nitrogen (N).
- So far, the best results for canopy management have been seen in early sown, long-season varieties with high yield potential and that are very responsive to N with high N-fertiliser inputs.

MORE INFORMATION

Plant growth regulators

Plant growth regulators in broadacre crops

PGRs and their agronomic and economic benefits to high yield potential cereal, pulse and oilseed crops

10.1 Plant Growth Regulators

A plant growth regulator (PGR) is an organic compound, either natural or synthetic, that modifies or controls one or more physiological processes within a plant. They include many agricultural and horticultural chemicals that influence plant growth and development. PGRs are intended to accelerate or retard the rate of growth or maturation, or otherwise alter the behaviour of plants or their produce. [1] This influence can be positive, e.g. larger fruit or more pasture growth, or negative, e.g. shorter stems or smaller plant canopies.

There are no Plant Growth Regulators registered for use on triticale in Australia.

In Australia, there have been mixed results in the ability of PGRs to promote increased yield and profits.

10.2 Canopy management

Key points:

- Correct identification of the key growth stages for input is essential, particularly during early stem elongation when the most important leaves of the crop canopy emerge.
- Knowledge of the status of soil moisture and soil nitrogen reserves and supply need to be taken into account in order to match canopy size to the environment.
- Crop models can help integrate crop development, environmental conditions and nutrient status in order to make better canopy-management decisions. [2]

10.2.1 What is canopy management?

The concept of canopy management was developed primarily in Europe and New Zealand, where production environments are different, but not dissimilar to the higher rainfall areas of southern NSW, Victoria and Tasmania.

Canopy management involves the use of several tools to manage crop growth and development, with the aim of maintaining canopy size and duration so as to optimise

1 P Lemaux (1999) Plant growth regulators and biotechnology. Presentation. Western Plant Growth Regulator Society, http://ucbiotech.org/resources/biotech/talks/misc/regulat.html

2 GRDC (2009) Canopy management. Factsheet. GRDC, https://grdc.com.au/__data/assets/pdf_file/0014/202523/canopy-management.pdf.pdf

photosynthesis that translates into greater grain production (Photo 1). [3] One of the main tools is the rate and timing of the application of fertiliser N. The main difference between canopy management and previous N topdressing research is that, in canopy management, all or part of the N inputs are tactically delayed until later in the growing season. This tends to reduce early canopy size, but the canopy is maintained for longer, as measured by green leaf retention, during grainfilling. [4]

Photo 1: *An example of the benefits of controlling canopy cover. The crop with the thinner crop canopy (left) yielded 6.18 t/ha and 12% protein, and crop with the thicker canopy (right) yielded 6.20 t/ha and 10.6% protein. Experiment conducted with Kellalac wheat sown 11 June, Gnarwarre in Victoria's high-rainfall zone. The crops received the same amount of nitrogen, but the timing of application differed.*

Source: GRDC

Adopting canopy management principles to avoid excessively vegetative crops may enable growers to ensure a better match of canopy size and yield potential, as defined by the water available.

Canopy management is not only about a delayed N strategy, but starts at seeding by determining the correct plant establishment for the chosen seeding date and row spacing. This must also take into account available soil moisture and nutrients (Figure 1). [5]

Other than sowing date, plant population is the first point at which the grower can influence the size and duration of the crop canopy. One of the main tools for growers to use is the rate and timing of application of fertiliser N.

If the canopy becomes too big, it competes with the growing heads for resources, especially during the critical 30-day period before flowering. This is when the main yield component (grain number per unit area) is set. Increased competition from the canopy with the head may reduce yield by reducing the number of grains that survive for grainfill.

After flowering, temperature and evaporative demand increase rapidly. If there is not enough soil moisture, the canopy dies faster than the grain develops, and results in small grain. Excessive N application and high seeding rates are the main causes of excessive vegetative production. Unfortunately, optimum N and seeding rates are season-dependent. In droughts, N application and seeding rates that would be regarded as inadequate in normal conditions may maximise yield, whereas higher input rates may result in progressively lower yields. In years of above-average rainfall, yield may be compromised by using normal input rates. At the extreme, excessive early growth results in haying-off. In this situation, a large amount of

3 N Poole (2005) Cereal growth stages. GRDC, https://www.researchgate.net/file.PostFileLoader.html?id=5780fa6bf7b67e860b4def31&assetKey=AS%3A381929540079624%401468070506798

4 G McMullen (2009) Canopy management in the northern grains region: the research view. NSW DPI, http://www.nga.org.au/results-and-publications/download/31/australian-grain-articles/general-1/canopy-management-tactical-nitrogen-in-winter-cereals-july-2009-.pdf

5 GRDC (2009) Canopy management. Factsheet. GRDC, https://grdc.com.au/__data/assets/pdf_file/0014/202523/canopy-management.pdf.pdf

biomass is produced using a lot of water and many other resources, and later in the season there is insufficient moisture to keep the canopy photosynthesising and not enough stored water-soluble carbohydrates to fill the grain. Therefore, grain size and yield decrease.

To attain maximum yield, it is important to achieve a balance between biomass and available resources. The main factors that growers can manage are:

- plant population
- row spacing
- inputs of N
- sowing date
- weed, pest and disease control
- plant growth regulation with grazing

Of these, the most important to canopy management are N, row spacing and plant population. [6]

Applying N or fungicide at stem elongation increases the opportunity to match input costs to the potential yield for that season. While seeding applications may still be required for healthy establishment, crop models help support decisions on application timing. Models such as APSIM and Yield Prophet® simulate growth stage and season.

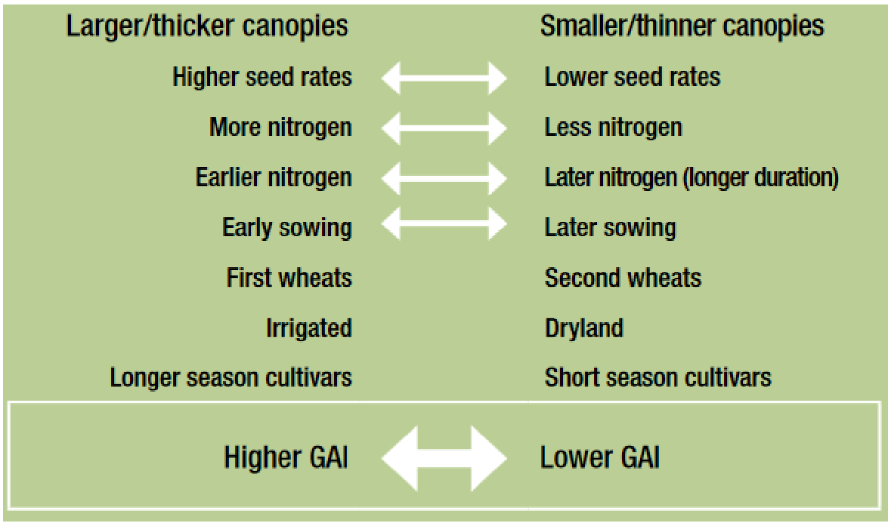

Figure 1: *Factors under the grower's control that influence canopy density, size and duration. GAI = green area index (amount of green surface area).*

Source: GRDC

The timing and rate of N application should also be considered in conjunction with the inter-related factors of:

- soil moisture
- soil nitrogen reserves
- seeding date
- seed rate and variety

To practice canopy management, it is important to understand the principal interactions between the growth stages of plants, available water and nutrients, and disease pressure. They are complex, but tools from simple visual indicators through to crop models can assist.

MORE INFORMATION

Zadoks growth scale

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

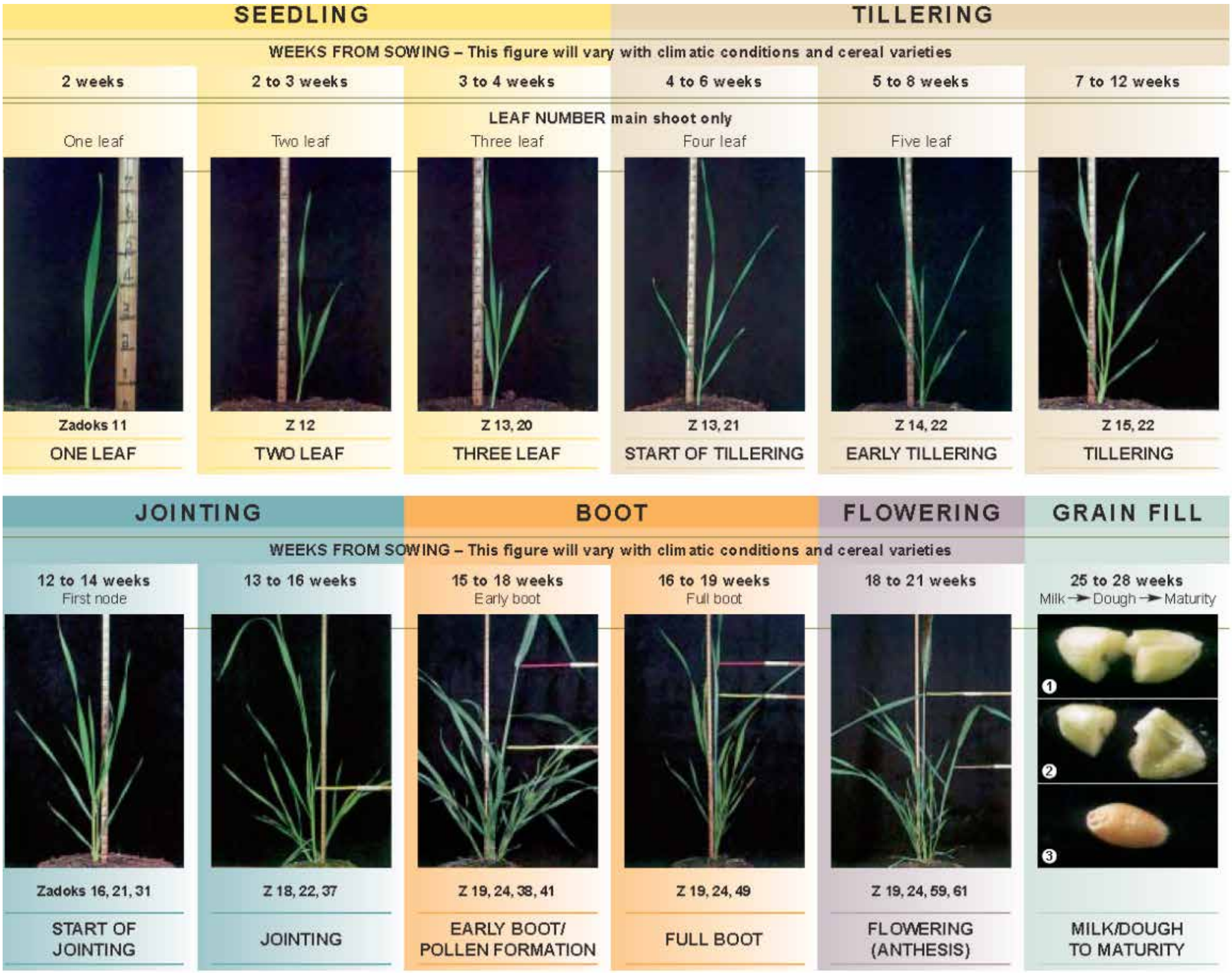

Figure 2: *Zadoks growth scale for cereal growth stages.*

Source: NVTOnline.

IN FOCUS

Canopy management in the Liverpool Plains

From 2006 to 2009 trials were conducted by a collaborative group of NSW DPI, Northern Grower Alliance, AgVance Farming, and Nick Poole from the Foundation for Arable Research in New Zealand. Their work was funded by GRDC. They focused on the interaction on delayed N applications in high-yielding wheat crops on the Liverpool Plains, (note that results for wheat may be similar to those expected in triticale).

To test if canopy management principles did improve crop performance in Northern Region cereal crops, the researchers established trials using overhead irrigation systems to supplement the water supply at the critical growth stages when urea was applied to the soil surface. N was applied in different combinations at three growth stages during each season: to the seedbed (SB), during early stem elongation (GS 31), or after flag-leaf emergence (GS 39). Details of the research sites and treatments are in Tables 1 and 2.

Table 1: *Nitrogen timings.*

Treatment	At sowing (SB)	Stem elongation (GS 31)	Flag-leaf emergence (GS 39)
No N	–	–	–
Single application	100% N––	– 100% N–	––100% N
Split applications	50% N–50% N	50% N 50% N –	– 50% N 50% N

Source: McMullen 2009

Table 2: *Overview of canopy management trials.*

Year	2006	2007	2008
Location	Caroona	Caroona	Spring Ridge
Sowing date	27 June	14 of July	29 May, 3 July
Variety	Ventura	Ventura	EGA Gregory and Ventura
Starting Nitrate-N (0–90 cm)	25 kg N/ha	74 kg N/ha	78 kg N/ha
Previous crop	2005, sorghum	2006, sorghum	2007, sorghum
Total N applied	110 kg N/ha	140 kg N/ha	160 kg N/ha
In-crop rainfall	234 mm (123 mm irrigation)	285 mm (150 mm irrigation)	450 mm (including irrigation)

Source: McMullen 2009

Results

In 2006 and 2007, the response to tactically delaying N until later in the growing season was relatively consistent for main to late-sown, short-season crops (cv. Ventura). In both years, delaying or splitting fertiliser N did not result in significant increases in grain yields compared to applying N to the seedbed. Grain yield was maintained when N was split between SB and GS 31. Delaying all N until after GS 31, or splitting application between GS 31 and GS 39 resulted in lower grain yields but higher grain proteins.

In 2008, the responses when all N was delayed were much the same as in 2006 and 2007, with no advantage in delaying N. However, there was a 12% increase in grain yield when the application of N was split between SB and GS 31. Over the three years, with late June or July sowings there was an average 0.3 t/ha benefit to splitting N between SB and GS 31 over the standard SB treatment (yield neutral in 2006, plus 0.2 t/ha in 2007 and plus 0.7 t/ha in 2008).

The results from the main sowing time in 2008 were encouraging, but one of the key questions after 2006 and 2007 was what the response in early sown, long-season crops would be. In 2008, EGA Gregory was sown on the 29 May to assess these responses. The researchers were surprised by the magnitude of the response. As in previous years, the site was strongly responsive to N; in fact, canopy size as measured by crop dry matter showed a threefold reduction by delaying N until GS 31 (Figure 3). When treatments were delayed to flag-leaf emergence and flowering, the canopies were still significantly smaller than when N was applied to the seedbed. However, by crop maturity all delayed N treatments, except when all N was applied after GS 39, had reached higher peak dry-matter levels compared to the SB-applied N treatment.

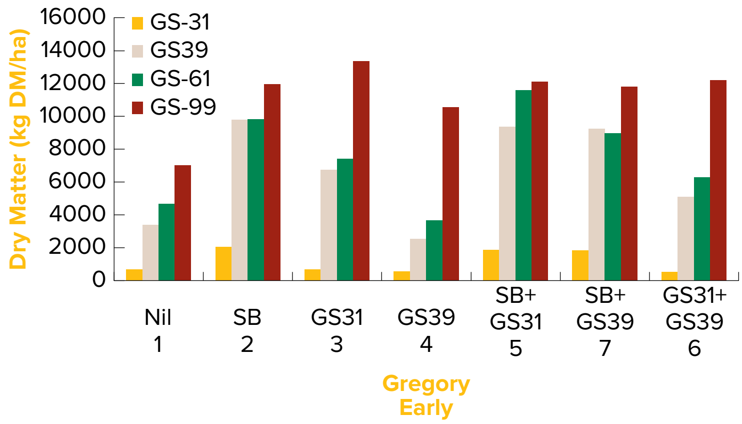

Figure 3: *Effect of delayed N on crop dry matter (kg dry matter/ha) of early sown wheat, cv. EGA Gregory, in 2008.*

Source: McMullen 2009

The large differences in canopy size translated into very strong grain yield and protein responses (Figure 4). For the longer-season EGA Gregory, all delayed N treatments resulted in significantly higher grain yields compared to the SB- applied N.

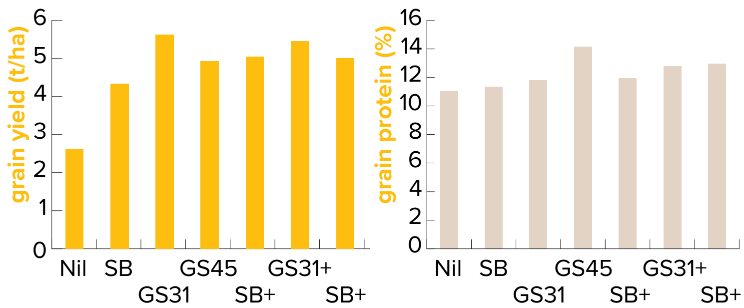

Figure 4: *Effect of delayed N on grain yield and protein of early sown wheat, cv. EGA Gregory, in a trial in 2008.*

Source: McMullen 2009

The highest yield was attained when all N was delayed until GS 31, which gave more than 1 t/ha extra yield, a result that appeared to be linked to the crop canopy staying greener for longer during grainfill. This increase in yield was accompanied by increased grain proteins for all delayed treatments, the greatest of which was when all N was applied after flag-leaf emergence at booting (GS 45). [7]

7 G McMullen (2009) Canopy management in the Northern grains region: the research view. NSW DPI, http://www.nga.org.au/results-and-publications/download/31/australian-grain-articles/general-1/canopy-management-tactical-nitrogen-in-winter-cereals-july-2009-.pdf

10.2.2 Canopy management in a nutshell

1. Adjust canopy management based on paddock nutrition, history, and seeding time to achieve target head density.
2. Lower end of range (80–100 plants/m^2)—suitable for earlier sowings or high fertility and/or low yield potential, low-rainfall environments.
3. Higher end of the range (150–200 plants/m^2)—suitable for later sowings, lower fertility and/or higher-rainfall regions.
4. During stem elongation (GS 30–39), provide the crop with necessary nutrition (particularly N at GS 30–33, pseudo-stem erect–third node), matched to water supply and fungicides to:
5. maximise potential grain size and grain number per head;
6. maximise transpiration efficiency;
7. ensure complete radiation interception from when the flag leaf has emerged (GS 39); and
8. keep the canopy green for as long as possible following anthesis.

The timing of the applied N during the GS 30–33 window can be adjusted to take account of the target head number; earlier applications in the window (GS 30) and can be employed where tiller numbers and soil nitrogen seem deficient for the desired head number. Where tiller numbers are high and crops are still regarded as too thick, N can be delayed further, until the second or third node (GS 32–33), which will result in fewer tillers surviving to produce a head. [8]

10.2.3 Setting up the canopy

Research has shown that extra tillers produced by more plants per unit area are more strongly correlated to yield than are extra shoots stimulated by increased nitrogen at seeding.

Boosting tiller numbers with seeding N results in greater tiller loss between stem elongation and grain fill. This occurs specifically in two situations: in low-rainfall, short-season environments; and when soil moisture is limited. In these situations moisture and nutrient resources are used before the stems lengthen to produce biomass that fails to contribute to grain yield. Indeed, diverting these resources to unsuccessful tillers limits the potential of surviving tillers.

Therefore, identifying the correct population for a particular sowing date, soil-nitrogen reserve and region is the basis for setting up the crop canopy.

10.2.4 Status of soil moisture

Under Australian conditions, soil moisture is the biggest driver of the size and duration of the crop canopy of cereals. Therefore, an understanding of how much water a soil can hold, and how much water a soil is holding at seeding and stem elongation, are central to canopy management. Knowing the soil Plant Available Water Capacity (PAWC) is also important.

The start of stem elongation (GS 30) is the pivotal point for deciding on inputs, as from this point canopy expansion is rapid, and nitrogen and water reserves in the soil can be quickly used up.

If soil moisture is limited at the start of stem elongation, the ability to manipulate the crop canopy with nitrogen is limited. In many cases the best canopy management is not to apply inputs such as nitrogen and fungicides.

Modelling demonstrates that by setting up a smaller crop canopy, growers can reserve limited supplies of moisture stored in the for use at grainfill, rather than have it depleted by excessive early growth. However, in higher-rainfall regions and in a good season, setting up a small canopy may result in yield falling below potential.

8 N Poole, J Hunt (2014) Advancing the management of crop canopies. GRDC, https://grdc.com.au/resources-and-publications/all-publications/publications/2014/01/gc105-canopymanagement

Calculating potential yield and then plotting actual rainfall against decile readings for the region is a way of getting a broad picture of whether there will be sufficient soil moisture to consider additional nitrogen at stem elongation.

The decision-support tool Yield Prophet® (developed in Australia) and the Sirius Wheat Calculator (developed in New Zealand) offer simple tools to record and assess multiple options that cover the relationship between growing plants and the environment, including available water and nutrients.

10.2.5 Soil nitrogen

It is important to have an understanding of soil-N reserves to the depth of the root-zone. Higher soil-nitrogen reserves provide much more flexibility in managing the canopy with nitrogen applied tactically during stem elongation.

It is difficult to use visual appearance unless you have a benchmark; this has led to the concept of the N-rich strip (Photo 2). [9] A useful guide that requires no sophisticated equipment is to apply an excess of nitrogen at sowing, for example 50–100 kg N/ha, to 2 m × 10 m area of the paddock, and use that as a benchmark. [10]

Photo 2: *An N-rich strip gives a large difference in visual appearance that can help the grower set a benchmark for N use: the enriched strip was given 110 kg N/ha at seeding. Here it is viewed at GS 31, when only low soil reserves of N (25 kg N/ha, 0–90 cm) remain. Left: 443 tillers/m^2 in N-rich soil. Right: 266 tillers/m^2).*

Source: GRDC

During winter and spring, by comparing crop vigour (tiller number) and greenness in these small N-rich areas with the rest of the crop, an indication of N supply can be obtained. The advantage of using the plant rather than depending totally on a soil test is that the plant directly registers soil-N supply, whereas the soil test measures the soil-nitrogen reserve, which crop roots may not always be able to access.

This visual difference can be quantified by using crop sensors that measure the light reflectance from the crop canopy. By measuring reflectance at the red and near-infrared wavelengths, it is possible to quantify canopy greenness using a number of vegetative indices, the most common of which is termed the Normalised Difference Vegetative Index (NDVI). This index gives an indication of both biomass present and the greenness of that biomass. Canopy sensing can be done remotely from aircraft or satellites, or with a hand-held or vehicle-mounted sensor.

10.2.6 Seeding rate and date

Achieving the correct plant population is fundamental if sufficient tillers are to be set. Seeding rates need to be adjusted for seed size and planting date; if this does not occur the first step in controlling the canopy is lost. How many plants are targeted depends on:

- region—as a general guide, drier regions sustain lower plant populations than wetter environments; and

9 GRDC (2009) Canopy management. Factsheet. GRDC, https://grdc.com.au/__data/assets/pdf_file/0014/202523/canopy-management.pdf.pdf

10 GRDC (2009) Canopy management. Factsheet. GRDC, https://grdc.com.au/__data/assets/pdf_file/0014/202523/canopy-management.pdf.pdf

- sowing date—earlier sowings require lower plant populations compared to later sowings, as the tillering window is longer and more tillers are produced per plant.

Overall, earlier planting provides greater opportunities to manipulate the crop canopy during the stem elongation period: the plant's development periods are extended along with the earlier tillering period.

10.2.7 Row spacing

Key points:

- Increased interest in no-till farming has created a trend for wider spacing of crop rows (Figure 5). [11]
- In general, increasing row spacing up to 50 cm has minimal effect on cereal yield when yield potential is less than 2 t/ha.
- In higher-rainfall areas, where cereal crops have higher potential yields, significant yield decreases have been recorded with row spacing greater than 25 cm.
- The yields of broadleaf crops vary in their response to wider row spacing.
- Precision agriculture allows for easier inter-row sowing and fertiliser applications at wider row spacing. [12]

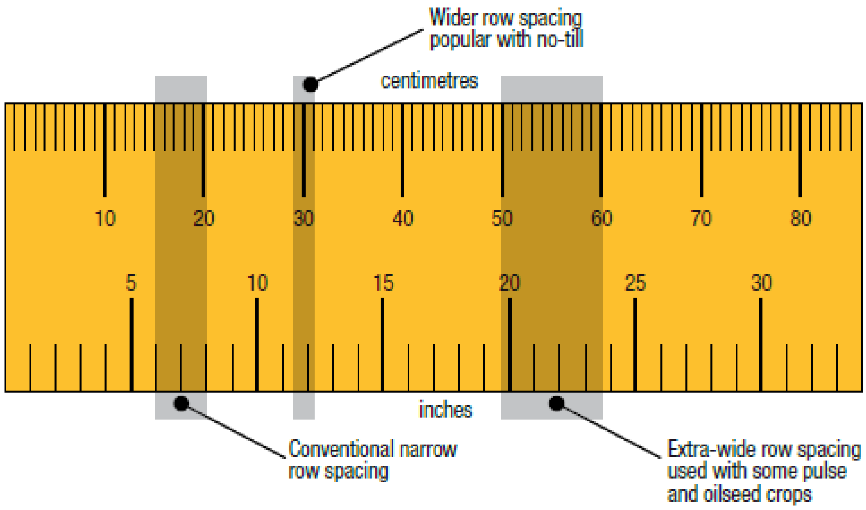

Figure 5: *Common row spaces in metric and imperial measurements.*

Source: GRDC

Yield

There are a number of reasons why growers might wish to pursue wider row spacing in cereals, e.g. residue flow, and disease control. However, in canopy-management trials conducted from 2007–2010 on wheat grown in a wide range of rainfall scenarios, increasing row width reduced yield.

- The yield reduction in wheat was particularly significant when rows were wider than 30 cm.
- Crop row spacing is an important factor for weed competition (Photo 3). [13]
- At row widths of 30 cm, the reduction in wheat yield compared to narrower 20–22.5 cm row spacing depended on overall yield potential:
- At yields of 2–3 t/ha yield reduction was negligible.

11 GRDC (2011) Crop placement and row spacing, Southern. Factsheet. GRDC, https://grdc.com.au/Resources/Factsheets/2011/02/Crop-Placement-and-Row-Spacing-Southern-Fact-Sheet

12 GRDC (2011) Crop placement and row spacing, Southern. Factsheet. GRDC, https://grdc.com.au/__data/assets/pdf_file/0015/210264/crop-placement-and-row-spacing-southern-fact-sheet.pdf.pdf

13 WeedSmart (2015) Narrow row spacing: is it worth going back? WeedSmart, http://weedsmart.org.au/narrow-row-spacing/

- At yields of 5 t/ha yield reduction was 5–7%, and averaged about 6%.
- Data from a single site suggested that wheat's position in the rotation may influence its yield response in wider row spacing. In wheat-on-wheat plantings, there was less yield reduction with wider rows than in an equivalent trial at the same site which was in wheat after canola. [14]

Photo 3: *Narrow row spacing (left) and wide row spacing (right). The higher the yield potential, the greater the negative impact of wider rows on crop yields.*

Source: WeedSmart

Plant spacing

- Increasing row width decreases the plant-to-plant spacing within the row, leading to more competition within the row and lower 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.
- Limited data indicates that increasing seeding rates so that the average plant-to-plant spacing in the row drops below 2.5 cm are either negative or neutral in terms of grain yield.
- Planting seed in a band (as opposed to a row) will increase plant-to-plant spacing, but may also increase weed germination and moisture loss because there is greater soil disturbance. [15]

Dry matter

- Rows of 30 cm and more reduced harvest dry matter relative to rows of 22.5 cm and under, with differences growing steadily (in kilograms per hectare) from crop emergence to harvest, by which time differences were in the order of 1–3 t/ha depending on row width and growing-season rainfall.
- The reduction in dry matter in wide rows was also significant at flowering (GS 60–69), frequently 1 t/ha reduction when row spacing increased 10 cm or more over a 20 cm base. This could be important when considering harvesting for hay rather than grain. [16]

Grain quality

- The most noticeable effect of row width on grain quality was on protein: wider rows reduced yield and increased grain protein, but the net nitrogen taken off the paddock is about the same.

14 N Poole, J Hunt (2014) Advancing the management of crop canopies. GRDC, https://grdc.com.au/resources-and-publications/all-publications/publications/2014/01/gc105-canopymanagement

15 N Poole, J Hunt (2014) Advancing the management of crop canopies. GRDC, https://grdc.com.au/resources-and-publications/all-publications/publications/2014/01/gc105-canopymanagement

16 N Poole, J Hunt (2014) Advancing the management of crop canopies. GRDC, https://grdc.com.au/resources-and-publications/all-publications/publications/2014/01/gc105-canopymanagement

- 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. [17]

Nitrogen management

The way nitrogen is managed has not been found to interact with row spacing, so optimum N regimes for narrow rows (22.5 cm or less) can be the same as for wider rows (30 cm or more). The greater nitrogen efficiency observed with N applied at stem elongation was more important with narrow row spacing, since higher yields lead to a tendency for lower protein. [18]

10.2.8 In-crop nitrogen

Delaying N inputs from seeding until stem elongation (GS 30–31) means they can be better matched to the season. So, in a dry spring, no application may be warranted. In spring, with adequate rainfall to justify N application, project trials have shown stem-elongation N to give yields equal to or better than wheat crops grown with seeding N, providing there is some level of N in the soil at sowing. However, applying N in advance of a rain front to ensure good incorporation has been found to be more important than applying it at an exact growth stage. While GS 31 should be the target growth stage for in-crop N application, the window can be expanded from GS 25 to GS 31 in order to take advantage of rainfall. Even applications delayed until flag leaf can be successful where starting soil nitrogen is not too low (Figure 6). [19]

Figure 6 presents the results from winter wheat-cropping trials across Australia on trials on the use of in-crop solid nitrogen at stem elongation. The trials showed that, where soil-nitrogen reserves are low, N applied at stem elongation is not always the most appropriate strategy if yield is to be optimised. Stem-elongation N applications were found to be less appropriate with shorter-season varieties and late-sown crops. Drought conditions during the trial period (2006 to 2008) limited the results from these trials. They assessed N use at stem elongation in cereals grown on wider row spacings (30–35 cm, compared to 17.5–20 cm. However, at the same seeding rate, moving to wider rows was found to reduce the number of tillers per unit area and final ear population and yield, the latter by approximately 6% in the high-rainfall zone (HRZ). [20]

17 N Poole, J Hunt (2014) Advancing the management of crop canopies. GRDC, https://grdc.com.au/resources-and-publications/all-publications/publications/2014/01/gc105-canopymanagement

18 N Poole, J Hunt (2014) Advancing the management of crop canopies. GRDC, https://grdc.com.au/resources-and-publications/all-publications/publications/2014/01/gc105-canopymanagement

19 GRDC (2009) Canopy management. Factsheet. GRDC, https://grdc.com.au/__data/assets/pdf_file/0014/202523/canopy-management.pdf.pdf

20 GRDC (2009) Canopy management. Factsheet. GRDC, https://grdc.com.au/__data/assets/pdf_file/0014/202523/canopy-management.pdf.pdf

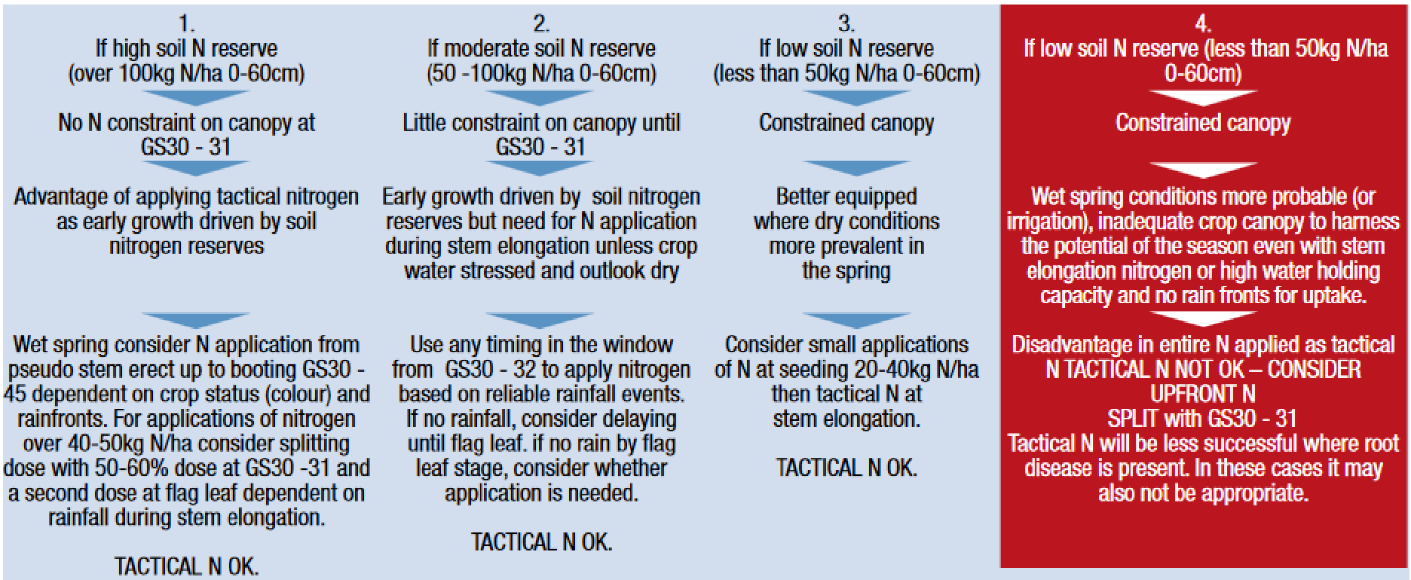

Figure 6: *Broad scenarios for N application, based on soil-nitrogen levels.*

Source: GRDC

MORE INFORMATION

Canopy management factsheet

Cereal growth stages

Advancing the management of crop canopies

Canopy management in the northern grains region: the research view

Limitations of tactical nitrogen application

The main limitation to tactical N application is the ability to reliably apply N before a rain event, when it would be applied to enable roots to access soluble N in the root-zone. Predicted rain fronts may pass without yielding anything; therefore, dependably applying N throughout the season is risky.

Foliar N application is gaining popularity; however, this is only suitable for relatively low rates of N addition. Where higher N input is required, an efficient system to apply N into the wet soil profile; i.e. after rain, needs to be devised.

As technologies such as NDVI imaging and paddock management in zones become prevalent, the addition of N later in the crop cycle will also become more prevalent and will force the development of equipment to make the system work.

By combining knowledge gained from trials and from paddock experience, the aim of improving the economic outcome of the season by manipulating the most costly input is taking shape. Adoption of these techniques would be further aided by the development of efficient, in-soil N-application equipment.