**Crop Competition management options for herbicide-resistant weeds (DAQ00197)**

**Literature review, meta-analysis, gap analysis and trial design recommendations**

**Project team**

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# 1. EXECUTIVE SUMMARY

Adoption of selective in-crop herbicides, conservation agriculture (CA) and hence knockdown fallow herbicides has led to widespread development of herbicide resistance (HR) in Australia’s cropping systems. HR is now the major constraint to sustainable cropping systems, leading to significant profit loss via increased weed management costs on farm.

Crop competition is widely accepted as an important tactic for suppressing weed growth and maintaining crop yield. Agronomic choices influence crop competition, including crop species and cultivar, row spacing, crop density and row orientation. All these cultural control tactics have been shown to impact on the control of in-crop weeds.

This report covers the three key grain growing regions of Australia, namely western, southern and northern. The western region covers from north of Northampton through to Albany in the south to Esperance in the east, within the annual rainfall isohyets of about 300-600mm. The area has a Mediterranean climate with most rainfall in winter, where crops are grown under rain fed conditions. The southern region runs from central New South Wales in the north, Victoria and Tasmania, and to the western edge of cropping in South Australia. The region has a winter-dominant rainfall pattern and is predominantly mixed cropping (mainly winter rain fed but with some irrigation of summer crops) and livestock. The northern region runs from Dubbo and the Liverpool Plains areas in the south (southern-central New South Wales) to Clermont in the north (northern Central Highlands of Queensland) and is comprised of irrigated and broad-acre dryland grain production areas.

Common weeds cross the regions are annual ryegrass, wild radish, wild oat and fleabane. In the western and southern regions, other key weed species include brome grass and barley grass. In the northern region other key species include feathertop Rhodes grass, common sowthistle and awnless barnyard grass. The incidence of HR is increasing across all the regions.

This scoping study, was conducted by weed experts from each of the three regions, and it involved a comprehensive review of literature, a meta-analysis of available data and a knowledge gap analysis of needs for future research, development and extension (RD&E).

This report presents:

* Priority weed species (**Page 2**),
  + Common weeds across the regions are annual ryegrass, wild radish, wild oat and fleabane, while:
  + Windmill grass and feathertop Rhodes grass are emerging problems.
  + Weeds specific to regions include brome grass and prickly lettuce for the western and southern regions, and sweet summer grass for the northern region.
* A literature review for each region (**Page 3**),
  + More research has been done in the western and southern regions compared with the northern, due to the earlier onset of herbicide resistance in annual ryegrass and wild radish.
  + Most of the research has been done on wheat.
  + Most of the research has been done on the crop competition factors of density, row spacing and cultivar.
  + Mimic or sown weeds were commonly used to establish uniform stands (e.g. oats, millet, canola).
* A meta-analysis of pooled data (**Page 51**),
  + An increase in crop density commonly resulted in a decrease in weed growth. This was consistent across crops and regions and for different weed species.
  + Cultivars can differ in their competitive ability across crop species with more competitive cultivars resulting in a decrease in weed growth measures. However, not all studies show a difference between cultivars and the effects of different cultivars can be inconsistent as affected by season. There appears to be little difference between lupin cultivars.
  + A row orientation of east-west, as opposed to north-south, generally results in a reduction in weed growth measures, especially in the western region. However, results are inconsistent, with one southern region study having the opposite result.
  + A decrease in row spacing generally resulted in a decrease in weed growth measures. This effect was consistent across crop species and regions. However, in several studies, wider row crops resulted in a reduction in weed growth due to interaction with in-crop control such as herbicide application.
  + Skip rows research has only been conducted in the northern region. Generally, solid planting reduces weed growth measures compared with skip rows.
  + An early sowing time generally reduced weed growth. However, there has been little research on this crop competition factor.
* A knowledge gap analysis (**Page 60**),
  + For the western region, research is needed on:
    - Canola across all crop competition factors;
    - Field pea for cultivar and crop density; and,
    - Chickpea for cultivar, crop density and row spacing.
  + For the southern region, research is needed on:
    - Lupin, faba bean, chickpea for cultivar, crop density and row spacing; and,
    - Canola for row spacing.
  + For the northern region, research is needed on:
    - Chickpea, faba bean, mungbean and maize for cultivar, crop density and row spacing; and,
    - Wheat and barley for cultivars.
* Identified future RD&E needs (**Page 67**),
  + National RD&E Needs
    - Breeding for and evaluation of competitive ability of the most important crops is required. Also, understanding of the traits and genetics that influence competitive ability (e.g. allelopathy, early vigour). Cultivars in National Variety Trials should be rated on early ground cover. This could be by using green seeker technology. Assessment will be needed across seasons to provide reliable averages.
    - Can gains be made in the competitive ability of weakly competitive crops (e.g. pulses)? Such crops represent a weak phase in the crop rotation (in terms of crop competition) and therefore gains should be pursued. Need to encourage farmers and breeders to grow more competitive varieties.
    - Varietal differences – although quite a bit of research has been done, there are new varieties being released periodically and therefore this type of research should continue as a routine process, maybe as part of the National Variety Trials.
    - Fertiliser rates and more efficient fertiliser placement (horizontally and vertically) to favour the crop over the weed, measuring impact of crop competitiveness ability on weed control. This type of work has generally been done in weed-free environments only. There is scope to do more work here to give advantage to crops over weeds.
    - There are insufficient data across all regions on key weed species. For example in the west, most research is on annual ryegrass and wild radish. Table 1 (Page 2) has identified other key weeds for which little data exists. This is a major issue across all regions.
    - The effect of the timing of weed emergence on the efficacy of crop competition.
    - Do specific crop rotations seem to out compete weeds compared to others? Using existing or new long-term experimental sites to evaluate change in weed populations.
    - Farmers need more guidance and demonstration/extension as to how to use crop competition and how to best fit it in the farming system. How to integrate into an IWM system.
    - If crop and cultivar competitiveness information is available it should be in crop production agronomy guides.
  + Western Region RD&E Needs
    - Row spacing and density – need work on canola, grain legumes (lupin, chickpea and field pea).
  + Southern Region RD&E Needs
    - Row spacing and density – need work on grain legumes (lupin, chickpea and field pea)
    - Legumes – weakness in the rotation in terms of crop competition – need to look at breeding for competitive ability.
    - Row spacing and crop density in pulses is less of a crop competition question and more a question of disease management.
    - Need work on barley and oats.
    - Row orientation - weed competition aspect.
  + Northern Region RD&E Needs
    - Lack of information on row spacing and crop density for key weeds in key crops.
    - Sorghum vs maize competitiveness for key weed species.
    - Mungbeans – row spacing and density work.
    - Chickpeas – what gains can be made?
* A protocol for future improved R&D for crop competition (**Page 69**)

The future RD&E requirements identified are needed in order to increase grower adoption of crop competition by 20% by 2020.

Our recommendations in order to reach this target are:

1. Focus on the key weed species is important to develop the priority order to fill knowledge gaps.
2. Future crop competition research requires national funding, coordination and communication for:

* National breeding for competitive ability traits
* Regional packages for agronomy
* Research consistency to improve the quality of research outputs

We recommend that GRDC supports *A National Crop Competition Program* to improve communication, coordination and quality of RD&E on crop competition for the Grains industry of Australia.

1. We recommend a monograph (scientific refereed literature review) of this report be produced in conjunction with a short (4-8 page) extension document, to promote nationally, crop competition as a weed management tactic.

4. Specific Research Needs: While the principles underpinning agronomy of crop competition are well-understood, basic research on traits for breeding is needed. In addition, strategic and applied research on crops by competition factors at the regional level.

This scoping study provides a frame work for GRDC future investment in RD&E to optimise communication, collaboration and coordination of investments across Australia.

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# 4. INTRODUCTION

The aim of this project is to build the capacity of farmers and advisors (provide knowledge and create understanding) to effectively integrate/utilise crop competition as a tactic for improved weed management. By 2020 it is planned that there will be a 20% increase in growers effectively using cultural weed management (crop competition) as a tactic to reduce current economic losses and to minimise control costs.

A team of weed scientists from the western, southern and northern GRDC regions was sponsored by GRDC to:

* Identify priority weed species.
* Conduct a comprehensive review of literature on crop competition as a cultural weed management tactic.
* Conduct a meta-analysis of pooled data from the literature to identify common trends.
* Conduct a knowledge gap analysis based on the literature review and meta-analysis.
* Identify future RD&E needs.
* Define an approach for future experimentation.
* Provide recommendations.

The project team met on two occasions; 10th February (Toowoomba) and 8th May 2015 (Sydney).

Across all Australian grain growing regions, herbicides have been heavily relied upon for in-crop weed management. This reliance has resulted in widespread herbicide resistance in a range of common in-crop weed species. Herbicide resistance is a major limiting factor in the effective management of in-crop weeds. As herbicide-resistant individuals survive herbicide treatments, other non-herbicide weed management tactics are required, including crop competition.

Competitive crops have been shown to have a positive impact on in-crop weed suppression and maintaining crop yield. There are several agronomic practices that can influence the competitiveness of a crop. These include crop species and cultivar, row spacing, density, seeding methods and row orientation. Furthermore, the competitive ability of a crop can be influenced by fertiliser placement, depth and time of sowing, effective control of insects and diseases, and a complex interaction of weather and soil conditions.

Crop competition has commonly been used in Australia to increase the yield and thereby profitability of crops prior to the advent of selective herbicides and in organic crops. However, with the spread of herbicide resistance, there has been a renewed interest in competitive crops for weed management. It is important to provide farmers with effective and reliable crop competition options for significant adoption of the tactic as part of integrated strategies.

There has been some research during the last 20 years on crop competition across all Australian grain growing regions, and published in refereed scientific journals, while some more recent research has been reported only in GRDC Crop Updates. There is a need to review all available literature to identify current knowledge and required future RD&E needs.

# 5. PRIORITY WEED SPECIES

The project team identified the most important key weed species for each region and prioritised these based on current and future threats of herbicide resistance (Table 1).

## 5.1 Key findings

Common weeds across the regions are annual ryegrass, wild radish, wild oat and fleabane, while:

* Windmill grass and feathertop Rhodes grass are emerging problems.
* Weeds specific to regions include brome grass and prickly lettuce for the western and southern regions, and sweet summer grass for the northern region.
* There is a more limited range of species in the western region reflecting the simpler rotations and limited ecological zones compared with the southern and northern regions.
* Identifying the key weed species is important to develop the priority order to fill RD&E gaps.

Table . Key weeds for each region based on low or high priority. Species underlined are considered to be highest priority in relation to herbicide resistance.

|  |  |  |
| --- | --- | --- |
|  | **Highest priority** | **Lower priority** |
| **Western** | Wild radish, annual ryegrass, barley grass, brome grass | Wild oats, spiny emex, cape weed, wireweed, fleabane, Indian hedge mustard, silver grass, prickly lettuce, common sowthistle, button grass, tar vine, feathertop Rhodes grass, African love grass, windmill grass |
| **Southern** | Annual ryegrass, barley grass, brome grass, wild oats, wild radish, fleabane, Indian hedge mustard, cape weed, silver grass, common sowthistle, turnip weed | Fumitory, wireweed, bedstraw, bifora, vetch, prickly lettuce, feathertop Rhodes grass, windmill grass, |
| **Northern** | Annual ryegrass , wild oat, common sowthistle, fleabane, awnless barnyard grass, sweet summer grass, feathertop Rhodes grass | Black bindweed, Brassica ssp., windmill grass, liverseed grass |

# 6. **LITERATURE REVIEW**

## 6.1 **Summary of references**

A comprehensive review was undertaken of reported research on crop competition across the wheat belt of Australia from the early 1980’s to now for each region. The list of references shown in Table 2 provides the weed species, crop species and crop competition factor examined in each study. The table shows if the data from the reference was used in our meta-analysis and identifies a reference ID for each reference. This reference ID is used in summary tables throughout the literature review and in the meta-analysis. Some key points from this summary of references are:

* More work was done in the western and southern regions compared with the northern, due to the earlier onset of herbicide resistance in annual ryegrass and wild radish.
* Most of the research has been done on wheat.
* Most of the research has been done on crop competition factors of density, row spacing and cultivar.
* Mimic or sown weeds were commonly used to establish uniform stands (e.g. oats, millet, canola).
* Out of a total of 88 references, only 46 were used in the meta-analysis because these papers had data in a form that was easily accessible.
* Some experiments were confounded by crop rotation and other weed management practices, including herbicide application, therefore making it difficult to extract main crop competition effects.

Table . List of references and coinciding reference identification (ID).

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **WESTERN REGION** | | | | | |
| **Reference ID** | **Reference** | **Weed Species** | **Crop Species** | **Crop Competition Factor(s)** | **Used in meta-analysis** |
| 1 | Borger *et al* (2014) | Ryegrass | Wheat, barley | Row orientation, Seeding rate | ✔ |
| 2 | Borger *et al* (2010) | Ryegrass, wild radish | Barley, canola, field pea, lupin, wheat | Row orientation | ✔ |
| 3 | Cousens & Mokhtari (1997) | Ryegrass | Wheat | Cultivar |  |
| 4 | French & Maiolo (2007a) | Wild radish | Lupin | Row spacing, Seeding rate | ✔ |
| 5 | French & Maiolo (2007b) | Ryegrass | Lupin | Planting date, Crop cultivar | ✔ |
| 6 | Hashem & Reithmuller (2006) | Ryegrass | Wheat | Row spacing, Seeding rate |  |
| 7 | Hashem & Borger (2010) | Ryegrass | Wheat, barley, canola | Crop species, Cultivar |  |
| 8 | Hashem & Douglas (2005) | Ryegrass, brome grass, silver grass, Guildford | Wheat | Cultivar |  |
| 9 | Hashem & Wilkins (2002) | Wild radish | Lupin, wheat | Rotation |  |
| 10 | Hashem *et al* (2006a) | Wild radish | Lupin | Cultivar |  |
| 11 | Hashem *et al* (2006b) | Ryegrass, wild radish, brome grass, Guildford | Wheat | Seeding rate, Cultivar |  |
| 12 | Hashem *et al* (2015) | Ryegrass | Wheat, lupin, canola | Row spacing |  |
| 13 | Hashem *et al* (2002) | Ryegrass | Wheat | Row spacing, Seeding rate | ✔ |
| 14 | Hashem *et al* (2004) | Wild radish | Lupin | Cultivar |  |
| 15 | Hashem *et al* (2013) | Ryegrass | Wheat, lupin, chickpea | Row spacing |  |
| 16 | Izquierdo *et al* (2003) | Ryegrass | Barley | Crop density |  |
| 17 | Minkey (2002) | Ryegrass, wild radish | Wheat, Barley, Canola | Row spacing, Seeding rate | ✔ |
| 18 | Minkey & Ashworth (2012) | Ryegrass | Wheat | Sowing time |  |
| 19 | Minkey *et al* (2000) | Ryegrass | Wheat | Row spacing, Seeding rate | ✔ |
| 20 | Minkey *et al* (1999) | Ryegrass | Wheat | Row spacing, Seeding rate | ✔ |
| 21 | Newman (2014) | Ryegrass | Wheat | Row spacing, Seeding rate |  |
| 22 | Newman & Hashem (2012) | Ryegrass | Barley, cereals | Cultivar | ✔ |
| 23 | Newman & Weeks (2000) | Brome grass, ryegrass | Wheat | Row spacing, Seeding rate | ✔ |
| 24 | Newman & Zaicou-Kunesch (2013) | Ryegrass, wild radish | Wheat | Seeding rate | ✔ |
| 25 | Pathan *et al* (2005a) | Ryegrass, wild radish | Barley, canola, field pea, lupin, wheat | Row orientation | ✔ |
| 26 | Pathan *et al* (2005b) | Wild radish | Lupin | Cultivar | ✔ |
| 27 | Pathan *et al* (2006a) | Ryegrass, wild radish | Barley, wheat | Row orientation | ✔ |
| 28 | Pathan *et al* (2006b) | Wild radish | Lupin | Sowing time, Cultivar |  |
| 29 | Paynter & Hills (2009) | Ryegrass | Barley | Crop density, Planting date | ✔ |
| 30 | Paynter (2010) | Ryegrass | Barley | Row spacing | ✔ |
| 31 | Peltzer (1999) | Ryegrass | Barley, oats, triticale, wheat | Seeding rate, Row spacing | ✔ |
| 32 | Riethmuller (2005) | Ryegrass | Wheat | Row spacing, Stubble | ✔ |
| 33 | Riethmuller (2010) | Ryegrass | Canola | Row spacing, Stubble | ✔ |
| 34 | Zaicou & Gill (1993) | Brome grass | Wheat, barley | Seeding rate, Crop species |  |
| **SOUTHERN REGION** | | | | | |
| **Reference ID** | **Reference** | **Weed Species** | **Crop(s)** | **Crop Competition Factor(s)** | **Used in meta-analysis** |
| 1 | Anon (2005) | Grass weeds | Barley, wheat | Row spacing | ✔ |
| 2 | Auld *et al* (1983) | Ryegrass | Wheat | Crop density |  |
| 3 | Bennet (2006) | Ryegrass | Wheat | Cultivar | ✔ |
| 4 | Bennet (2009) | Ryegrass | Wheat | Crop density, Cultivar |  |
| 5 | Burke (2009) | Brome grass | Barley | Cultivar, Row spacing | ✔ |
| 6 | Burnett *et al* (2006) | Ryegrass | Wheat, oats | Crop species |  |
| 7 | Cook & Shepperd (2009) | - | Barley, wheat | Row spacing, Row orientation |  |
| 8 | Cook *et al* (2014) | Barley grass, wild turnip | Wheat | Row orientation | ✔ |
| 9 | Egarr *et al* (2014) | Triticale (as mimic) | Wheat | Cultivar | ✔ |
| 10 | Eslami *et al* (2006) | Wild radish | Wheat | Crop density | ✔ |
| 11 | Ferrier (2014) | Brome grass | Wheat | Rotation |  |
| 12 | Gabb (2011) | Ryegrass | Wheat | HWSC |  |
| 13 | Hunt (2015) | Ryegrass | Canola, wheat, barley | Crop species, Crop density |  |
| 14 | Hunt *et al* (2013) | Volunteer cereals, common heliotrope | Canola, wheat, barley | Rotation |  |
| 15 | Jess *et al* (2008) | Ryegrass | Wheat, barley | Rotation |  |
| 16 | Kleemann & Gill (2007) | Ryegrass | Faba bean | Wide rows |  |
| 17 | Lemerle *et al* (2001) | Ryegrass or wheat (as mimic) | Canola | Cultivar |  |
| 18 | Lemerle *et al* (2014) | Ryegrass or wheat (as mimic) | Canola | Cultivar | ✔ |
| 19 | Lemerle *et al* (2006) | Ryegrass | Wheat | Cultivar |  |
| 20 | Lemerle *et al* (2004) | Ryegrass | Wheat | Cultivar, Sowing rate | ✔ |
| 21 | Lemerle *et al* (2013) | Ryegrass | Wheat | Row spacing, Crop density |  |
| 22 | Lemerle *et al* (1995) | Ryegrass | Wheat, barley, triticale, oats, canola, lupin, cereal rye & field pea | Cultivar, Crop species |  |
| 23 | Lemerle *et al* (2006) | Ryegrass | Field pea | Row spacing, Sowing rate |  |
| 24 | McDonald (2002) | Ryegrass or wheat (as mimic) | Field pea | Cultivar | ✔ |
| 25 | McDonald *et al* (2007) | Canola (as mimic) | Lupin | Cultivar | ✔ |
| 26 | Medd *et al* (1985) | Ryegrass | Wheat | Crop density, Plant arrangement |  |
| 27 | Moodie *et al* (2014) | Brome grass | Various | Rotation |  |
| 28 | Paridaen (2014) | Ryegrass, Wild radish | Canola, pasture | Sowing rate |  |
| 29 | Porker & Wheeler (2014) | Oats (as mimic) | Barley | Cultivar | ✔ |
| 30 | Rebetzke *et al* (2007) | - | Wheat | Sowing time |  |
| 31 | Swan *et al* (2015) | Ryegrass | Various | Rotation |  |
| 32 | Taylor & Craig (2012) | Brome grass | Barley, wheat | Crop species | ✔ |
| 33 | Weston *et al* (2015) | Fleabane, witchgrass | Barley, canola, cereal rye, oats, triticale, wheat | Crop species | ✔ |
| 34 | Zerner & Gill (2010) | Ryegrass, mustard or oats (as mimic) | Wheat | Cultivar | ✔ |
| 35 | Lemerle *et al* (2015) | Ryegrass | Canola | Crop density |  |
| **NORTHERN REGION** | | | | | |
| **Reference ID** | **Reference** | **Weed Species** | **Crop(s)** | **Crop Competition Factor(s)** | **Used in meta-analysis** |
| 1 | Brill *et al* (2012) | Fleabane | Wheat | Row spacing, Crop density |  |
| 2 | Brooke & Cook (2012) | Canola or oat (as mimic) | Barley, wheat | Cultivar, Crop density | ✔ |
| 3 | Felton (1976) | Barnyard grass, pigweed, thornapple | Wheat | Row spacing | ✔ |
| 4 | Felton *et al* (2004) | Triticale (as mimic) | Chickpea, faba bean, canola, wheat | Row spacing |  |
| 5 | Holl& *et al* (1982) | Unknown | Sorghum | Row spacing | ✔ |
| 6 | Martin *et al* (1987) | Wild oat | Wheat | Seeding rate | ✔ |
| 7 | Osten (2007b) | Unknown | Sunflower | Row spacing, Crop density | ✔ |
| 8 | Osten (2007a) | Sweet summer grass | Sorghum | Row spacing, Crop density , Skip row | ✔ |
| 9 | Osten (2006) | Mungbean (as mimic) | Sorghum | Skip row, Crop density |  |
| 10 | Osten (2006) | Millet (as mimic) | Sorghum | Skip row, Crop density |  |
| 11 | Osten & McCosker (2002) | Unknown | Barley, wheat | Crop species, Row spacing, Crop density | ✔ |
| 12 | Osten *et al* (2002) | Chickpea (as mimic) | Wheat (unsprayed) | Row spacing, Crop density | ✔ |
| 13 | Osten *et al* (2006) | Millet or Mungbean (as mimic) | Sorghum, sunflower | Skip row, Row spacing | ✔ |
| 14 | Radford *et al* 1980 | Wild oat | Wheat | Crop density | ✔ |
| 15 | Van Ryswyk *et al* (2004) | Bladder ketmia, amaranthus | Buckwheat | Sowing time |  |
| 16 | Walker *et al* (1999) | Paradoxa grass | Various | Row spacing |  |
| 17 | Walker *et al* (2002) | Paradoxa grass, wild oat | Wheat | Crop density | ✔ |
| 18 | Whish *et al* (2002) | Wild oat, turnip weed | Chickpea | Row spacing |  |
| 19 | Widderick (2002) | Common sowthistle | Barley, wheat | Row spacing, Crop density , Crop species | ✔ |
| 20 | Wu *et al* (2010) | Millet (as mimic) | Sorghum | Cultivar, Crop density | ✔ |

## 6.2 Regional literature reviews

The three regional reviews of literature describing research on crop competition are each divided into:

* summary,
* introduction,
* competition factors and interactions (species, cultivar, density, row spacing, row orientation, sowing time, depth of sowing, nutrition, soil characteristics (site) and rainfall (season) , and
* discussion.

The literature reviews were prepared by Chris Johnasen and Abul Hashem (western region), Andrew Storrie (southern region) and Vikki Osten and Michael Widderick (northern region). Therefore, each review has taken a slightly different approach and style.

The studies included in the literature reviews look at either individual or multiple crop competition factors across various crops, weeds, rotations, seasons and sites, and research approaches are very varied.

### 6.2.1 **WESTERN REGION**

***Summary***

Increased herbicide use accompanying the adoption of minimum tillage practices in the Western Australian Wheatbelt has resulted in increased herbicide resistance in the major weed species. There is thus a need to examine cultural options for weed management, in the context of conservation agriculture. Crop competition with weeds provides one avenue in this regard and this review covers studies on the topic conducted in the WA Wheatbelt from the 1990s.

Many studies have shown that increasing seeding rate (to 100-400 kg/ha) and reducing row spacing (down to 9 cm) of barley and wheat significantly reduces growth and seed production of weeds, mainly annual ryegrass. Fewer studies with canola, lupin, field pea and chickpea have also indicated such plant population and row spacing effects but to a lesser extent. The latitude of the WA Wheatbelt is sufficiently high to ensure lower light penetration into east-west oriented crop rows than north-south ones. This effect has been shown to enhance competition of wheat and barley with weeds, however results with canola, lupin and field pea remain inconsistent.

Cereal crops have been shown to be more effective competitors with weeds than lupin, pea or canola, with barley and oats more competitive than wheat. Within a species it is possible to identify cultivar differences in ability to compete with weeds within any one experiment, but these differences are inconsistent geographically and temporally. There is currently insufficient justification to specifically breed for increased competitiveness but multi-location testing of recently released cultivars for competitiveness remains worthwhile.

In the absence of use of pre-emergence herbicide, early sowing has been shown to be more advantageous than late sowing in conferring a competitive advantage of crop over weed seedlings. However, this is not always the case due to a range of factors affecting relative advantages, such as crop and weed species and population density and rainfall distribution. Cross sowing has been found to be advantageous for competition against weeds by providing a more uniformly spaced plant stand and hence more effective shading.

Liming of the soil, to combat soil acidity prevalent in the WA Wheatbelt, has been found to decrease ryegrass competition with barley and wheat but increase the incidence of brome grass. The relative effects of increasing soil pH on crop and weed are unclear. Placement of more soluble nitrogen fertilizer near the seed, but not so close as to cause toxicity, can favour crop seedling over weed growth.

From multi-location trials conducted over several years there is an indication that crop competition effects are greater at drier locations; however, insufficient data are available to draw conclusions on climatic effects on crop competition with weeds. Similarly, there are no trials conducted on contrasting soil types at the same location from which to conclude about soil effects.

As crop competition itself is only ever likely to partially control weeds, it needs to be incorporated into integrated weed management strategies, which in turn need to be incorporated into integrated crop management strategies. There are inevitable trade-offs in this regard, such as an increase in canopy density suppressing weeds but encouraging foliar disease.

Priorities for future research would include: further characterization of plant population and row width and orientation effects on canola and grain legumes; determination of traits conferring competitiveness that can be used in breeding programs; fertilizer manipulations favouring crop plants over weeds; and a more comprehensive assessment of crop rotation effects.

***Introduction***

Research on crop-weed competition in Western Australia has focussed on the major crops within the Western Australian (WA) Wheatbelt. The WA Wheatbelt covers from north of Northampton in the north through Albany in the south to Esperance in the east within the annual rainfall isohyets of about 300-600 mm. The area has a Mediterranean climate with most rainfall in winter, when crops are grown under rainfed conditions. Main crops of the WA Wheatbelt are wheat, barley, oats, canola and grain legumes such as lupin, field pea and chickpea. The Wheatbelt lies within the GRDC Western Zone, which is to the south-west of a line from approximately north of Carnarvon to the Nullarbor Plain.

About 90% growers in WA Wheatbelt are now in no-till (Crabtree 2010). The adoption of minimum tillage cropping in the Western Australian Wheatbelt over the previous three decades (D’Emden *et al* 2008) has inevitably resulted in increased herbicide use for weed management. This has led to substantial increases in herbicide resistance of the major weed species of the cropping systems (Hashem *et al* 2001; Owen *et al* 2012; Owen *et al* 2014). While resistance to selective herbicides belonging to ACCase, ALS-inhibitor, Photosystems II and Phenoxy herbicide groups is very widespread within the WA Wheatbelt, resistance to glyphosate is a serious concern. As of now, five weed species - annual ryegrass (*Lolium rigidum* Gaudin), wild radish (*Raphanus raphanistrum* L.), windmill grass (*Chloris truncata* R. Br.), red brome (*Bromus rubens* L.) and barnyard grass (*Echinochloa crus-galli* (L.) P. Beauv.)- have already developed resistance to glyphosate within WA (Preston 2015). Although glyphosate is primarily a herbicide for fallow weed management, the introduction of Roundup Ready® canola will enable this herbicide to be used selectively in crops and thus place greater selection for glyphosate resistance.

Other major weeds such as doublegee (spiny emex; *Emex australis* Steinh.), brome grass (*Bromus* spp.), barley grass (*Hordeum leporinum* Link**)**, silver grass (*Vulpia* spp.), wild oats (*Avena fatua* L.), and Indian hedge mustard (*Sisyimbrium orientale* L.) have already developed resistance to some herbicides or are likely to do so.

There is thus a need for wider deployment of alternative cultural weed management strategies. A particularly important option is to exploit the competitive ability of crops with weeds, thereby decreasing the need for herbicide application, or at least increasing options for their more strategic and effective use. Earlier studies have shown effects of increasing density of cereal crops, mainly wheat, in reducing weed competition but more recent studies have covered additional crops and further strategies of competitively combatting weeds. This review summarizes developments in crop competition related weed management in the major crops of the WA Wheatbelt, namely wheat, barley, canola, lupin and field pea.

Most common rotations within the Western Australian Wheatbelt include wheat-wheat, wheat-barley, barley-canola, cereal-lupins, oats-canola, cereal-pulses (chickpea, field pea or faba bean). The most economically important winter weeds that have been addressed or are yet to be addressed within these rotations are annual ryegrass, wild radish, capeweed (*Arctotheca calendula* (L.) Levyns), spiny emex, brome grass, silver grass, wild oats, Indian hedge mustard and Guilford grass (*Romulea rosea* (L.) Eckl.).

***Crop Competition Factors***

**Crop Species**

The relative ability of a particular crop species to compete with weeds will vary with environmental conditions, crop agronomy and weed species (Table 3). However, it is generally found that cereal crops are more competitive than other crop types, due to their early growth vigour and hence ability to intercept more light at earlier growth stages (Blackshaw *et al* 2007). In the WA Wheatbelt, when grown in the same trial, wheat and barley have been found to be more competitive with weeds than canola, field pea or lupin (Table 3) (Borger, Hashem *et al* 2010; Hashem and Borger 2010). Hashem and Wilkins (2002) also found that lupin was more sensitive to competition from wild radish than wheat, in a wheat-lupin rotation. Among cereals, oats and barley were more competitive with annual ryegrass and wild radish than wheat or triticale; canola was also included in this trial and was least competitive (Peltzer 1999). Newman and Hashem (2012) showed that barley was a better competitor with ryegrass than most of the wheat cultivars it was compared with. This was attributed to the greater biomass production of barley.

Table . Summary of field trials in the WA Wheatbelt comparing crop species for their ability to compete with weeds.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Location** | **Year** | **Weed(s)1** | **Conclusion** | **Reference** |
| Merredin | 2004, 2005 | RG, WR; minor emex, capeweed | Wheat=barley>lupin=pea>canola | **(2)** Borger *et al* (2010) |
| Avondale | 2002, 2004 |
| Meckering | 2008, 2009 | RG | Barley>wheat>>canola | **(7)** Hashem and Borger (2010) |
| Wongan Hills | 2008, 2009 | RG |
| Merredin | 1997-2001 | WR | In wheat-lupin rotation lupin more sensitive to WR competition | **(9)** Hashem and Wilkins (2002) |
| Eradu | 2010, 2011 | RG | Less RG in barley than 7 wheat varieties under test | **(22)** Newman and Hashem (2012) |
| Wongan Hills | 2010,  2011 | RG |
| Newdegate | 1998 | RG, WR | Oats and barley more competitive than wheat and triticale at low seeding rate (50 kg/ha) but no difference between the cereals at higher seeding rates | **(31)** Peltzer (1999) |
| Geraldton | 1991 | Brome | Barley>wheat | **(34)** Zaicou and Gill (1992) |

1. RG = annual ryegrass; WR = wild radish

**Cultivar**

Within a crop species, it is possible to detect cultivar differences in ability to compete with weeds, or maintain yield under weed pressure (Table 4). Cousens and Mokhtari (1998) compared 17 wheat cultivars for their competitiveness with annual ryegrass over four sites (Beverly, Wongan Hills, Merredin, Mount Barker) and two years (1994, 1995). In any one trial cultivar differences in ability to maintain yield in the presence of weeds were measurable but there was a lack of consistency over sites and years. Only one cultivar, Halberd, consistently ranked as a good competitor. Newman and Hashem (2012) also found inconsistent effects of seven wheat cultivars in competition with annual ryegrass, over two sites (Eradu, Wongan Hills) and two years (2010, 2011). However, they recorded a close negative correlation between wheat and ryegrass biomass. This suggests that light interception ability or an increased ability of particular wheat cultivars to compete with ryegrass for soil or fertilizer nitrogen (Palta and Peltzer 2001) determined competitiveness. Hashem and Borger (2010) also found variable responses in crop-weed competition among four cultivars each of wheat, barley and canola over location and year.

Table . Summary of field trials in the WA Wheatbelt comparing crop cultivars for their ability to compete with weeds.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Location** | **Year** | **Crop** | **Weed(s)1** | **Conclusion** | **Reference** |
| Avondale | 1994, 1995 | Wheat | RG | Competitive effect variable over site/year; only one cultivar consistently competitive | **(3)** Cousens and Mokhtari (1998) |
| Wongan Hills | 1995 |
| Merredin | 1995 |
| Mt Barker | 1995 |
| Merredin | 2006 | Lupin | RG | Mandelup and Belara more competitive than Tanjil | **(4)** French and Maiolo (2007a) |
| Meckering | 2008 | Wheat, barley, canola | RG | Among 3 cultivars for each crop, differences in RG suppression but variable over season and site | **(7)** Hashem and Borger (2010) |
| Meckering | 2009 | Wheat, barley, canola |
| Wongan Hills | 2008 | Wheat, barley, canola |
| Wongan Hills | 2009 | Wheat, barley, canola |
| Katanning | 2003 | Wheat | Guildford (mainly in 2003), silver, brome, RG (mainly in 2004) | CLEARFIELD wheat more effective at suppressing weeds that 2 other wheat varieties | **(8)** Hashem and Douglas (2005); **(11)** Hashem *et al* (2006b) |
| Katanning | 2004 |
| Mullewa | 2003 | Lupin | WR | Tanjil best at <5 WR /m2 and Belara at 10-20 WR/m2 | **(14)** Hashem *et al* (2004) |
| Wongan Hills | 2003 |
| Eradu | 2010, 2011 | Wheat | RG | Significant effects on RG among 7 cultivars but not consistent between sites | **(22)** Newman and Hashem (2012) |
| Wongan Hills | 2010, 2011 |
| Merredin | 2004 | Lupin | WR | Belara=Tallerack>Tanjil | **(25)** Pathan *et al* (2005a) |
| Merredin | 2005 | Lupin | WR | Mandelup> Belara> Tanjil | **(10)** Hashem *et al* (2006a); **(28)** Pathan *et al* (2006b) |
| Wongan Hills | 2004, 2005 |
| Beverley | 2005 | Barley | RG | Baudin, Flagship and Hamelin  more competitive than Buloke,  Gairdner and Vlaming | **(29)** Paynter and Hills (2009) |
| Calingiri |
| Gibson |
| Katanning |

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Gibson | 2005 | Barley | RG | Significant differences among 4 cultivars but they differed among sites. | **(30)** Paynter (2010) |
| Katanning |
| Meckering |
| Mt. Madden |
| Newdegate | 1998 | Wheat | RG, WR | No differences between 5 varieties tested | **(31)** Peltzer (1999) |

1. RG = annual ryegrass; WR = wild radish

Paynter and Hills (2009) compared six barley cultivars for their ability to compete with annual ryegrass at three plant densities and two sowing dates over five locations across the WA Wheatbelt. They found that cultivars Baudin, Hamelin and Flagship were more competitive than Buloke, Gairdner and Vlamingh. Differences between cultivars in competiveness did not appear related to plant height but may have been due to differences in establishment, tillering and time to maturity. In a comparison of four barley cultivars at two row spacings, and with and without annual ryegrass, Baudin suffered less yield loss due to ryegrass competition than Dash, Gairdner and Vlamingh (Paynter 2010). Ryegrass biomass and tiller number were also less in Baudin plots than with the other cultivars, except at one (Merredin) of four trial sites.

Lupin is particularly sensitive to competition from wild radish, with only 3 radish plants/m2 able to reduce lupin grain yield by 27 to 46 % (Pathan *et al* 2005a). In trials at Merredin and Wongan Hills during 2003-05, biomass and grain yield of lupin cultivar Belara was consistently less affected by wild radish competition than that of cultivar Tanjil (Table 5) (Hashem *et al* 2004; Pathan *et al* 2005a; Hashem *et al* 2006b; Pathan *et al* 2006b). In 2005, a newly released cultivar, Mandelup, suffered less yield loss than both Tanjil and Belara (Hashem *et al* 2006; Pathan *et al* 2006b). It was further found that early sown lupins could compete with wild radish better than late sown ones (Pathan *et al* 2006b).

Besides weed competition, soil and weather conditions and pest and disease status affect growth and yield of a particular cultivar. Thus across field experiments where these factors inevitably vary, it is difficult to identify consistent cultivar differences in weed competitiveness. However, from established crop-weed biomass relationships, it can be suggested that cultivars with early growth vigour and a propensity to close the crop canopy at the earliest would be more competitive with weeds. The question whether it is worthwhile to breed for increased competitiveness with weeds was addressed by Brennan *et al* (2001). Considering various breeding procedures for wheat, including early and advanced generation selection for competitiveness, they concluded that the agronomic manipulation of simply increasing crop density would be more economically viable than any breeding program incorporating competitiveness for weeds as an objective. Paynter and Hills (2009) also noted that, while it is possible to identify cultivars more competitive with weeds, the genetic effect may be subsidiary to possible agronomic remedies to weed competition.

**Crop density**

Regardless of crop species, the ability of crops to compete against weeds increases as crop density increases. Commonly grown crops in the WA Wheatbelt have been shown to compete with weeds as crop density increased (Table 5). Zaicou and Gill (1992) quantified the depressive effect of increasing populations of wheat and barley on brome grass, noting that barley was more competitive than wheat. Subsequent studies with wheat found that increasing the population density could effectively reduce weeds, with annual ryegrass being the main target weed (Minkey *et al* 2000) but with barley being a stronger competitor than wheat.

Table . Summary of field trials in the WA Wheatbelt on effects of crop density on weeds, expressed as seed rate (kg/ha) or plant population (plants/m2).

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Location** | **Year** | **Crop** | **Treatments** | **Weed(s)1** | **Conclusion** | **Reference** |
| Merredin | 2010 | Wheat | 60, 120 kg/ha | RG | RG seeds/m2 64% lower | **(1)** Borger *et al* (2014) |
| Merredin | 2011 | Wheat, barley | 50, 100 kg/ha | RG | RG seeds/m2 75% lower |
| Wongan Hills | 2010 | Wheat | 60, 120 kg/ha | RG | RG seeds/m2 84% lower. Wheat yield increase 17% |
| Wongan Hills | 2011 | Wheat, barley | 50, 100 kg/ha | RG | RG seeds/m2 26% lower |
| Katanning | 2010 | Wheat | 60, 120 kg/ha | RG | RG seeds/m2 13% lower.  Wheat yield increase 40% |
| Katanning | 2011 | Wheat, barley | 50, 100 kg/ha | RG | RG seeds/m2 35% lower |
| Wongan Hills | 2006 | Lupin | 0, 10, 20, 40, 80, or 120 plants/m² | WR | WR biomass approx. halved by increasing lupin population | **(5)** French and Maiolo (2007b) |
| Merredin | 2001, 2003 | Wheat | 50, 100 kg/ha | RG | RG head numbers decreased and wheat yield increased | **(6)** Hashem and Riethmuller (2006) |
| Mullewa | 2003 | Wheat | 50, 100 kg/ha | RG |
| Meckering | 2009 | Wheat | 60, 120 kg/ha | RG | 13% yield increase for barley at Meckering, no other yield responses. Effect on ryegrass heads not reported | **(7)** Hashem and Borger (2010) |
| Meckering | 2009 | Barley | 75, 150 kg/ha | RG |
| Meckering | 2009 | Canola | 2.5, 5 kg/ha | RG |
| Wongan Hills | 2009 | Wheat | 60, 120 kg/ha | RG |
| Wongan Hills | 2009 | Barley | 75, 150 kg/ha | RG |
| Wongan Hills | 2009 | Canola | 2.5, 5 kg/ha | RG |
| Wongan Hills | 2001, 2002 | Wheat | 50, 75, 100, 125, 150 kg/ha | WR, RG | Higher seeding rate could compensate lower herbicide rate | **(11)** Hashem *et al* (2006b) |
| Merredin | 2001 | Wheat | 50, 100 kg/ha | RG | Increased wheat yield and RG heads/m2 reduced by up to 50% | **(13)** Hashem *et al* (2002) |
| Wongan Hills | 1996 | Barley | 65, 109, 268 plants/m2 x 0-500 plants/m2 RG | RG | Mutual competitive effects of barley and RG quantified | **(16)** Izquierdo *et al* (2003) |
| Merredin | 2000 | Canola | 5, 10, 20, 40 kg/ha | RG | Not reported | **(17)** Minkey (2002) |
| Merredin | 2001 | Wheat | 50, 100, 200, 400 kg/ha | RG | Around 75% reduction in RG plants/m2 |  |
| Meckering | 2000 | Wheat | 50, 100, 150 kg/ha | RG | Nearly 50% RG kill without herbicide |  |
| Goomalling | 2000 | Wheat | 60, 120, 180 kg/ha | WR | 60-70% reduction in WR biomass |  |
| Merredin | 1999 | Barley | 50, 100, 200, 400 kg/ha | RG | 50-70% reduction in RG heads/m2; only marginal yield increase | **(19)** Minkey *et al* (2000) |
| Merredin | 1998 | Wheat | 50, 100, 200, 400 kg/ha | RG | Up to 90% reduction in RG heads/m2 and increased wheat yield at high RG burden | **(20)** Minkey *et al* (1999) |
| Mingenew | 2013 | Wheat | 60, 90 and 120 kg/ha | RG | Weeds data not reported but reduction implied. Little effect on wheat yield | **(21)** Newman (2014) |
| Mingenew | 1999 | Wheat | 30, 60, 90, 120 kg/ha | RG, brome | 70-75% reduction in brome tillers/m2 and increased wheat yield and lower screenings | **(23)** Newman and Weeks (2000) |
| Mingenew | 2012 | Wheat | 40, 80,120,160 kg/ha | RG | 60% reduction in RG seeds/m2 but little effect on wheat yield | **(24)** Newman and Zaicou-Kunesch (2013) |
| Binnu | 2012 | Wheat | 40,80,120,160 kg/ha | WR | 60% reduction in WR dry matter (g/m2) and 30% increase in wheat yield | **(23)** Newman and Weeks (2000) |
| Beverley  Calingiri  Gibson  Katanning | 2005 | Barley | 75, 150, 300 kg/ha | RG | Across sites, RG tillers/m2 reduced 40-50% and barley yield increased | **(29)** Paynter and Hills (2009)  **(31)** Peltzer (1999) |
| Newdegate | 1998 | Wheat, oats, barley, triticale | 50, 100, 200, 400 kg/ha | RG, WR | 60-90% reduction in RG seeds/m2, for all species |
| Geraldton | 1991 | Wheat,  barley | 30, 50, 70, 90 kg/ha | Brome | Clear effect of crop density on brome seed; barley more competitive than wheat | **(34)** Zaicou and Gill (1992) |

1. RG = annual ryegrass; WR = wild radish

High seeding rate of wheat reduced radish biomass and increased wheat yield in the absence of chemical control although the screening rate was high (Hashem *et al* 1998). They also found that autumn tickle and high seed rate of wheat reduced annual ryegrass heads by 20% and increased wheat yield by 51-69%. Izquierdo *et al* (2003) found that increasing the barley seed rate through 25, 50, 200 kg/ha, resulting in 69, 109, 268 plants/m2, respectively, could reduce ryegrass spike density by 85% at Wongan Hills. Paynter and Hills (2009) found that increasing barley seeding rate through 75, 150, 300 kg/ha (60-160 plants/m2) reduced ryegrass tiller number across several WA Wheatbelt locations, as did reduction of row spacing from the range of 36-50 cm to 18-25 cm (Paynter 2010). However, in a farmer (D & R Lamplugh) implemented trial with barley at Kellerberrin in 2003, ryegrass density increased as barley sowing rates increased from 20 to 60 kg/ha but ryegrass decreased as wheat density increased from 60 to 100 kg/ha (KDG 2004), suggesting that barley outcompetes ryegrass only in the range of higher seed rates.

Increasing seeding rate of canola from 5 to 40 kg/ha decreased ryegrass numbers, as did reducing the row width from 27 to 9 cm at high seed rates (Table 5) (Minkey 2002). Riethmuller (2010) also found that reducing row width of canola from 36 to 9 cm markedly supressed seed production of ryegrass. Lupin could reduce biomass of wild radish over the range of 10-120 plants/m2 but reducing row spacing from 50 to 25 cm reduced weed population only when the lupin population was >80 plants/m2 (French and Maiolo 2007b).

**Row spacing**

Another way to increase crop competitive ability to suppress weeds is to reduce the row width (Table 6). It was generally found that increasing the wheat sowing rate over the range 30 to 400 kg/ha, and decreasing row spacing from 27 to 9 cm, decreased germination, tillering and seed set of ryegrass, without detrimental effects on wheat yield or screenings (Minkey *et al* 1999). Riethmuller (2005) concluded that wheat yield decreased by around 4% for every 5 cm row spacing increase over 18 cm, which correlated with an increase in ryegrass density. Newman (2014) concluded that it is more efficient and cost effective to increase crop competition through narrow row spacing in combination with optimal plant density than simply increasing the seeding rate for current crop row spacing. Newman (2014) also compared different row configurations, paired rows and ribbon sowing compared with equally spaced rows, but found no clear effect on weed competition.

Table . Summary of field trials in the WA Wheatbelt on effects of row spacing on weeds.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Location** | **Year** | **Crop** | **Treatments** | **Weed(s)1** | **Conclusion** | **Reference** |
| Merredin | 2001, 2003 | Wheat | 9.5, 19 cm | RG | Narrow spacing doesn’t reduce RG heads/m2 | **(6)** Hashem and Riethmuller (2006) |
| Mullewa | 2003 | Wheat | 9.5, 19 cm | RG |
| Cunderdin | 2012 | Wheat | 22, 44 cm | RG | Fewer weeds at narrow spacing with weeds reducing with each crop | **(12)** Hashem *et al* (2015) |
| Cunderdin | 2013 | Lupin | 22, 44 cm | RG |
| Cunderdin | 2014 | RR2 canola | 22, 44 cm | RG |

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Merredin | 2001 | Wheat | 9.5, 19 cm | RG | 20% reduction in RG heads/m2 at 9.5 cm at low seed rate | **(13)** Hashem *et al* (2002) |
| Cunderdin | 2012 | Wheat | 22, 44 cm | RG | No effect of row spacing on weeds or crop yield | **(15)** Hashem *et al* (2013) |
| Cunderdin | 2012 | Lupin | 22, 44 cm | RG |
| Merredin | 2012 | Wheat | 22, 44 cm | RG | No effect of row spacing on weeds but higher yield at wide spacing due to low soil moisture |
| Merredin | 2012 | Chickpea | 22, 44 cm | RG |
| Merredin | 2001 | Wheat | 9, 18, 27 cm | RG | Closer spacing reduced RG plants/m2 only at high seeding rates | **(17)** Minkey (2002) |
| Merredin | 1999 | Barley | 9, 18, 27 cm | RG | Heads/m2 halved by closer spacing at low seed rate but effect marginal at higher rates | **(19)** Minkey *et al* (2000) |
| Merredin | 1998 | Wheat | 9, 18, 27 cm | RG | Closer spacing decreases RG heads/m2 by <20% at low seed rate but by >50% at high seed rate | **(20)** Minkey *et al* (1999) |
| Mingenew | 2013 | Wheat | 15, 22, 30 cm and paired rows | RG | Reduce row spacing at optimum seed density for max. weed control | **(21)** Newman (2014) |
| Mingenew | 1999 | Wheat | 18, 36 cm | RG, brome | Tillers/m2 reduced by 30% at closer spacing, more so higher seed rates | **(23)** Newman and Weeks (2000) |
| Merredin | 2004 | Wheat | 18, 36 cm | RG | Row spacing effects on weeds varied among crops but no data given | **(26)** Pathan *et al* (2005b) |
| Avondale | 2002 | Barley | 18, 36 cm | RG |
| Avondale | 2004 | Lupin, canola, pea | 18, 36 cm | RG |
| Merredin | 2004, 2005 | Wheat, barley, canola, lupin, pea | 18, 36 cm in 2004 and 23, 60 cm in 2005 | RG, WR; minor emex, capeweed | No clear effects of row spacing but E-W row orientation advantage | **(27)** Pathan *et al* (2006a); **(2)** Borger *et al* (2010) |
| Avondale | 2002, 2004 | Wheat, barley, lupin, canola, pea | 18, 36 cm | RG, WR; minor emex, capeweed |
| Newdegate | 1998 | Wheat, oats, barley, triticale | 18, 36 cm, 18 cm cross-seeded for wheat | RG, WR | Little effect on RG seeds for row sowing but big effect when cross-seeded | **(31)** Peltzer (1999) |
| Merredin | 2004 | Wheat | 9, 18, 27, 36 cm | RG | RG plants reduced to 15% where burnt and 40% where not burnt with closer spacing | **(32)** Riethmuller (2005) |
| Merredin | 2009 | Canola | 9, 18, 27, 36 cm | RG | Narrow spacing reduces RG seed by 60% | **(33)** Riethmuller (2010) |

1. RG = annual ryegrass; WR = wild radish; 2. Roundup Ready®

Thus, there are sufficient data to confirm that increasing light interception by either increasing crop plant population or decreasing row spacing can markedly reduce populations and reproductive potential of the major weed species of the WA Wheatbelt. However, such positive effects of reducing row spacing were not always found (Hashem and Riethmuller 2006; Borger *et al* 2010; Hashem *et al* 2013). The limit as to how narrow row spacing should be would be determined by requirements for stubble management, use of trifluralin, accommodation of machinery or the degree of drought limitation (which would cause intra-plant competition for water at high densities).

Competition for light may not entirely explain the competitive effects between weeds and cereal crops. Palta and Peltzer (2001) found that earlier emergence of ryegrass in relation to wheat resulted in lower uptake of fertilizer and soil N by wheat, with consequent depressive effects on wheat growth and yield.

***Weed control with wide rows****:* While acknowledging the advantages of narrow row spacing in increasing competition with weeds, there has been a trend to wider row spacings in the WA Wheatbelt, mainly for lupin. Wider than traditional row spacings are favoured mainly for optimising use of limiting soil water but also for stubble management and improved crop establishment. This lessens the crop’s ability to compete with weeds but, by separating the bulk of the weed population from crop rows, it opens possibilities for targeted inter-row control by mechanical means or non-selective herbicides.

The advent of shielded spraying equipment allows inter-row spraying of knockdown herbicides while the crop is growing. This works effectively with lupins at 50-75 cm row spacing ( Hashem *et al* 2005; Maling *et al* 2007; Hashem  *et al* 2008). Weeds within the crop row can be controlled by selective herbicides requiring minimal area coverage, by precise targeting of spray nozzles (Collins and Roche 2002) or banding of herbicides at sowing (Crabtree *et al* 2002).

Mechanical cultivation between rows, however, has not proved very effective when compared to use of herbicides. In trials with lupin in fields heavily infested with ryegrass at Wongan Hills during 1998-2001, Collin and Roche (2002) found that inter-row cultivation, by 20 cm wide sweeps or non-powered rotary hoe was not as effective as herbicide applied with a spray shield in reducing ryegrass biomass and maintaining lupin yield. They noted that cultivation stimulated ryegrass germination and suggested that cultivation might be more effective where ryegrass population was less. They also tried glyphosate-impregnated weed wipers and flame weeding and found these techniques to be also less effective than herbicide sprays. In trials at Wongan Hills and Merredin in 2006, Hashem *et al* (2008) similarly found that inter-row tillage was much less effective than inter-row herbicide application in wide-row lupin. With tillage, weed control barely exceeded 50%, crop damage was 9-44% and yield loss (c.f. weed free control) was 5-55%. Hashem *et al* (2005) tried mowing between rows of lupins at York in 2003 followed by application of Spray.Seed® (a mixture of paraquat and diquat). This gave 75% control of inter-row annual ryegrass plants and a 13% yield increase over an untreated control plot. When wild radish was targeted, glyphosate and Spray.Seed® application after mowing gave about 90% control.

Peltzer *et al* (2009) point to some of the challenges facing weed control at wide row spacings. Timing of action against inter-row weeds becomes crucial, and is very site dependent. Effective use of spray shields is required to minimize crop damage. Undesirable shifts in weed composition may occur; for example, Peltzer *et al* (2007) found that mid-season inter-row cultivation stimulated wild radish emergence by 50% above the control. However, development of herbicide resistance in weeds in wide rows remains a problem, as herbicides remain the most effective control measure. Peltzer *et al* (2009) contend that wide row weed management increases options for slowing development of herbicide resistance, by allowing more site specific weed management, such as by sensor or map-based targeting of weeds and judicious use of herbicides with different modes of action (Hashem *et al* 2007). However, the most effective way of combatting development of herbicide resistance is to increase options for mechanical control. Although earlier efforts in this regard have not been as successful as herbicide use in reducing weeds and maintaining crop yields, it is proposed that development of mechanical options needs renewed emphasis.

**Row orientation**

Some weed species may exhibit greater sensitivity to shading by green canopy of another plant species than other species (Ballaré *et al* 1990). Some studies within the Western Australian Wheatbelt confirmed the relative sensitivity of weeds to shading by the crop. This effect can potentially be enhanced by the latitude of the region, between 28 and 33°S, and the fact that the growing season is through the winter, when the angle of the sun to the horizon is at its lowest. This can be as low as 35° during winter, although it ranges from 39 to 61° in spring, when crops reach maturity (Borger *et al* 2010). Therefore, less light should penetrate the crop canopy when crop rows are aligned east-west (E-W) rather than north-south (N-S). The extent to which crop row orientation can influence weeds has been evaluated in the WA Wheatbelt over the previous 15 years (Table 7).

Table . Summary of field trials in the WA Wheatbelt on effects of row orientation, either east-west (E-W) or north-south (N-S), on weeds.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Location** | **Year** | **Crop** | **Weed(s)1** | **Conclusion** | **Reference** |
| Merredin | 2010 | Wheat | RG | % weed dry biomass in E-W vs N-S: 8% | **(1)** Borger *et al* (2014) |
| Merredin | 2011 | Wheat, barley | 22% |
| Wongan Hills | 2010 | Wheat | 8% |
| Wongan Hills | 2011 | Wheat, barley | 42% |
| Katanning | 2010 | Wheat | 113% |
| Katanning | 2011 | Wheat, barley | 54% |
| Merredin | 2004, 2005 | Wheat | RG, WR; minor emex, capeweed | % weed dry biomass in E-W vs N-S: 90% in 2004 and 29% in 2005 | **(2)** Borger *et al* (2010); **(26)** Pathan *et al* (2005b); **(27)** Pathan *et al* (2006a) |
| Merredin | 2004, 2005 | Barley | 79% in 2004 and 53% in 2005 |
| Merredin | 2004, 2005 | Canola | 64% in 2004 and 29% in 2005 |
| Merredin | 2004, 2005 | Lupin | 75% in 2004 and 30% in 2005 |
| Merredin | 2004, 2005 | Pea |  | 120% in 2004 and 63% in 2005 |  |
| Avondale | 2002, 2004 | Wheat | 19% in 2002  Over sites/years 31% crop yield increase in E-W |
| Avondale | 2002, 2004 | Barley | 13% in 2002 and 76% in 2004  Over sites/years 34% crop yield increase in E-W |
| Avondale | 2002, 2004 | Canola | 74% in 2002 and 137%in 2004  Over sites/years 15% crop yield increase in E-W |
| Avondale | 2002, 2004 | Lupin | 100% in 2004  Over sites/years 3% crop yield decrease in E-W |
| Avondale | 2002, 2004 | Pea | 64% in 2004  Over sites/years 8% crop yield increase in E-W |

1. RG = annual ryegrass; WR = wild radish

Extensive studies on the effect of row orientation on weed incidence of major Wheatbelt crops were conducted at Merredin and Beverley (Avondale Research Station) during 2002-05 (Pathan *et al* 2005b; Pathan *et al* 2006a; Pathan *et al* 2006b; Borger *et al* 2010;). East-west orientation of barley and wheat crop rows, compared to N-S, reduced weed biomass by 51 and 37 %, respectively, averaged over 2002 and 2004 trials at Merredin and 2004 and 2005 trials at Beverley (Borger *et al* 2010). Major weed species in these studies were annual ryegrass and wild radish, although capeweed and spiny emex were also present. Respective yield increases of wheat and barley with E-W orientation were 24 and 26%. However, across these trials, row orientation did not consistently nor overall significantly affect weed load or grain yield of canola, field pea or lupin. Light interception in the centre of the row at noon was lower in E-W than N-S rows in all crops but to a greater extent in wheat and barley (Borger *et al* 2010). These row orientation studies were done at both narrow and wide row spacings, 23 vs 60 cm at Merredin and 18 vs 36 cm at Beverley. The previously observed effects of reduced row spacing in reducing weed load were obtained, but row spacing had no effect on crop yield in these trials (Borger *et al* 2010).

In farmer implemented on-farm trials with lupin at Kellerberrin in 2003, two farms out of three reported fewer weeds with E-W rather than N-S orientation but lupin yield was only significantly increased by E-W orientation in one out of three farms (KDG 2003)

The depressive effect of E-W, compared to N-S, crop row orientation on weed incidence, in this case measured as annual ryegrass seed production, on wheat and barley was confirmed in trials at Merredin, Wongan Hills and Katanning during 2010-11, although there was no significant effect on wheat at Katanning in 2010 (Borger *et al* 2014). Seed rate (50 or 60 vs 100 or 120 kg/ha) was also included as a factor in these trials and previously observed depressive effects of higher seeding rate of wheat and barley on weed seed production were confirmed. Crop yield was generally higher at higher seed rates and with E-W orientation, although not consistently so across location, crop and year.

Therefore, using E-W orientation can be superimposed on seed rate and row width effects to further enhance weed competition, in wheat and barley at least. It is a cost free input, provided there are no logistical difficulties in running machinery E-W. However, further studies are needed with the non-cereal crops to determine if row orientation can effectively enhance crop competition with weeds.

**Sowing time**

Since moisture is the most influential factor for the rainfed crop production systems, early occurrence of rainfall often leads growers to sow crops early in the season without waiting for the emergence of weeds to be killed by knockdown herbicides. By contrast, delayed onset of rainfall would prompt farmers to go for dry sowing of crops such as canola, lupins and often cereals without allowing the weeds to emerge to be killed by knockdown herbicides before sowing. Even in the case of a good season break, farmers will tend to sow crops without waiting for weeds to emerge. In the paddocks where the weed burden is high, growers may wait longer after season break for weed emergence, kill the weeds by knockdowns and sow the crop 1-3 weeks late. This is likely to reduce weed density in the crop but the potential risk that is associated with delayed sowing of crop is a significant reduction in grain yield, regardless of crops.

It may be expected that the faster crop seedlings can establish and progress towards canopy closure the greater will be their ability to compete with weeds. Indeed, Rerkasem *et al* (1980) and Palta and Peltzer (2001) showed that the earlier ryegrass emerges relative to wheat, the greater is the competitive effect of ryegrass on wheat growth and yield. Particularly in rainfed cropping systems dependent on in-season rainfall, the sooner a crop can be planted on the opening rains the greater should be its competitive advantage. In their experiments across five sites in 2005, Paynter and Hills (2009) showed that the effect of increasing plant population of barley in reducing tiller number of annual ryegrass was larger when the planting date was advanced by around 20 days. In this case ryegrass seed was broadcast on the surface of plots just prior to sowing of barley. The greater yield, and presumably biomass formation (although not reported), obtained with early sowing suggest more shading of ryegrass when barley is sown early. If delayed sowing is not used for pre-sowing weed control, through cultivation or herbicide application, these results suggest that early sowing reduces weed seed production compared with delayed sowing if weed control is effective.

Similar to the above effect obtained with barley, early sown lupin was better able to compete with wild radish over radish densities of 3 to 28 plants/m2 (Pathan *et al* 2006b). In this case also radish was sown along with lupin seed, in the first and third weeks of May 2005. However, no sowing date effects were found in another trial with lupin at Merredin (French and Maiolo 2007a). This was attributed to seasonal differences in rainfall differentially affecting emergence of weeds and lupin; and in this case the main competing weed was annual ryegrass rather than radish.

Contrary to most of the sowing date effects reported with barley and lupin, Minkey and Ashworth (2012) found later sowing of wheat to be more advantageous in ryegrass management than early sowing. In this case, however, the early sowing was dry sowing, before the opening rains. Dry sowing offers the potential of earliest possible seedling establishment of crop, and hence competitive ability with weeds, and the yield advantage to be gained from an extended growing period. They tested the effect of dry sowing of wheat at Cunderdin in 2011, as compared with sowing into moist soil two weeks later. However, in plots not treated with herbicide, they found greater ryegrass control and higher grain yield in delayed-sown plots. They concluded that an effective herbicide was needed if the potential of dry sowing is to be achieved, and weed competition minimized. It appears that there are several site-specific factors, such as soil water status at the break of season, crop species and weed regime that will determine which sowing date will result in maximum competitive ability of the crop.

Hashem *et al* (1998) concluded that, regardless of management levels (tickling, seeding rate and herbicides), late sowing reduced in-crop ryegrass density compared to normal sowing time but late sowing also reduced yield of wheat by 20%. The extent of reduction in grain yield of wheat due to late sowing was greater at 60 kg/ha than at 120 kg/ha seed rate. Application of diuron under late sowing with 60 kg/ha reduced wheat yield more than that of trifluralin.

**Sowing depth and method**

***Sowing depth*:** In WA, there have been no reported studies on the effect of crop sowing depth on subsequent crop competition with weeds. Sowing depth of the crop species can affect the ability of the crop to compete with weeds, as this determines the initial growth vigour of crop seedlings in relation to weed seedlings. For wheat and barley in rainfed Mediterranean environments sowing deeper than 5cm delays emergence (Photiades and Hadjichristodoulou 1984). However, optimum sowing depth is determined by current and expected soil moisture availability.

***Sowing method:*** Weeds are predicted to have least advantage if crop is planted in a square pattern rather than rectangular (Fischer and Miles 1973). Sowing method can modify the spatial arrangements of crops while weeds remain randomly positioned. Cross sowing, or sowing half the seed and fertilizer in one direction and the other half at right angles, has the potential to increase competitive ability of a crop through more even spacing of plants. At Newdegate in 1998, Peltzer (1999) found that cross sowing, in comparison with conventional sowing, minimized ryegrass seed production in wheat sown at high (150 kg/ha) but not at low (50 kg/ha) seed rate. In comparing cross sowing with conventional sowing of wheat at Merredin and Mullewa in 2001 and 2003, Hashem and Riethmuller (2006) found a trend (although not significant) to fewer ryegrass heads and higher wheat yield with cross sowing in two out of three trials. However, in a farmer (K. Leake) implemented on-farm trial at Kellerberrin in 2004, no significant effect of increasing seed rate, from 70 to 140 kg/ha, or of cross sowing at either rate was found for wheat (KDG 2004) but ryegrass density was substantially reduced (personal communication K Leake 1999).

**Crop rotation**

Previous cropping history and the consequent weed seed bank can affect the ability of the current crop to compete with weeds. A depleted seed bank can increase effectiveness of competition of the current crop with weeds. Hashem and Wilkins (2002) imposed a series of treatments on a wheat-lupin rotation at Merredin during 1997-2001, resulting in a range of wild radish burdens for each subsequent crop. They established relationships between crop yield and radish population, with a 50% grain yield reduction of wheat at around 50 radish plants/m2 and 50% lupin grain yield reduction at about 15 radish plants/m2. Thus the extent of wild radish control in the previous crop, by various chemical and cultural means, determined the extent of crop-weed competition in the subsequent crop, with lupin being much more sensitive to weed control in the preceding wheat crop than wheat in the preceding lupin crop. In a wheat-lupin rotation trial conducted at Merredin from 1997 to 2000, Hashem *et al* (unpublished data) found that use of autumn tickle and high seed rate with an application of 2,4-D ester (Management treatment B in Table 8) reduced seed set, and could reduce wild radish seedling emergence by 86% in 1998, 55% in 1999 and 50% in 2000 compared to an untreated control. In this rotation trial the radish emergence in 1997 was 6% higher in the high seed rate plots than the untreated control.

Table . Effect of chemical and non-chemical treatments on the emergence of radish seedling in wheat-lupin rotation at Merredin from 1997 to 2001.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Management | Wild radish seedlings (plants/m2) | | | |
|  | 1997 | 1998 | 1999 | 2000 |
| A (Untreated) | 204 | 343 | 196 | 151 |
| B (97 AT+HSR+24DE; 99 AT+HSR+2,4DE) | 218 | 45 | 89 | 75 |
| C (97 SSR +Jaguar; 99 SSR+2,4-DA) | 186 | 61 | 79 | 19 |
| D (No seed production of radish) | 225 | 17 | 57 | 10 |
| AT= autumn tickle; HSR = High seed rate (120 kg/ha); 2,4DE = 2,4-D Ester; SSR = Standard seed rate (60 kg/ha); 97 = 1997 season; 99 = 1999 season. | | | | |

The benefits of break crops in enhancing weed management, and hence reducing weed competition in the subsequent crop, have been discussed for the WA Wheatbelt by Flower *et al* (2012) and Seymour *et al* (2012). Similarly, inclusion of a pasture phase provides options for depleting seed banks for subsequent crops, through the effect of grazing, cutting for hay or silage or application of selective herbicides (Doole and Pannell 2008).

**Nutrition**

There are few studies on the effect of fertilizer addition on competition between crops and weeds in the WA wheatbelt, and of those only nitrogen (N) has been tested. Fertilizer N can be a major determinant of the growth of both cereals and their companion, non-leguminous, weeds. Palta and Peltzer (2001) demonstrated the strong competitive effect of ryegrass with wheat in uptake of both soil and fertilizer N, which ultimately affects growth and yield of wheat. Factors such as N fertilizer type, rate, timing and placement, and soil water status affecting N availability, could affect the differential response of cereal crops and weeds to N fertilizer (Blackshaw *et al* 2004). A greater response to N of the crop plant could facilitate its competition with weeds.

At a medium rainfall (300-400 mm rain per annum) site at Cunderdin in 2012 and 2013, row placement of a liquid fertilizer high in immediately available N, Flexi N®, stimulated emergence of annual ryegrass more than less soluble urea granules, and more at a wide row spacing of wheat of 44 cm as compared to 22 cm (Hashem *et al* 2015). However, at a dry site, and in a drought year, at Merredin in 2012, production of ryegrass heads was less with Flexi N® than urea granules (Hashem *et al* 2013). This was explained as the Flexi N® being less available than urea granules in the dry soil. Pearce *et al* (2012) found that placement of nitrogen (N) fertilizer, at 40 kg N/ha, with the seed reduced wheat plant density due to N toxicity. With reduced plant density they observed, but did not quantify, increased weed incidence, consistent with previous studies on effect of wheat density on weeds.

More research is required to understand how best to apply N fertilizer, and other nutrients for that matter, to maximize crop growth and yield yet minimize competition by weeds.

**Soil Characteristics**

Soil conditions and nutrient availability can have differential effects on the growth of crop and weed species, and thus affect the ability of the crop to compete with weeds. Soil acidity is a major crop constraint in the WA Wheatbelt and lime is increasingly being applied to raise soil pH (Flower and Crabtree 2011). Gazey and Andrew (2010) measured the effect of lime rates up to 5 t/ha, applied in 1991 at Kellerberrin on a soil with surface pH 4.8, on wheat and barley yields and weed biomass in 2008 and 2009. In the intervening period the plots were cropped with a rotation of 2-3 wheat with 1 lupin. Wheat and barley yields increased with lime application but ryegrass biomass decreased (quantified in 2009 for barley but observed for wheat in 2008). In trials at Merredin, Wongan Hills and Eradu, Hashem and Borger (2014) applied lime at rates of 0-5 t/ha in 2010. There were no lime effects on yield of wheat and lupin crops grown during 2010 to 2012 or on the weed burden. In 2013, however, density of ryegrass, wild radish and barley grass decreased with increasing lime level, and yield of barley was increased significantly with lime treatment at two of the four experimental sites.

Contrary to suppressive effects of liming on weeds, at Wongan Hills and Katanning during 2001-04, brome grass populations in wheat increased with liming (Hashem *et al* 2006).

**Rainfall**

The major spatial differences across the WA Wheatbelt in the winter growing season, determining relative growth of crops and weeds, and competition between them, would be soil type, temperature and rainfall. Although soil types vary considerably within the WA Wheatbelt, from sands to loamy clays, it is difficult to relate crop-weed competition to them. No experiments were done on contrasting soil types with similar weed regimes at the same location, and hence the same temperature and rainfall regime. Further, as fertilizer is applied to such trials to alleviate nutrient stress, the main effect of soil type on crop and weed growth would most likely be soil moisture holding capacity. However, multi-locational and multi-seasonal trials have assessed differences in temperature and rainfall regimes. Temperatures in the WA Wheatbelt during May to September decrease from north (average monthly max. 19-24 °C, average monthly min. 7-11 °C) to south (max. 15-19 °C, min. 5-8 °C). Annual rainfall, with most falling in winter, declines from west (~600 mm) to east (~300 mm).

Of the major weeds, annual ryegrass is distributed throughout the Wheatbelt, following no particular spatial pattern (Owen *et al* 2007; Borger *et al* 2012; Owen *et al* 2014). Its occurrence in a particular paddock depends more on factors such as the cropping system or crop-pasture rotation, prior extent of weed control and hence seed bank, etc. The other major weed, wild radish, is also found throughout the Wheatbelt but is more prevalent in northern areas (Walsh *et al* 2007; Borger *et al* 2012), suggesting a preference for warmer temperatures. Ryegrass incidence has changed little over time (from 1997 to 2008) whereas wild radish incidence has increased, and incidence of weeds such as brome grass, silver grass and wild oat has declined over time (Borger *et al* 2012).

It is difficult to ascertain the extent to which crop competition effects on weeds varies over space and time due to interactions with other factors, such as agronomy and pest and disease incidence. Trials conducted within the same study over different locations and years are more likely to give space/time insights, as they would have similar design and agronomy. The factor affecting crop competition likely to be most dominant between sites and over time is rainfall, rather than temperature or soil type, due to the inherent rainfall variability of this rainfed cropping environment.

Paynter and Hills (2009) studied competition between barley and annual ryegrass at five Wheatbelt sites varying in growing season rainfall in 2005. Ryegrass appeared to be more competitive with barley at the drier sites of Mt Madden and Beverley, which had the lowest barley yields, than at the wetter sites of Calingiri, Gibson and Katanning. However, there was no consistent effect of increasing barley density at high and low ryegrass populations on barley yield across sites. Effects of increasing barley density on any ryegrass parameter were not presented for each site.

Borger *et al* (2014) studied the effect of increasing crop density and east-west vs north-south row orientation of barley and wheat crops on seed production of annual ryegrass at three sites differing in growing season rainfall in a dry (2010) and wet (2011) year. There is a tendency for greater effectiveness of higher density and east-west orientation with lesser rainfall, but not unequivocally (Table 9).

Table . Effect of year and location on growing season rainfall and proportion of ryegrass seeds in high versus low density and east-west versus north-south row orientation treatments of wheat and barley crops. Data derived from Borger *et al* 2014.

|  |  |  |  |
| --- | --- | --- | --- |
| Year | Location | | |
| Merredin | Wongan Hills | Katanning |
| *Growing season rainfall (mm)* | | | |
| 2010 | 139 | 144 | 191 |
| 2011 | 255 | 395 | 352 |
| *Proportion ryegrass seeds in high vs low crop density (%)* | | | |
| 2010 | 37 | 16 | 87 |
| 2011 | 25 | 74 | 66 |
| *Proportion ryegrass seeds in east-west vs north-south row orientation (%)* | | | |
| 2010 | 55 | 8 | 114 |
| 2011 | 22 | 42 | 54 |

An earlier study (2002-05), however, suggested a greater effect of east-west row orientation in suppressing weeds (mainly ryegrass and wild radish) in barley and wheat crops at the wetter site of Beverley than at Merredin (Borger *et al* 2010). There were no consistent site or year effects when this treatment was applied to canola, field pea or lupin.

***Discussion***

Some crop species appear to be consistently more competitive than others across location and season of Western Australian Wheatbelt. However, increases in crop density appear consistently to endow increased competitive ability to a crop species, particularly cereal crops, regardless of their inherited competitive ability as in the case of close row spacing compared to wide row spacing. Therefore barley, oats and wheat crops grown at high density at close row spacing would be more competitive to suppress weeds in a good season than when grown at low density. Competiveness of individual cultivars within a given crop variety appear to vary across season and location making it too difficult to recommend. However, availability of information on the competitiveness of cultivars at the time variety release would benefit growers. Amelioration of the problem soil such as low pH may stimulate competiveness of crop species that is otherwise limited in growth and is less competitive.

It is clear that increasing canopy light interception effectively suppresses weeds but manipulation of this factor needs to be weighed against considerations besides weeds. Denser canopies may increase risk of foliar disease (Burdon and Chilvers 1982) and lead to premature exhaustion of scarce soil water. The cost of higher seed rates would adversely impinge on the economics and adjustment of row spacing would be governed by equipment needs and capability. However, the use of east-west row orientation does not interfere with other agronomic considerations and this can easily be incorporated into any integrated crop management package, at little or no cost.

Although there are substantial differences between crops grown in the WA Wheatbelt in competitive ability with weeds, crop choice for a given year or longer term rotation is predominantly determined by soil-climate suitability and expected economic return; only minor consideration would be given to weed control, unless weeds have become a major threat to the farming enterprise. Similarly, in WA Wheatbelt studies, cultivar differences in competiveness have so far been found to be too small and inconsistent to confidently include this factor in an IWM or ICM package as yet. Nevertheless, meaningful differences have been found in Eastern Australia, for wheat (Lemerle *et al* 1996), canola (Lemerle *et al* 2010) and pea (McDonald 2003), and the search for cultivars with a clear advantage in being able to better compete against weeds, while retaining other desirable agronomic traits, is worth pursuing in WA.

Sowing time, method and depth are primarily determined by considerations other than weed management, factors such as soil moisture availability over time and seed drill characteristics. Nevertheless further research is required to understand and quantify how variations in sowing procedure could favour crop seedling over weed establishment. There is scope for adjustment of the timing and placement of fertilizers, particularly N, to favour the crop over weeds (Kirkland and Beckie 1998). That is, to stimulate seedling growth so as to achieve canopy cover at the earliest; however, this may be better suited to higher rainfall environments as too vigorous early crop growth could exhaust limited soil water reserves. Further evaluation of methodology, applicable to the circumstances of the WA Wheatbelt, for banding of N below or near crop rows so as to favour crop over weed seedling growth, while avoiding crop toxicity, is required.

***Future Research Needs:*** While much has been learned over the previous two decades about how crops can compete with weeds, the following research is required if cultural weed management is to progress in the WA Wheatbelt.

* Optimum densities and row width and orientation for weed suppression and maximisation of yield have been established for wheat and barley in the WA Wheatbelt. However, this information is far from clear for canola and the grain legumes. Further such experimentation is warranted, in multi-locational on-farm trials spanning rainfall environments.
* Previous studies on cultivar differences in ability to compete with weeds have also produced inconsistent results, across location and year. Logically, cultivars with high early growth vigour (EGV) should have an advantage in this regard, at least where soil water is adequate at the establishment phase. However, where soil water is limiting, EGV may result in intra-crop competition for water, ultimately slowing crop growth. Nevertheless, for most crops and in most situations where they are normally grown EGV is considered as a desirable trait – e.g. to more quickly establish an exploitative root system, to minimize soil evaporation, to maximize use of incident sunlight, etc. There is a need for research to assess the scope for exploiting cultivar differences, by comparing cultivars clearly differing in traits such as EGV, tillering/branching pattern, leaf shape, etc. Then it would be possible to more realistically assess whether it would be worthwhile specifically breeding for greater competitive ability with weeds. However, there is a continuing need to screen newly released varieties for their competitive ability to ascertain their value against particular weed backgrounds.
* Inclusion of information on the competitiveness of cultivars along with other information at the time of variety release would benefit growers.
* Although much research has been done in the WA Wheatbelt on rate, placement and timing of fertilizers, it has usually been done in a weed-free situation. There is scope to examine how various manipulations in this regard can influence crop competition with weeds. Rates, placement and timing of fertilizer N for cereals and canola should be most influential.
* Use of wide row spacings, particularly for crops such as lupins, makes inter-row cultivation more feasible. It appears that further machinery development is required to fully exploit this opportunity.
* Studies are required to examine the role of soil applied herbicides on root pruning and changes in crop competitive ability.

***Conclusions***

Sufficient progress has been made in quantifying canopy density and arrangement effects of wheat and barley on competition with weeds, mainly ryegrass and wild radish, to validate this as a viable component of weed management. However, even though they are less competitive with weeds than cereals, more research is required to determine the extent to which canopy density and arrangement of canola, lupin, field pea and chickpea can be manipulated to effectively compete with weeds. Interaction with various crop growing conditions make it difficult to determine consistent cultivar differences in ability to compete with weeds and thus it is suggested that more strategic research is required to identify specific traits conferring competitiveness. Only then would it seem justified to specifically breed for competitiveness, among the other breeding priorities. However, it remains worthwhile to screen new cultivars for their competitive ability, such that this characteristic can be listed along with their other identifying features.

Although crop sowing time and method have been found to influence crop competitiveness with weeds there is little scope for manipulating these factors to specifically address weed management as they are primarily determined by other considerations, such as early season rainfall and equipment available. However, there does appear to be scope for adjusting rate, placement and timing of fertilizer, particularly N, application so as to favour crop seedlings over weeds.

A more comprehensive dataset from a systematic distribution of sites across the Wheatbelt would be required to assess the effect of climatic factors, or more specifically soil available water, on crop competitiveness with weeds. Similarly, to ascertain effects of soil type, and distinguish them from climatic effects, experiments would need to be done on contrasting soil types at the same location. However, it is suggested that there is further information to be gained on crop rotational effects on weeds and their susceptibility to crop competition by a retrospective assessment of weed dynamics in different rotations in farmers’ fields and long-term trials.

In view of the many possible components of weed management, chemical and non-chemical, it is necessary to practically and economically fit current knowledge on crop competition effects on weeds into an IWM package. Further, this IWM package needs to be integrated into an ICM package. This would require comprehensive involvement with grower groups and individual growers, and a continued monitoring of outcomes to identify most appropriate combinations of factors.

### 6.2.2 SOUTHERN REGION

***Summary***

Crop competition research has not been as common as might have been expected, particularly detailed replicated research. Up until recently the availability of cheap and effective herbicides reduced the perceived need for non-herbicide weed management tactics, despite the ever increasing levels of herbicide resistance.

It is also obvious from this review that non-herbicide weed research is more difficult than herbicide experiments due to high levels of variability in weed numbers, as well as being labour intensive and expensive to conduct.

Most research has been conducted on annual ryegrass (*Lolium rigidum*) with six trials on brome grass (*Bromus diandrus*) and three including wild oats (*Avena* spp.). Wild radish is the main broadleaf weed in trials. Mimic weeds such canola, culinary mustard, wheat, triticale or domestic oats have been used in an effort to reduce variability in weed populations.

Most of the row spacing research conducted in the last 30 years has measured crop yield with little work looking at the interaction with weeds (Scott *et al* 2013). There are three reviewed papers on effect of row spacing, or spatial arrangement, in wheat (Auld *et al* 1980; Medd *et al* 1985; Lemerle *et al* 2004), and minimal research in barley (Burke 2009), and pulses (Kleemann & Gill 2007).

Crop density/ sowing rate trials have shown that increasing crop density reduces weed biomass, while the amount of rain in spring has the greatest influence on ryegrass seed production (Medd *et al* 1985; Eslami *et al* 2006; Bennet 2009; Lemerle *et al* 2014). One paper reported that increasing lentil density reduced the seed production of mimic weed canola (McDonald 2007).

The greatest number of papers were related to cultivar effects where they investigated competitive effects of crop on weed biomass and seed production and the tolerance of crop to weed competition. Wheat had the greatest number of papers (Brennan *et al* 2001; Lemerle *et al* 2001; Bennet 2006; Rebetzke *et al* 2007; Zerner and Gill 2010; Egarr *et al* 2014; Weston *et al* 2014). Lemerle *et al* (1995) compared 2 cultivars of wheat, barley, oats, cereal rye, triticale, canola and field peas over two seasons. Porker and Wheeler (2013) as part of the Southern Barley Agronomy Project **(**DAN00173**)** showed there are significant differences in competitive ability and weed tolerance between cultivars. Lemerle *et al* (2014) looked at canola cultivars. Late season height of peas appears to be the main characteristic in reducing ryegrass biomass and seed numbers (Lemerle 2006; McDonald 2007) while McDonald (2007) found no difference between cultivars in reducing the biomass or grain yield of mimic weed canola. McMurray (pers. comm.) believes there are significant cultivar differences in chickpea vigour and ground cover although this hasn’t been tested against weeds.

There has only been one small field experiment on row orientation where there were no consistent results on effect on barley grass and wild turnip (Cook *et al* 2014).

***Introduction***

The GRDC southern region runs from central NSW in the north to the western edge of cropping in South Australia. The region is predominantly mixed cropping and livestock which saw a temporary increase in the proportion of cropping in the early 1990’s due to an over-correction in the wool price. The real driver for the widespread adoption of reduced tillage farming in the last 10 to 15 years was the decline in the price of glyphosate and development of planting equipment better able to handle stubble (Storrie 2014). During this time the proportion of growers in many districts using no-till has plateaued at 90 per cent (Llewellyn & D’Emden 2009).

Rainfall distribution in southern NSW and Victoria tends to be non-seasonal with a trend to winter dominance as you move west into South Australia. There is also an increasing trend for a greater proportion of the rain to fall in summer (Hayman *et al* 2012) which in turn decreases the amount of growing season rainfall.

There has also been a reduction in the number of non-cereal crops in the rotation with a major factor being below average rainfall from 2000 until 2010. Cereal crops are seen as being more reliable and resilient during dry springs. Late ‘breaks’ to the season also reduce the optimum sowing window for lupins, faba beans and canola.

Herbicide resistance has been increasing in the Southern Region on a par with the increase in reduced cultivation farming and the continued use of selective in-crop herbicides.

Broster (2015) gives a good visual summary of herbicide resistance in annual ryegrass across Australia, with Group A ‘fop’ resistance widespread in the Southern Region with resistance to Group A ‘dim’ and Group B chemistry less widespread and some hotspots of trifluralin resistance in south eastern South Australia and western Victoria. Glyphosate resistance in ryegrass is also increasing rapidly (Broster 2014; Preston 2015).

Another growing herbicide resistance threat in the drier areas is the widespread existence of Group B resistant brome grass due to the over reliance on imidazolinone resistant canola, wheat and barley to control this weed (Boutsalis *et al* 2014). There is also widespread resistance to Group B herbicides in sowthistle (*Sonchus oleraceus*) and prickly lettuce (*Lactuca serriola*), while resistance to phenoxy Group I herbicides has been found in Indian Hedge mustard (*Sysymbrium orientale*) and wild radish (*Raphanus raphanistrum*).

It can be clearly seen that multiple weed species have populations resistant to a range of herbicide modes of action and the situation is unlikely to improve despite extension programs promoting better weed management practices to growers and advisers.

Therefore there is an ever-increasing need to incorporate non-herbicide management practices such as crop competition and more varied rotations into the farming systems of the Southern Region.

***Crop Competition Factors***

**Cultivar**

Table . Summary of field trials in the southern region on effects of cultivar on weeds.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Location** | **Year** | **Crop** | **Treatments** | **Weed(s)** | **Conclusion** | **Reference** |
| Roseworthy; Angas; Winulta; Pinnaroo; Rudall; | 2010-13 | Wheat | Various cultivars | Triticale | Measured weed tolerance and suppression of weed seed set. Cultivars with a vernalisation requirement have poor early vigour. Genetics available to make further improvements. | **(9)** Egarr *et al* (2014) |
| Wagga, NSW | 1992-93 | Wheat, barley, triticale, oats, canola, lupin, cereal rye & field pea | 2 cultivars | ARG | Order of greatest to least competitive: oats = rye = triticale > canola > spring wheat = spring barley > field peas = lupins. Only the more competitive crops (oats, rye & triticale) suppressed weed growth and reduced weed seed numbers. Cultivar differences were only noted in the wheat and barley but the barley was season dependent. | **(22)** Lemerle *et al* (1995) |
| Sthn NSW | 1995-97 | Wheat | 12 cultivars | ARG | 80% of variation in yield due to variety x environment interaction; 4% due to weed x variety x environment; Weed x variety 0.3%. | **(17)** Lemerle *et al* (2001) |
| Wagga NSW | 2009-10 | Canola | 16 cultivars | ARG, wheat | Significant differences in competitive ability of canola cultivars. | **(18)** Lemerle *et al* 2014; **(35)** Lemerle *et al* (2015) |
| Roseworthy | 1997-98 | Field pea | Various cultivars | ARG, wheat | Pea height is a major factor in competition with wheat and ARG. Maturity had little effect. Leaf type affected competition before flowering only. | **(24)** McDonald (2002) |
| Minlaton, SA; Horsham, Vic. | 2002-03 | Lentils | Various cultivars | TT canola as mimic - 5 densities | Mimic weed (canola) density on lentil yield. No difference between cultivars on effect of canola growth. Yields declined with increasing canola density. 25 canola plants reduced lentil yield by 30-44% | **(25)** McDonald *et al* (2007) |
| Karoonda, SA | 2013 | Barley | 23 cultivars | *Avena sativa* | More vigorous varieties Fathom and Maritime show superior weed competiveness. | **(29)** Porker & Wheeler (2013) |
| Wagga; Condobolin | 2012-14 | Wheat, barley, oats, canola, rye x1, triticale x1 | Various cultivars | ARG; fleabane; windmill grass; *P. capillare*, fumitory; | Effect of crop growth & stubbles on weed suppression. Fleabane more suppressed in grazing wheat, oats, canola and grain barley stubble. | **(33)** Weston *et al* (2015) |
| Roseworthy | 2010 | Wheat | 12 cvs | ARG, wild oat, *B. juncea* | Wyalkatchem, the most suppressive wheat genotype reduced weed seed production by up to 92%, 65% and 53% for mustard, ryegrass and oats. | **(34)** Zerner & Gill (2010) |

ARG = Annual ryegrass

Brennan *et al* (2001) modelled the economics on introducing selection for wheat competitive ability, looking at what point in the breeding program to introduce the selection. This was relatively early days for herbicide resistance so some of the assumptions such as the length of time for resistance to develop have not been mirrored by experience. The premise was that selecting for competitive crop traits would reduce the rate of cultivar improvement for yield and grain quality, and the earlier in the program this was done the slower the yield improvement due to rejection of a greater number of lines. However current breeding programs have identified the main trait of coleoptiles length confers improved competitive ability and can be selected earlier in the breeding program without slowing yield improvement (Rebetzke *et al* 2007).

Lemerle *et al* (2001) compared 12 wheat cultivars over 3 years at 7 sites in southern NSW and found that crop grain yield was not a good measure of competiveness with weeds with over 80 per cent of the yield variation due to cultivar x environment interactions. This was confounded by the difficulty in establishing consistent weed populations between sites and years.

Over 6000 wheat lines have been evaluated for competitive ability and vigour by the University of Adelaide at Roseworthy. As part of this project Zerner and Gill (2010) studied the competitive ability of 14 lines of wheat at a density of 200 plants m-2 in the presence annual ryegrass, wild oats and the faux weed *Brassica juncea*. Wyalkatchem was the most suppressive cultivar reducing weed seed production by up to 92 per cent, 65 per cent and 53 per cent, in mustard, ryegrass and oats respectively. The degree of weed tolerance of wheat genotypes varied with weed species, with grain yield losses ranging between 3-21 per cent in mustard, 18-49 per cent in ryegrass and 39-63 per cent in oats. Genotypes with high tolerance to weeds were also likely to have high suppressive ability on weeds.

This project has now been transferred to Rebetzke, CSIRO (CSP00182), who will cross Cycle 5 and 6 lines with current cultivars, although to-date these lines haven’t been tested against weeds.

On the Eyre Peninsula Bennet (2006) found there was a significant interaction between crop density and wheat cultivar with cv Wyalkatchem being the most competitive of the 4 cultivars trialled. This cultivar produced the highest level of suppression of ryegrass and the highest grain yields. Similar work was conducted in 2008 and 2009 with 4 cultivars sown at 180, 300 and 400 plants m-2. Crop yield increased with density and there were significant difference in yield between cultivars although this had no effect on ryegrass seed set due to the wet spring.

Egarr *et al* (2014) investigated wheat cultivar competition with the mimic weed cereal rye, at 5 sites over 4 years in South Australia. They found that cv Axe gave the best suppression of weed seed set while cv Gladius showed the best yield tolerance. Cultivars that required vernalisation performed poorly against weeds. Cv Yitpi yielded well however was poor at suppressing weeds.

Weston *et al* (2014 & current) conducted trials at Condobolin and Wagga comparing two contrasting cultivars (grazing & non-grazing) of wheat, barley, oats, canola and rye/triticale. In-crop weed data is being gathered but the most of the available data relates to possible allelopathic effect of stubble. Data shows similar in weed suppression by stubbles and crop yield. Witchgrass (*Panicum capillare*) is suppressed more by the stubble of grazing wheat and triticale while fleabane (*Conyza* spp.) was more suppressed in the stubble of grazing wheat, oats, canola and grain barley. Wheat appears to rely on early vigour and canopy competition although the suppressive ability of stubbles differ with cultivar. Canola crops appear to have some in-crop suppressive ability, however stubbles can suppress some weeds for 3 to 5 months. To-date Hyola 50 is the most promising line.

The above project UCS00200 will run for another 4 years and is part of James Mwendwa’s PhD thesis.

Work by Lemerle *et al* (1995) over two consecutive years at Wagga compared barley cultivars Skiff and O’Connor in the presence of 300 ryegrass plants m-2 and found that Skiff had a 43 per cent reduction in yield compared with 10 per cent for O’Connor, while in the second year both cultivars lost over 50 per cent yield. Ryegrass produced 50,000 seeds m-2. Barley appears a poor competitor with ryegrass in these trials probably due to acidic soils. Seasonal conditions or an explanation why the huge differences in yield loss for cultivar O’Connor between years were not explained.

The Southern Barley Agronomy Project **(**DAN00173**)** aimed to add value to the NVT system and test the response or sensitivity of varieties to agronomic practices by comparing the yield and quality responses of new varieties, under a range of management practices and environments, including how these lines react to weed competition.

Porker and Wheeler (2013) found there are considerable differences between the competitive ability of barley cultivars from trials conducted in South Australia at Turretfield (2011-13) and in Karoonda in 2013. Semi-dwarf cultivars have less competitive ability and are more similar to wheat in their ability to compete with weeds. Some cultivars lack early vigour while tall varieties with early vigour can reduce weed seed set by 50 per cent more than semi-dwarf cultivars whole maintaining high yields.

Work by Lemerle *et al* (1995) over two consecutive years at Wagga Wagga found that there were only minor differences between grain yield in the presence of ryegrass for oat cultivars Echidna (semi-dwarf grain) and Coolabah (mid-season grazing-grain) for both years.

Cereal rye and triticale were found to be similar in response to presence of annual ryegrass and there were significant differences in grain yield between cultivars Tahara and Muir in the dryer year, but not the wetter year (Lemerle *et al* 1995).

Lemerle *et al* (1995) found significant differences in grain yield between canola cultivars Barossa and BLN555 in response to ryegrass competition in a wet year but no differences in a dry year.

Recent work by Lemerle *et al* (2014) shows large differences in the competitive ability between canola genotypes with ryegrass and volunteer wheat. Crop yield tolerance was best in vigorous hybrid cultivars and there were significant differences between seasons with ryegrass causing more yield loss across genotypes in a dryer year. There was a weak correlation between crop tolerance to weeds and weed suppression.

This could be explained by the fact that canola tends to be a good compensator for yield in the presence of weeds. A wet spring allows canola to produce more grain while having little effect on weed biomass or weed seed production.

A range of trials have been conducted looking at the competitive ability of field peas against weeds. There are significant differences in competitive ability between pea genotypes and McDonald (2003) found that tall cultivars reduced biomass of ryegrass and wheat more than shorter cultivars. Crop maturity had little effect on competitive ability, although shorter season cultivars give more opportunity for reducing weed seed set through crop topping and harvest seed management.

One trial in the early 1990s compared cultivars Dundale and Dinkum in a ryegrass population of 300 plants m-2 and found the peas were choked out by the grass (Lemerle *et al* 1995).

Lemerle *et al* (2006) compared a conventional cultivar with a semi-leafless field pea cultivar at 18 and 36cm row spacings and 3 sowing rates. The conventional cv Dundale reduced weed biomass the more than the semi leafless cultivar, while weed biomass decreased slightly with increasing pea seeding rate. Pea yield also increased with seeding rate.

McMurray (pers. comm.) outlined the dilemma of trying to use crop competition in pulses was that early vigour leads to dense canopies where shading leads to leaf senescence and crop disease. The only viable characteristics are late season competition to reduce weed seed set. The main characteristic for late season competition in pulses is crop height.

McDonald *et al* (2007) used 4 differing lentil genotypes to compare the effect of mimic weed (canola) at 4 densities on yield and the effect of 4 lentil sowing rates on canola. There were no differences between cultivars on effect of canola growth, although canola yield was reduced with increasing lentil density. Lentil yields declined with increasing canola density with 25 canola plants reducing lentil yield by 30-44 per cent. While early lentil vigour did not affect canola yield it increased lentil yield.

The canola cultivar used was a less competitive line and yield losses would have been higher by using a more vigorous canola cultivar.

McMurray (pers. comm.) said that there are significant chickpea cultivar differences in vigour and ground cover according to trials conducted in South Australia, however too much early vigour leads to disease problems.

**Crop density and seeding rate**

Table . Summary of field trials in the southern region on effects of crop density/seeding rate on weeds.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Location** | **Year** | **Crop** | **Treatments** | **Weed(s)1** | **Conclusion** | **Reference** |
| Ungarra, SA | 2006 | Wheat | 80, 140, 200 kg/ha | ARG | Significant difference in ARG seed set between 160 and 240 wheat plants/m2. No difference for ARG plant numbers. | **(3)** Bennet (2006) |
| Lower EP, SA | 2009 | Wheat | 180, 300, 450 plants/m2 | ARG | Waterlogged acid soils gave ARG upper hand. Crop density and cv had no effect on ARG parameters. | **(4)** Bennet (2009) |
| Roseworthy, SA | 2003-04 | Wheat | 100, 200, 400 plants/m2 | Radish  0, 15, 30, 60 plants/m2 | Wheat density had major effect on yield loss from radish as did radish density on wheat. | **(10)** Eslami *et al* (2006) |
| Sthn NSW | 1999-2000 | Wheat | 18, 36 cm  80-700 plants/m2 | ARG | ARG suppressed at higher crop densities but unaffected by row spacing. | **(21)** Lemerle *et al* (2013) |
| Sthn NSW | 1993 & 95 | Field peas | 18, 36 cm  80, 160, 240 kg/ha (1993); 61, 123, 184, 246 kg/ha (1995) | ARG | No effect of row spacing. Impacts from higher seeding rates on weed suppression were relatively small but weed biomass did reduce as crop density increased. The impact was greater in the taller cultivar. Field peas will need other weed mgmt tactics in conjunction with crop competition. | **(23)** Lemerle *et al* (2006) |
| Manildra, NSW | 1975-80 | Wheat | 40, 75, 150, 200, 400 plants/m2 | ARG | The effect of ryegrass was substantially reduced by increasing wheat sowing density from 40 or *75* to 200 plants m-2. | **(26)** Medd *et al* (1985) |

ARG = Annual ryegrass

Medd *et al* (1985) found that the effects of ryegrass competition on yield was greatly reduced by increasing wheat density from 40 or 75 plants m-2 to 200 plants m-2 across a range of spacial arrangements.

On the lower Eyre Peninsula Bennet (2009) found that by increasing wheat density of 4 cultivars from 180 plants m-2 through to 450 plants m-2 increased yield by 0.8 to 1 t ha-1under heavy competition from ryegrass in a wet spring.

Nine trials from Wagga to Wongan Hills over two seasons showed at least 200 plants m-2 was required to suppress ryegrass over a range of seasons and doubling density from 100 to 200 plants m-2 reduced ryegrass dry matter by 50 per cent. Wheat yields declined on average by 5 per cent at 425 plants m-2. Cultivar differences were not significant and grain quality did not decline at these high seeding rates (Lemerle *et al* 2004).

Eslami *et al* (2006) investigated the interaction between wheat at 0, 100, 200 and 400 plants m-2 with wild radish at 0, 15, 30 and 60 plants m-2 over two seasons. At the highest radish density wheat dry matter was reduced by 50 per cent and 20 per cent at 100 and 400 wheat plants m-2 respectively. Wheat grain yield followed similar trends. There was no decline in wheat yield with increasing wheat density. Increasing wheat density reduced radish dry matter and seed production with high wheat densities reducing radish seed production from approximately 61,000 to 7,100 seeds m-2 with a wet November-December.

McDonald *et al* (2007) found that mimic weed (canola) yield was reduced with increasing lentil density in three trials over 2 years.

**Row Spacing**

A great deal of row spacing research has been conducted however the majority of work has not studied its interaction with weeds (Scott *et al* 2013).

Table . Summary of field trials in the southern region on effects of row spacing on weeds.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Location** | **Year** | **Crop** | **Treatments** | **Weed(s)** | **Conclusion** | **Reference** |
| Birchip, Vic. | 2005 | Wheat,  barley | 18, 35 cm | ARG, Brome, WO | Narrow rows gave significant reduction in weed biomass. No effect on crop yield or quality | **(1)** Anon (2005) |
| Manildra, NSW | 1978-80 | Wheat | Rhomboidal, square and rectangular planting configuration. | ARG | Looks only at impact on crop yield. Square sowing resulted in significant yield increases over rectangular arrangements in one experiment. There was a consistent significant trend over all experiments over 3 years, of decreasing yield with increasing rectangularity as density was decreased. | **(2)** Auld *et al* (1983) |
| Woomelang; St Arnaud | 2009 | Barley | 15, 22.5, 30cm | ARG, Brome grass | Row spacing effects on yield were negligible in a year with a dry spring. However, significant effects on plant density, shoot density and brome grass populations were observed. | **(5)** Burke 2009 |
| Roseworthy | 2006 | Wheat, barley, faba bean | 18, 36, 54 cm | ARG | Dry season. Yields for cereals @ 18 cm > 36 + 54 cm. Faba yield higher at 36 + 54 cm. | **(16)** Kleemann & Gill (2007) |
| Wagga Wagga | 1997-98 | Wheat | 18, 36 cm  5 densities (80 to 700 plants/m2) | ARG | ARG suppressed at higher crop densities but unaffected by row spacing in the presence of herbicide. | **(21)** Lemerle *et al* (2013) |

ARG = Annual ryegrass

Serious attempts to quantify the effect of row spacing on crop competitive ability with ryegrass began in Australia in the late 1970s where four trials were conducted near Manildra, NSW, over 3 years looking at the spacial arrangement of wheat plants and its effect on crop yield and ryegrass biomass (Auld *et al* 1983). The main conclusion of the first paper was that “square patterns” of plant placement will give higher yields than rectangular placement as the wheat population drops below 200 plants m-2.

Medd *et al* (1985) using the same data set concluded there was little effect of spacial pattern on weed competition, when expressed as crop yield, however there was a greater effect on ryegrass dry matter by increasing crop density from 40 or 75 to 200 plants m-2.

Lemerle *et al* (2013) suggested from two trials with row x seeding rate x herbicide rate interactions that seeding rate and therefore crop density were more important than row spacing in competition with ryegrass in the presence of post emergent herbicides. All treatments still contained ryegrass at crop maturity.

Trials at Birchip and Marnoo, Victoria, compared wheat and barley at two row spacings and two plant populations on the interaction with ryegrass, brome grass and wild oat. Row spacing did not affect yield or quality of wheat, however barley had higher yields at 18 cm spacing compared with 35 cm spacing. At the Birchip site, where weed populations were significantly higher than the Marnoo site, narrow rows reduced weed biomass significantly, wheat at 250 plants/m2 giving significant reductions in weed biomass at 18 cm row spacing. Barley was equally suppressive at both densities at 18 cm spacing and positively correlated at 250 plants m-2 at the 35 cm spacing.

A trial at Woomelang, Victoria, compared the effects of 15, 22.5 and 30 cm rows by 4 cultivars where brome grass density was reduced from 28 plants m-2 at 30 cm rows to 12 plants/ m2 with 15 cm rows. The same trend was observed prior to harvest with 66 to 21 brome grass heads/m2. Cultivar differences were inconclusive (Burke 2009).

Wider row spacing in pulse crops have been shown to have little negative effect on yield in the absence of weeds. Kleemann and Gill (2007) found that increasing spacing to 54 cm from 18 or 36 cm increased the yield of faba bean in the absence of weeds whereas where ryegrass was not controlled the wider row crop yielded less than 160 kg ha-1. They felt that the wider rows stimulated fewer ryegrass plants to germinate and establish while shifting the period of major water use to later in the season produced more pods per plant.

Wide rows also allow other weed control opportunities such as inter-row shielded spraying of knockdown herbicides or cultivation, although the current registrations of herbicides for such uses are limited. Better airflow reduces humidity reducing disease pressure. It may also facilitate better spray coverage of fungicides and insecticides.

**Rainfall zones**

The low rainfall zone appears to be well serviced with SARDI linking up through the GRDC funded Low Rainfall Collaboration Project picking of groups from Condobolin in NSW to Minnipa in South Australia. Much of this work has been looking at the effects of break crops on the major grass weeds annual ryegrass and brome grass. However, as mentioned in the crop sequence section much of the weed data is confounded by herbicide use.

The higher rainfall areas of south east of NSW and south east South Australia is where the CSIRO is doing much of its crop sequence work.

### 6.2.3 NORTHERN REGION

***Summary***

Over the past five years, very little field research has been conducted in the northern grain region (NGR) on utilising crop competition for management of key weeds (e.g. fleabane, awnless barnyard grass, feathertop Rhodes grass, sowthistle, annual ryegrass, wild oats, liverseed grass, sweet summer grass) in the major grain and oilseed crops (sorghum, sunflower, mungbean, wheat, barley and chickpea). For the 10 year period (2000-2010) prior, some research had been undertaken in sorghum, sunflower, wheat and chickpea with focus predominantly on row spacing and crop population/density impacts. Most of these studies utilised *mimic* species rather than specific problem weeds. Much of the crop competition research undertaken pre-2000 (and some into the early 2000s) was centred on measuring impacts on crop yield rather than on weed numbers, biomass or seed production.

There have been no major specific crop competition studies on the individual key weeds except for wild oats (Radford *et al* 1980; Martin *et al* 1987; Walker *et al* 2002; Whish *et al* 2002). Minor or one-off studies have been conducted for sweet summer grass (Osten, project report 2002), feathertop Rhodes grass (Osten 2011), sowthistle (Widderick 2002), fleabane (Brill *et al* 2012), paradoxa grass (Walker *et al* 1999) and awnless barnyard grass (Felton 1976; Holland and McNamara 1982).

There has been no crop competition for weed control research undertaken in the region inmungbean, maize, oats, lupins and field peas. The major focus has been in sorghum (Holland and McNamara 1982; Osten unpublished/project reports 2002-05; Osten *et al* 2006; Wu *et al* 2010), sunflower (Osten *et al* 2006; Osten unpublished/project reports 2003-04 and 2006-07), wheat (Radford *et al* 1980; Martin *et al* 1987; Walker *et al* 1999; Osten unpublished/project reports 2000 and 2002; Walker *et al* 2002; Widderick 2002; Felton *et al* 2004; Brooke and Cook 2015) and barley (Walker *et al* 1999; Osten unpublished project report 2000; Widderick 2002; Brooke and Cooke 2015). Minor and or one-off studies have been undertaken in or included triticale (Brooke and Cook 2015), chickpea (Whish *et al* 2002; Felton *et al* 2004), soybean (Felton 1976), faba bean and canola (Felton *et al* 2004) and buckwheat (Van Ryswyk *et al* 2004). The buckwheat study focused on night cultivation rather than any crop competition attribute, although the study did show that buckwheat is a very competitive crop due to its rapid growth and thick canopy.

Generally and in most cases, narrowing row widths and increasing crop densities impacted positively by reducing weed numbers, weed biomass and or weed seed production across the studies.

***Introduction***

The northern grain region of Australia covers irrigated and broad-acre dryland grain production areas from Dubbo and the Liverpool Plains areas in the south of the region (southern-central New South Wales) to Clermont in the north (northern Central Highlands of Queensland). The northern region is sub-tropical, receiving both summer and winter rainfall. The more northern areas are summer dominant and then this becomes more winter dominant further south. Major winter crops in the region are wheat, barley and chickpea and major summer crops are sorghum and mungbeans, with cotton also a feature. However, many other crops are also able to be grown in the region, offering opportunity for regular crop and herbicide rotation.

Conservation agriculture continues to dominate crop production systems and as such heavy reliance is placed on herbicides for fallow and in-crop weed management. As a result, there are 23 weed species confirmed as resistant in the northern region (Heap 2015). Therefore, farmers are seeking non-chemical approaches for weed management to improve the control of herbicide resistant weeds and to preserve key herbicides for future use. Current research into non-chemical approaches includes burning for depletion of seed banks (e.g. Feathertop Rhodes grass), harvest weed seed control for destruction of weed seeds at harvest, and strategic tillage to manipulate seed banks.

Crop competition is another non-chemical/cultural tactic used in the northern region to improve the efficacy of weed control in crop, but its use is not common place. In contrast, wide row cropping is common in summer crops, especially in central Queensland, where moisture can be a limiting factor to summer crop production. Wide row crops enable inter-row weed control by way of shielded application of herbicides or inter-row cultivation. However, wide row crops offer little to no crop competition and can therefore present an opportunity for weed proliferation if inter-row practices are not successful.

***Crop competition factors***

The crop competition factors covered in this review include row spacing, row orientation, crop density and seeding rate, varietal differences, rotation, sowing time and depth and nutrition.

**Cultivar**

Two studies have been conducted in the NGR on the competitiveness of sorghum cultivars, one in southern Queensland (SQ) and one in central Queensland (CQ) during the 2000s. While both studies contained some identical cultivars, the responses were not the same for the cultivars in common.

Wu *et al* (2010) conducted studies in SQ in 2003 and 2004 to determine the differential competitiveness of six sorghum cultivars (*Pacific MR43, 85G83, 86G87, Bonus MR, MR Buster* and *MR Goldrush*) with Jap millet (*Echinochloa esculenta*) sown as a *mimic* *weed* for awnless barnyard grass (*E. colona*). The cultivars were sown on 1 m row spacings at 3 densities (4, 6 and 7.5 plants/m2). They reported that the early growth traits of height, shoot biomass and daily growth rate of the sorghum adversely affected the height, biomass and seed production of the mimic weed. *MR Goldrush* and *Bonus MR* were determined as the most competitive cultivars having the least weed seed produced. The cultivars were ranked as follows (most to least competitive): *MR Goldrush / Bonus MR / Pacific MR 43 / 85G83 / MR Buster / 86G87.* The results suggested that the rapid early crop growth was the contributing critical factor for competition against the millet.

The CQ study (Osten 2007a) was undertaken in 2002 in a growers paddock and utilised the natural sweet summer grass (*Brachiaria eruciformis*) densities present (moderate to high at ~ 50 plants/m2). The trial evaluated cultivars *Bonus MR* (a full season or slow cultivar), *85G83* (a medium cultivar) and *86G87* (a quick cultivar) sown at several densities (25, 41, 57 and 71 000 plants/ha) on three row configurations (0.75 m solid, 1.5 m solid and 0.75 m double skip). When the data were pooled for crop density and row configuration, the competitive ranking of the cultivars (most to least competitive, according to mean weed numbers present and percent ground cover) was as follows: *86G87 = 85G83 > Bonus MR*. While this result is directly opposite to the competitive ranking in the Wu *et al* (2010) study, it does reflect the maturity length of the cultivars – the quickest was the most competitive and the slowest was the least competitive. The differences between the studies may have something to do with location (cultivar behaviour in the environment, season) and the target weed species (competitiveness).

While several studies have been undertaken on weed competition in sunflower in the NGR, only one study has examined cultivars for competitiveness. The study by Osten (2007b) (also reported in Osten and Wu 2006) compared cultivars *Hysun 38* and *Hysun 47* at various row spacings and densities against a natural suite of low density broadleaved weeds. In this instance no significant difference existed between the cultivars for impact on final weed biomass when data were pooled for crop density and row spacing, although *Hysun 38* had less weed biomass and appeared to be a more robust cultivar in this trial. It is possible and probable that cultivar differences in terms of competitiveness might be detected under higher weed density situations.

In contrast to the southern region, very little research on wheat and barley varieties for weed competition has been undertaken in the northern region, and the work that has been undertaken has been confined to the Tamworth – Trangie areas of New South Wales.

Brooke and Cook (2015) reported on trials conducted in Trangie during 2014. In the row orientation trial reported above, they found no differences between the barley cultivars *Commander* and *La Trobe* with both having similar levels of weed biomass present at time of measurement. The *EGA Gregory* wheat cultivar was more competitive than *Lancer* but not significantly so. However, they did record significantly less weed biomass in the barley cultivars compared to the wheat cultivars, indicating barley to be more competitive than wheat.

In a barley competition trial conducted in 2014 and also reported in Brooke and Cooke (2015), eight barley cultivars (*La Trobe, Scope, Compass, Commander, Granger, Buloke, Gardiner* and *Urambie*) were evaluated along with two wheat varieties (*Spitfire* and *Sunvale*) and a single triticale cultivar (*Canobolas*) for impacts on weed yields (sown oats in this case). All crops and cultivars were sown at 100 plants/m2. The single triticale cultivar *Canobolas* was as competitive as the best barley cultivars (*Granger, Compass, Scope* and *La Trobe* which were all equal). Next competitive barley cultivar was *Gardiner* which was similar to *Commander* and both were significantly better than *Buloke*. *Urambie* was significantly least competitive of the barleys. The triticale was significantly more competitive than both the wheat cultivars and the *Spitfire* wheat was significantly better than *Sunvale* wheat.

Varieties/cultivars for most crops change regularly so this may be a reason why little effort has been invested in weed competition studies using varieties. Many varieties tend to be district specific so their application for weed competition will be constrained and the returns on dollars invested in such research will be limited.

Table . Summary of field trials in the northern region on effects of cultivar on weeds.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Location** | **Year** | **Crop** | **Treatment** | **Weed(s)** | **Conclusion** | **Reference** |
| Central and Northern NSW | 2014 | Wheat, barley | 2 wheat, 8 barley cultivars | Oats as mimic | Varietal differences evident | **(2)** Brooke and Cook (2015) |
| Southern Queensland | 2003-05 | Sorghum | 6 cultivars | Millet as mimic | Two cultivars were more competitive | **(20)** Wu *et al* (2010) |

**Crop density and seeding rate**

Most crop density / seeding rate studies in sorghum have been undertaken in conjunction with row spacing studies. These combined studies make up most of the crop-weed competition research undertaken in the NGR over the past 25 years and is not just confined to sorghum.

The *Belvue* sorghum study in CQ in 2002 showed that as sorghum population increased from 25 000 through to 71 000 plants/ha, the numbers of sweet summer grass plants reduced (50 down to 30/m2) with data pooled for variety and row spacing (Osten, 2007a). A 2003 CQ study using mungbean as a mimic broadleaf weed in sorghum sown at 6, 9 and 12 plants/m row showed little difference in weed biomass across the sorghum density range, however weed biomass measured from the row out to 25 cm decreased as crop density increased; a similar trend was noted for the positional biomass located 25 to 50 cm out from the crop row, however the differences between the crop densities was much less (Osten and Wu 2006).

Later (2005) CQ studies using Jap millet as a mimic weed also showed that weed biomass and weed seed production decreased for weeds located within 25 cm of the row as crop density increased from 6 to 12 plants per metre of row (Osten 2006). Similar studies in SQ showed little impact from increasing crop density in one trial (Osten and Wu 2006) but significant differences were recorded in a second trial (Wu *et al* 2010). In the latter, sorghum was grown at 4.5, 6 and 7.5 plants/m2. The high crop density (7.5 plants/m2) was more competitive than the lower densities, reducing the weed density by 22%, the weed biomass by 27% and weed seed production by 38%.

Three trials have been conducted in CQ evaluating crop population (as well as other factors) for competitiveness against the natural suite of weeds present at the trial sites. In all instances, weed densities were considered to be low. In the first trial (2003) weed biomass was not significantly impacted by crop populations of 30 000 and 45 000 plants/ha; similarly in the second trial (2004) no weed biomass impacts were noted for crop populations of 30, 45 or 60 000 plants/ha (Osten 2005). However, in the third trial weed biomass was significantly greater (3-fold increase) at the lowest crop population of 9000 plants/ha, but no differences were recorded at the commercially accepted populations of 18, 25 and 32 000 plants/ha. Across all trials there was a trend for more weeds as crop population decreased (Osten 2007b).

One study has been undertaken in the NGR on the relatively minor crop of soybean and this was reported by Felton (1976). He measured less weed biomass (thornapple, barnyard grass, common pigweed) at in-row crop densities of 40 plants/m compared to in-row densities of 10 plants/m but suggested the greatest weed impacts (greatest reductions) were a result of row spacing rather than crop density.

Most work on seeding rate and crop density in the NGR has centred on wheat.

Early work (1968 through to 1974) by Radford *et al* (1980) on the Darling Downs showed increased wheat seeding rate reduced the biomass of wild oats and also the seed production especially at low weed densities. The authors concluded that a wheat seeding rate producing 150 plants/m2 provided some degree of low-cost wild oat control; and that crop populations below 150/m2 were susceptible to wild oat competition.

At the same time (1968/69) in the Tamworth area, Martin *et al* (1987) conducted two trials in wheat with 6 crop densities across the trials also sown with varying wild oat densities. They found that increasing the density of wheat did not always result in reduced wild oat numbers, but competition from wild oats could be reduced by increasing the wheat seeding rate.

Later work by Walker *et al* (1999) showed that the inclusion of strategic tactics such as including barley in rotations and or increasing wheat seeding rates produced increased crop competition against paradoxa grass – these strategies applied over three years resulted in 97 % seedbank depletion. They also allowed for reduced dependence on herbicides in the system. This work led to further research (through 4 trials) (Walker *et al* 2002) to determine the effectiveness of crop competition for better weed control in conjunction with reduced herbicide rates for the management of wild oats and paradoxa grass in wheat. They concluded that paradoxa grass seed production could be reduced with 80 wheat plants/m2 and with 100 % herbicide rate. For wild oats, this was achieved with 130 wheat plants/m2 and 75 % herbicide rate. Alternatively, these same weed reductions could be achieved with 150 wheat plants/m2 and 50 % herbicide rate. They effectively demonstrated that herbicide rates could be reduced when coupled with competitive cropping (higher crop seeding rates).

Similarly in CQ, Osten and McCosker (2002) found that if crop populations of wheatand barley were kept high (100 plants/ha), herbicide rates could effectively be halved and excellent weed control could still be achieved. In some instances, barley at high seeding rates (and narrow row spacings) did not require any herbicides for effective weed control to be achieved. The main weeds of this trial included African turnip weed (*Sisymbrium thellungii*), New Zealand spinach (*Tetragonia tetragonoides*), Mexican poppy (*Argemone mexicana*), fireweed (*Senecio brigalowensis*) and common sowthistle (*Sonchus oleraceus*).

Another wheat –weed competition trial was undertaken in CQ (Osten *et al* 2002) with chickpea sown as a mimic weed. Four wheat populations (50, 75, 100 and 125 plants/m2) were sown and the chickpea weed established fairly evenly across the trial at 31 plants/m2. Early weed biomass measurements showed the wheat density to have no impact but this was not the case for weed seed yield – weed seed production decreased as crop density increased and greatest weed seed reductions occurred at wheat densities at or above 100 plants/m2.

More recent studies have been minor. Widderick (2002) showed a competitive crop such as barley or wheatsown at high densities (> 100 plants/m2) greatly reduced the number, biomass and potential seed set of common sowthistle (*Sonchus oleraceus*). In contrast, Brill *et al* (2012) found no positive impacts on subsequent fleabane (*Conyza bonariensis*) populations post-harvest when wheat was sown at a range of densities from 50 through to 200 plants/m2. In the most recent study, Brooke and Cook (2015) showed that doubling the seeding rate in barley cultivars *La Trobe* and *Scope* from 100 to 200 plants/m2 resulted in greater than 50 % reductions in weed biomass with oats as the mimic weed.

In nearly all instances except that of Brill *et al* (2012), increasing crop density resulted in a positive impact on the weeds - reducing either numbers, biomass and or seed production.

Table . Summary of field trials in the northern region on effects of crop density on weeds.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Location** | **Year** | **Crop** | **Treatment** | **Weed(s)** | **Conclusion** | **Reference** |
| Trangie | 2011 | Wheat | 50, 100 plants/m2 | Fleabane | Crop density had no significant effect on fleabane number/m2 | **(1)** Brill *et al* (2012) |
| Central and Northern NSW | 2014 | Wheat, barley | 100, 200 plant/m2 | Oats used as mimic | Increased competition at higher crop density | **(2)** Brooke and Cook (2015) |
| Tamworth | 1971 | Soybean | 10, 20, 40 plants/m | Awnless barnyard grass, Datura, Portulaca | Less weed biomass where in-row crop density was 40 compared to 10/m; but row spacing was a greater influence. | **(3)** Felton (1976) |
| Tamworth | 1968-69 | Wheat | 11,22, 44, 66, 88 kg/ha | Wild oat | Competition from the wild oat reduced by increasing seeding rate | **(6)** Martin *et al* (1987) |
| Gindie | 2002 | Sorghum | 30, 50, 70, 90 thousand seeds /ha | Sweet summer grass | Crop seeding rate had no significant impact on weed number | **(7)** Osten (2007a) |
| Emerald | 2003-07 | Sunflower | 10, 20, 30, 35, 40, 45 plants/m2 | Unknown | Low crop populations had significantly greater weed growth | **(8)** Osten (2007b) |
| Emerald | 2003 | Sorghum | 6, 9, 12 plants/m row | Mungbean as mimic | Crop density did not have significant impact on weed biomass | **(9)** Osten (2006) |

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Wowan | 2000 | Wheat, barley | 50, 100 plants/m2 | Unknown | High crop populations had fewer weeds. If crops populations are high, herbicide rate can be halved in wheat or not needed at all in barley | **(11)** Osten & McCosker (2002) |
| Emerald | 2002 | Wheat | 50, 75, 100, 125 plants/m2 | Chickpea as mimic | Crop population had no impact on early weed biomass. Weed seed yield was significantly less as crop population increased | **(12)** Osten *et al* (2002) |
| Darling Downs | 1968-74 | Wheat | Various 29 – 476 plants/m2 | Wild oat | Increases in seeding rate reduced the yield and seed production of wild oats | **(14)** Radford *et al* (1980) |
| Toowoomba | 1996 | Wheat, barley, chickpea, lupin | 75,100,150 plant/m2, 30/m2 for chickpea | Paradoxa grass | Focus is on crop rotation so difficult to extract clear effect of crop density. | **(16)** Walker *et al* (1999) |
| Southern Queensland | 1996-98 | Wheat | 50, 100, 150 plants/m2 | Paradoxa grass | Herbicide rates can be reduced in the presence of high crop densities | **(17)** Walker *et al* (2002) |
| Darling Downs | 2001 | Wheat, barley | 50, 75, 100, 150 plants per m2 | Sowthistle | Either crop at high crop density (≥100 plants/m2) greatly reduced weed numbers, biomass and seed set potential | **(19)** Widderick (2002) |
| Southern Queensland | 2003-05 | Sorghum | 44.5, 6, 7.5 plants/m2 | Millet as mimic | Higher crop density resulted in fewer weeds and less seed production | **(20)** Wu *et al* (2010) |

**Row spacing**

Between 1971 and 1974 Holland and McNamara (1982) conducted 6 field experiments examining row spacing in sorghum in northern New South Wales. Weed densities at two of the sites were very low. They found across the trials that weed growth generally increased with wider row spacings reflecting less competition from the sorghum but this was only significant in the first experiment.

Nearly 30 years later in 2002, the next sorghum row spacing – weed study in the NGR was undertaken in central Queensland (CQ) by Osten (2007a). Several sorghum cultivars were grown at several densities on three row spacings – 0.75 m solid, 1.5 m solid and 0.75 m double skip configurations (the latter had two rows 0.75 m apart followed by a gap of 2.25m created by the double skip then another two rows 0.75 m apart and so on repeated across the paddock). The intention behind the ultra-wide (double skip) spacing is to store soil water in the inter-row in water limiting environments as an attempt to guarantee some yield should no in-crop rain be received. Results from this trial showed no differences in sweet summer grass (*Brachiaria eruciformis*) weed numbers in the wider spaced rows but a significant reduction (~ 40 %) occurred in the narrowest row spacing.

During the early-mid 2000s further sorghum row spacing research was undertaken simultaneously in both southern and central Queensland (Osten *et al* 2006). All five trials (3 in CQ and 2 in SQ) included sorghum grown on 1 m solid, 1 m single-skip and 1 m double-skip configurations. Weed biomass was measured in all trials but weed seed production was only measured in four of the six trials. In all trials, mimic weeds were used (mungbean in first CQ trial then Japanese millet in the remaining 4 trials). Weed biomass increased as row spacing widened (except in the trial utilising mungbean as the mimic weed). Weed seed production responded the same. In SQ, weed seed production increased 2.2 to 2.5 fold when moving from solid to double skip configurations. In CQ, this was a 3 to 7 fold increase. Overall, weed seed production was greater in the SQ environment (up to 152 600 seeds/m2 *cf*. 37 400 seed/m2 in CQ).

Four CQ located trials conducted in 2003, 2004 2006 and 2007 examined the competitiveness of sunflower grown at a range of row spacings from 0.5 m out to 1.5 m (Osten 2007b). These trials utilised the natural suite of weeds at the sites and in all cases the weed density was low. Weed biomass was measured in all trials but weed number was only recorded in the two latest trials. Row spacing had no impacts on weed biomass in any trial but in did have significant impact on weed numbers in the trials where this parameter was measured. In both trials as row spacing widened, weed numbers increased (either doubled or tripled moving from 0.5 m to 1.5 m). Weed seed production was not measured.

The single study on soybean conducted by Felton (1976) showed that less weed growth occurred in the 0.5 m rows compared to the 1 m rows.

Whish *et al* (2002) examined the effect of row spacing and weed density on chickpea in two trials in 1996 – 1997. They grew the chickpea on either 32 or 64 cm rows in the presence of wild oats and turnip weed at a range (0 – 32 plants/m2) of weed densities. Their results showed no significant or measurable advantage from growing chickpea on the narrower rows.

Felton *et al* (2004) conducted three trials with a range of crops including chickpea, faba bean, canola and wheat with all grown on 32 and 64 cm rows in the presence of weeds (triticale as a mimic for wild oat) sown at densities of 0, 3, 9, 27 and 81 plants/m2. Unfortunately the paper failed to report any impacts of row spacing on the weed but focused on the weed impacts on yield.

Osten and McCosker (2002) conducted an IWM trial in CQ looking at barley and wheatsown on either 22.5 or 45 cm rows with herbicide applied at either nil, half and full rate to the natural suite of weeds at the trial site. Results showed main effect of row spacing did not have a significant impact on weed counts but the interaction of crop and row spacing did. Weeds counts were significantly reduced in barley as row spacing narrowed but this did not occur in the wheat. Barley had significantly less weeds on narrow rows compared to the wheat.

In a further CQ wheat – weed competition trial (Osten *et al* 2002), row spacing had significant impact on weed biomass – as row spacing widened, weed biomass increased and doubling the row spacing from 25 to 50 cm resulted in a near doubling of the weed biomass. The impact on weed seed yield was less dramatic with no differences measured for 25, 30 and 37.5 cm rows but a significant increase was recorded for weed seed as row spacing increased to 50 cm.

Remaining row spacing studies in wheat and barley are minor. Widderick (2002) reported that competitive crops such as barleyor wheat grown on narrow rows (25 cm) reduced common sowthistle (*Sonchus oleraceus*) numbers as well as reduced the biomass and seed set potential. Brill *et al* (2012) reported that as row spacing doubled from 33 to 66 cm in wheat, post-harvest fleabane numbers increased by 120 %.

Generally as row spacing increases, weed numbers, biomass and seed production increase as well but this is not always the case as shown here in chickpea, sunflower and one of the CQ wheat trials. Responses in the sunflower may have been different had the weed densities encountered been greater. Further, the single chickpea study reported here has its widest row spacing at 64 cm and this is no longer the norm in the NGR. Further work may be required to better reflect current industry practice e.g. evaluate chickpea rows at 1 m.

Table . Summary of field trials in the northern region on effects of row spacing on weeds

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Location** | **Year** | **Crop** | **Treatment** | **Weed(s)** | **Conclusion** | **Reference** |
| Trangie | 2011 | Wheat | 33, 66 cm | Fleabane | Significant increase in fleabane plants/m2 at th3e wider row spacing | **(1)** Brill *et al* (2012) |
| Tamworth | 1971 | Soybean | 25, 50, 75, 100 cm | Awnless barnyard grass, Datura, Portulaca | Less weed growth in the narrower crop rows | **(3)** Felton (1976) |
| Tamworth | 2001-03 | Chickpea, faba bean, canola, wheat | 32, 64 cm | Triticale as mimic | Did not discuss impact of row spacing on the weeds only weed impacts on crop yield (losses) | **(4)** Felton *et al* (2004) |
| Northern NSW | 1971-74 | Sorghum | 30, 75, 90, 120 cm | Awnless barnyard grass, Datura, Eragrostis, Tribulus | Weed growth increased with row spacing increases but only significant in 1 trial | **(5)** Holland & McNamara (1982) |
| Gindie | 2002 | Sorghum | 75, 150 cm solid and 75 cm double skip | Sweet summer grass | Significantly greater weed numbers and biomass on wider solid and double skip rows | **(7)** Osten (2007a) |
| Emerald | 2003-07 | Sunflower | 50, 100, 150 cm | Unknown | At moderate weed densities narrower rows had significantly less weed numbers | **(8)** Osten (2007b) |
| Emerald | 2003 | Sorghum | 1 m solid, single skip, double skip | Mungbean as mimic | Weed biomass was (unexpectedly) least in the double skip row configuration | **(9)** Osten (2006) |
| Emerald | 2005 | Sorghum | 1 m solid, single skip, double skip | Millet as mimic | Weed seed production significantly increased as row spacing widened | **(10)** Osten (2006) |
| Wowan | 2000 | Wheat, barley | 22.5, 45 cm | Unknown | Narrow rows had less weeds but only just significant | **(11)** Osten & McCosker (2002) |
| Emerald | 2002 | Wheat | 25, 30, 37.5, 50 cm | Chickpea as mimic | Widest rows had greatest weed biomass and weed seed yields | **(12)** Osten *et al* (2002) |
| Southern and central Queensland | 2003-06 | Sorghum | 1 m solid, 1 m single skip, 1 m double skip | Millet and Mungbean as mimic | Greater weed growth and seed production under skip configurations, particularly double skip; solid rows compete better but suffer greater penalties under weed pressure. | **(13)** Osten *et al* (2006) |
| Sunflower | 0.5, 1.0, 1.5 m | Unknown | No impacts from row spacing on weeds for low-moderate weed pressures although narrower rows tends to have less weed growth |
| Northern NSW | 1996-97 | Chickpea | 32, 64cm | Wild oat, turnip weed | No advantages found in planting crop on narrower rows | **(18)** Whish *et al* (2002) |
| Darling Downs | 2001 | Wheat, barley | 25, 50 cm | Sowthistle | Either crop on narrow rows (25 cm) greatly reduced weed numbers, biomass and seed set potential | **(19)** Widderick (2002) |

**Row orientation**

Row orientation studies have been limited in the northern region. This factor is not likely to have much impact in the region as the sun’s angle does not drop as dramatically with drops in latitude as it does in the southern region. Hence row orientation (E-W versus N-S) would infer little difference in shading of the inter-row particularly as one moves northward through the region. Trangie in NSW is located at 31.99oS which is has similar latitude to where trials in WA (by DAFWA) have been undertaken that have shown positive weed management benefits from east-west row orientation (Brooke and Cook 2015). Thus it could be inferred that similar responses would occur in eastern Australia

To date only three studies have been undertaken on row orientation in the NGR.

A study by Gardner and colleagues undertaken near Tamworth in 2012 cited in Brooke and Cook (2015) showed east - west orientated barley rows produced 30% suppression in weed biomass compared to the north – south aligned rows. The same report cited similar summer crop (sorghum) work by McMullen and Serafin but no impacts were reported for weed control or suppression.

Brooke and Cook (2015) conducted their own row orientation trials in 2014 at both Tamworth and Trangie although the former site was not reported in the paper. At Trangie they compared two wheat (EGA Gregory and Lancer) and two barley(Commander and La Trobe) varieties on E-W versus N-S row alignments and sowed *Juncea* canola as a substitute weed. They reported no visual differences in weed suppression for either crop in either row alignment. Weed biomass measurements showed no significant differences between row orientations within each variety although a trend was evident for less weed biomass in the east-west configurations for all varieties and crops.

**Rotation**

Only two studies have been undertaken in the NGR specifically on rotation for weed control.

Walker *et al* (1999) showed that in a long term trial on the Darling Downs, crop rotations that included wheat or barleywere more effective at reducing the paradoxa grass (*Phalaris paradoxa* ) seedbank (up to 97 % reduction) compared to rotations that included chickpea or lucerne phases. These rotations also compared reactive management tactics using herbicides at recommended rates with strategic tactics (minimising seed set by increased crop density in conjunction with nil or reduced herbicide rates). In all instances the strategic tactics produced substantially fewer weed seeds. But the authors concluded it was more the rotation that impacted on the weed seedbank replenishment than the tactics themselves.

In a long term trial in CQ, Osten (2011) showed that rotations with sorghum dramatically increased feathertop Rhodes grass (FTR) (*Chloris virgata*) numbers even if planted after a clean fallow period. However, the trial also demonstrated that FTR numbers and seed production could be significantly reduced if mungbean or sunflower were included in the rotation, and that these weed and seed reductions were due to the ability to apply in-crop Group A herbicides rather than any crop competition attributes.

Crop rotation for weed management purposes is an area that warrants further research in the NGR, particularly if targeted towards specific key problem weeds.

***Discussion***

It is evident that the effort invested in crop competition for weed management in the NGR has been minimal over the past 30 years and this is reflective of the herbicide based cropping systems that have dominated in that time. Further, not all of the crop-weed competition work that has been completed in the last 15 years has been published in the scientific community. With the advent and rapid escalation of herbicide resistance in the NGR, non-herbicide tactics are required more than ever before and this is likely to continue as more and more herbicides topple and lose their place. Few new herbicides are being developed so a greater use of cultural and competitive cropping is required. Further R, D and E is needed if growers are expected to quickly adopt this revitalised non-herbicide based weed management technology.

# 7. META-ANALYSIS OF DATA

The meta-analysis was designed to pool data sourced from the literature and to identify common trends from the data. Due to lack in consistency of data (variables and factors measured), it has not been possible to conduct a complete meta-analysis using all data sets. Instead, for individual crop competition factors, like-measurements have been compared to identify trends.

The meta-analysis consists of three components:

* A summary of the number of trials conducted in each region and for each weed species, shown in Figure 1,
* Graphs of data to explore trends between crop competition factors and measures of weed growth (Appendix A), and
* A summary of the pooled data across each region showing general trends (Table 16).

## 7.1 Number of trials in each region for each weed species

Research to date has focussed on a small number of key weeds in the western region with a focus on annual ryegrass and wild radish (Figure 1A). Similarly, research in the southern region has focussed on annual ryegrass. Research in the northern region is more limited, but most has been on wild oat or back ground weed species (represented as ‘Unknown’ in Figure 1C). In both the southern and northern regions, mimic weeds have commonly been used in place of target weed species.

**A**

**B**

**C**

Figure . Count of the number of trials conducted on crop competition effects on various weed species for (A) western, (B) southern and (C) northern regions. Graphs include all references included in the list of references (Table 2).

## 7.2 Graphs of data

The graphed data are presented in Appendix A as two types of graphs, line graphs and bar graphs, to show data from the references. In total, there are 64 graphs. Each weed growth measurement and crop competition factor were plotted separately. The line graphs were used mostly where the levels of the crop competition factor could be ordered, and the bar graphs where the levels were nominal (e.g. cultivars).

In the line graphs the different data sets are referred to by the reference ID number in brackets, followed by the site (and year if more than one, the number of the trial if multiple run at same location and year, and any other necessary information to distinguish different data sets), then if information was available whether the treatments were significantly different (Sign) or not (NS). Where applicable a key shows the line attributes used for the different weed species investigated.

The bar graphs showed each data set as a separate panel and different graphs were used for different crops. When the least significant difference (lsd) was available it was plotted on the graph with the data set.

The graphs have been used to identify trends in data and this has been collated in Table 16 and discussed below.

## 7.3 Summary of pooled data

Summaries of the pooled data (across regions) for each crop competition factor are given in Table 16. For each crop competition factor, the corresponding crop, region, reference number, weed species and measure of weed growth are provided along with the overall impact of the crop competition factor and a general trend, indicated as either positive (+), negative (-) or variable or with no difference (~). Key findings are as follows:

* An increase in crop density commonly resulted in a decrease in weed growth measures. This was consistent across crops and regions and for different weed species.
* Cultivars can differ in their competitive ability across crop species with more competitive cultivars resulting in a decrease in weed growth measures. However, not all studies show a difference between cultivars and the effects of different cultivars can be inconsistent as affected by season. There appears to be little difference between lupin cultivars.
* A row orientation of east-west, as opposed to north-south, generally results in a reduction in weed growth measures, especially in the western region. However, results are inconsistent, with one southern region study having the opposite result.
* A decrease in row spacing generally resulted in a decrease in weed growth measures. This effect was consistent across crop species and regions. However, in several studies, wider row crops resulted in a reduction in weed growth measures due to interaction with in-crop control measures such as herbicide application.
* Skip rows research has only been conducted in the northern region. Generally, solid planting reduces weed growth measures compared with skip rows.
* An early sowing time generally reduced weed growth measures. However, there has been little research on this crop competition factor.

Table . A summary of crop competition effects across crops, regions, weed species and weed growth measures showing general impacts and trends as either positive (+), negative (-) or variable or with no difference (~). Graph ID refers to the meta-analysis graph in Appendix A.

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Crop Competition Factor** | **Crop(s)** | **Region** | **Reference ID(s)** | **Graph ID(s)** | **Weed(s)** | **Measure(s) of weed growth** | **Impacts** | **Trend (+/-/~)** |
| Cultivar | Barley | S | 5 | A21, A22 | Brome grass | Seed heads/m2, Plants/m2 | Some varieties eg commander, produce less weed seed and weed plants/m2. | **~** |
|  | S | 29 | A18 | Oat (as mimic) | Seed yield (g/m2) | There are differences between cultivars. | + |
|  | N | 2 | A35 | Oat (as mimic) | Seed yield (g/m2) | Differences between cultivars | + |
|  | N | 2 | A43 | Canola (as mimic) | Weed biomass (g/m2) | No difference between cultivars. | - |
| Canola | S | 18 | A27 | Ryegrass, wheat (as mimic) | Weed biomass (g/m2) | There are differences across years and weeds. | ~ |
| Cereals | W | 22 | A1, A5 | Ryegrass | Tillers per m2, Weed biomass (g/m2) | Variability between cultivars and across sites. | + |
| W | 22 | A3 | Ryegrass | Weed seed head length (cm) | No difference between cultivars. | - |
| W | 22 | A2 | Ryegrass | Weed seed head per m2 | Differences between cultivars, although not significant. | - |
| Field pea | S | 24 | A23 | Ryegrass, wheat (as mimic) | Growth score (0-5) | There are differences between years and weeds. Cultivar Morgan is consistent in its suppression. | + |
| S | 24 | A16, A17 | Wheat (as mimic) | Weed seed yield | There are differences between years. | + |

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  |  | S | 24 | A23, A24 | Ryegrass, wheat (as mimic) | Growth score, seed production | Tall cultivars produce less growth and seed yield. | + |
| S | 24 | A23, A24 | Ryegrass, wheat (as mimic) | Growth score, seed production | Early cultivars tend to have more weed growth and seed production. The midseason cultivars seem to have the least?? | + |
| Lupin | W | 5, 26 | A4 | Wild radish | Weed biomass (g/m2) | Differences between cultivars, but not very big, and variability between sites. | ~ |
| Lentil | S | 25 | A26 | Canola (as mimic) | Weed biomass | No significant difference. | - |
| Sorghum | N | 20 | A38 | Millet (as mimic) | Weed height (cm) | Significant but small differences between cultivars. | + |
| N | 20 | A36, A37, A39, A40, A42 | Millet (as mimic) | Weed seed production/m2, fresh weight biomass, weed seed heads/m2, weed biomass and plants/m2 | Generally, the cultivars Bonus and Goldrush were more suppressive of each of these measures. | + |
| Wheat | S | 3 | A20 | Ryegrass | Plant number/m2 | No effect of cultivar on ryegrass numbers | - |
| S | 20 | A25 | Ryegrass | Weed biomass (g/m2) | There are differences, but they are inconsistent across seasons. | ~ |
| S | 3, 9, 34 | A19 | Ryegrass, oats (as mimic), triticale (as mimic), mustard (as mimic) | Weed seed/m2 | There are differences across sites and weeds. Difficult to assess as data sets all look at different cultivars. | **~** |
| N | 2 | A41 | Canola (as mimic) | Weed biomass (g/m2) | No difference between cultivars. | - |
| Crop density | Barley | W | 29 | A6 | Ryegrass | Tillers/m2 | As crop density increases, ryegrass tiller numbers reduce | + |
| N | 2 | A50 | Millet (as mimic) | Weed seed g/m2 | As crop density increases, weed seed yield decreases. | + |
| Sorghum | N | 20 | A45 | Millet (as mimic) | Weed height (cm) | Plant height varied across crop densities. | **~** |
| N | 20 | A46 | Millet (as mimic) | Weed seed heads/m2 | As crop density increases, weed seed heads decrease. | + |
| N | 20 | A47 | Millet (as mimic) | Fresh weed biomass (g/m2) | As crop density increases, fresh weed biomass decreases. | + |
| Sorghum/wheat | N | 17, 20 | A51 | Millet (as mimic), paradoxa grass, wild oat | Weed seed number (per m2) | As crop density increases, weed seed number per m2 decreases. | + |
| Wheat | S | 10 | A28, A29, A30 | Wild radish | Weed seed number (per m2), LAI, weed biomass (g/m2) | As crop density increases, weed biomass, LAI and weed seed number reduces. Most important from 0 to 100 plants/m2. | + |
| N | 12 | A50 | Sweet summer grass | Weed seed g/m2 | As crop density increases, weed seed yield decreases. | + |
| Wheat, Wheat/Barley, Barley, Sorghum, Sunflower | N | 7, 8, 14, 19, 20 | A44 | Wild oat, sowthistle, millet (as mimic), unknown, sweet summer grass | Weed plants/m2 | As crop density increases, plants per m2 generally decrease. | ~ |
| Wheat, Wheat/Barley, Sorghum, Sunflower | N | 7, 14, 19, 20 | A49 | Wild oat, sowthistle, millet (as mimic), unknown | Weed biomass (g/m2) | As crop density increases, weed biomass decreases. | + |
| Wheat/Barley | N | 11 | A48 | Unknown | Control rating (0-9) | As crop density increases, control rating increases. | + |
| Sowing rate | Wheat | N | 6 | A52, A53, A54 | Wild oat | Weed biomass (g/m2), plants per m2, tillers per m2 | As sowing rate increases, weed biomass, plant number and tiller number all decrease. | + |
| Row spacing | Barley | W | 30 | A11 | Ryegrass | Weed biomass (g/m2) | Weed biomass increases as row spacing increases | + |
| W | 30 | A9 | Ryegrass | Weed plants/m2 | Variability in results with either increase, decrease or no change in plant numbers as row spacing increases. | ~ |
| S | 5 | A31, A32 | Brome grass | Plants per m2 and weed seed heads/m2 | As row spacing increases, plants/m2, heads/m2 increases | + |
| S | 1 | A33 | Grass weeds | Dry weight biomass (g/m2) | As row spacing increased dry weight biomass significantly increased. | + |
| Canola | W | 33 | A8 | Ryegrass | Seed number/m2 | With stubble retained, big increase in ryegrass seed number with an increase in row spacing. | + |
| Lupin | W | 4 | A9 | Wild radish | Weed plants/m2 | Slight but non-significant reduction as row spacing increases. | - |
| Sorghum | N | 8 | A56 | Sweet summer grass | Plants/m2 | As row spacing increased, plants/m2 decreased. | + |
| N | 5 | A58 | Unknown | Weed biomass (g/m2) | As row spacing increased, weed biomass increased. | + |
| Sunflower | N | 7 | A56 | Unknown | Plants/m2 | As row spacing increased, plants/m2 increased. | + |
| N | 7, 13 | A58 | Unknown | Weed biomass (g/m2) | As row spacing increased, weed biomass either increased or didn't change. | ~ |
| Wheat | W | 31, 32 | A8 | Ryegrass | Seed number/m2 | Variability in results, possibly due to interacting factors of herbicide and seeding rate. | ~ |
| W | 23 | A7 | Ryegrass | Tiller number/m2 | As row spacing increased tiller number increased | + |
| W | 19, 20 | A10 | Unknown | Weed seed heads/m2 | Background weeds generally increase with increase in row spacing | + |
| W | 19, 20 | A10 | Ryegrass | Weed seed heads/m2 | Variable results. | ~ |
| S | 1 | A33 | Grass weeds | Weed dry weight biomass (g/m2) | As row spacing increased, biomass increased significantly. | + |
| N | 12 | A55 | Chickpea (as mimic) | Weed seed yield (g/m2) | As row spacing increases, generally weed seed yield increases. | + |
| N | 3, 12 | A58 | Pigweed, barnyard grass, thornapple, chickpea (as mimic) | Weed biomass (g/m2) | Variability in results for study 12. Most show an increase in biomass with an increase in row spacing. | ~ |
| Wheat/Barley | S | 1 | A33 | Grass weeds | Biomass (g/m2) | As row spacing increases, grass weed biomass increases | + |
| N | 11 | A57 | Unknown | Control rating (0-9) | As row spacing increased, control rating decreased. | + |
| N | 19 | A56 | Sowthistle | Weed plants/m2 | As row spacing increased, plants/m2 increased. | + |
| N | 19 | A58 | Sowthistle | Weed biomass (g/m2) | As row spacing increased, weed biomass increased. | + |
| Skip rows | Sorghum | N | 13 | A59, A61, A63 | Millet (as mimic) | Fresh weed biomass (g/m2), seed production per m2, weed biomass (g/m2) | As skip rows increase from solid to double skip, fresh weed biomass, seed production and dry weight biomass all increase. | + |
| N | 13 | A62 | Mungbean (as mimic) | Dry weed biomass (g/m2) | As skip rows increase from solid to double skip, dry weed biomass either doesn't change or decreases. | - |
| N | 8 | A60 | Sweet summer grass | Weed plants/m2 | As row spacing increased and skip row increased, weed plants/m2 increased. | + |
| Row orientation | Various | W | 2, 25, 27 | A12 | Ryegrass and wild radish | Weed biomass (g/m2) | Weed biomass is generally less in barley, wheat (strong response) and less in canola, lupin and field pea (variable or non-existent) in east-west orientation. | + |
| Wheat | W | 1 | A13 | Ryegrass | Seed number/m2 | Seed numbers are generally less in the east-west compared with the north south | + |
| S | 8 | A34 | Wild turnip | Plant number/m2 | More wild turnip in east-west orientation | - |
| S | 8 | A34 | Barley grass | Plant number/m2 | Variable results. | ~ |
| Wheat/Barley | W | 1 | A13 | Ryegrass | Seed number/m2 | Seed numbers are generally less in the east-west compared with the north south | + |
| N | 2 | A64 | Canola (as mimic) | Weed biomass (g/m2) | No significant difference but a general reduction in east/west orientation. | ~ |
| Sowing time | Barley | W | 29 | A14 | Ryegrass | Tillers/m2 | Tiller number increases with late sowing or no response | ~ |
| Lupin | W | 5 | A15 | Ryegrass | Weed biomass (g/m2) | Biomass increases with late sowing | + |

# 8. **KNOWLEDGE GAP ANALYSIS AND FUTURE RD&E NEEDS**

*Method*: In order to determine the knowledge gaps for crop competition, the project team of experts firstly ‘brainstormed’ an importance rating for each key crop competition factor and each key crop on a 1 to 5 scale for each region (Table 17A, 18A and 19A). The relative importance for each combination of crop competition factor and key crop was calculated by multiplying this product by 4. This meant the relative importance value could range from 4 to 100 (100 = highly important). Overall, the highest priority was given to crop competition factors of cultivar, density and row spacing. This is taken into account when identifying key knowledge gaps

Secondly, following the review of literature, an intuitive rating (0% = nothing available, 100% = completely covered) was made as to how completely each crop competition by crop factor had been researched for each region (Tables 17B, 18B and 19B).

Thirdly, to identify the knowledge gaps, the relative importance percentages (4-100%) were subtracted from the intuitive percentages (0-100%). Using these differences, priority levels were assigned using symbols (Tables 17C, 18C and 19C). If the differences ranged from -25 to 25, it was rated “OK”, -25 to -50 = !, -50 to -75 = !!, -75 to -100 = !!!, 25 to 50 = \*, 50 to 75 = \*\* and 75 to 100 = \*\*\*. When the relative importance percentage was greater than the intuitive percentage of coverage by the literature, this indicated a potential knowledge gap. The reverse indicated there was sufficient knowledge for that crop competition by crop factor.

Finally, the priority levels were assessed by the research team to come up with the list of national and regional priorities (See Page 67). In this process, the project team took into account the importance of the crop competition factor and the crop species in developing the following key findings. For example, in some cases sowing time, depth of sowing, and nutrition have been identified as knowledge gaps. This is largely due to the lack of research in these areas. However, since each of these crop competition factors is of low importance, we have not identified them as key knowledge gaps.

## 8.1 Key findings from the knowledge gap analysis

For the western region, research is needed on:

* Canola across all crop competition factors;
* Field pea for cultivar and crop density; and,
* Chickpea for cultivar, crop density and row spacing.

For the southern region, research is needed on:

* Lupins, faba bean, chickpea for cultivar, crop density and row spacing; and,
* Canola for row spacing.

For the northern region, research is needed on:

* Chickpea, faba bean, mungbean and maize for cultivar, crop density and row spacing; and,
* Wheat and barley for cultivars.

Table . Crop competition knowledge gaps for the western region as identified by (A) relative importance of each crop by crop competition factor out of 100 (each crop and crop competition factor were rated on a 1-5 scale, where 5 is highest importance), (B) intuitive percentage of coverage of crop by crop competition factor, (0% - nothing available, 100% - completely covered) to calculate (C) identified priority levels where !=literature doesn't meet priorities, \*=literature meets or exceeds priorities, OK=literature meets priorities. More symbols indicate greater emphasis (i.e. !! is a higher research priority than !).

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **(A)** | | | |  |  | |  | | |  | |  | | |  | | |  | | |  |  | |  | | |
| **Factor** | | | |  | Wheat | | Barley | | | Oats | | Canola | | | Lupins | | | Field Peas | | | Chickpeas | Faba beans | | Triticale | | |
|  | | | |  | 5 | | 4 | | | 3 | | 4 | | | 3 | | | 2 | | | 2 | 1 | | 1 | | |
| Crop species | | | | 5 | 100 | | 80 | | | 60 | | 80 | | | 60 | | | 40 | | | 40 | 20 | | 20 | | |
| Cultivar | | | | 4 | 80 | | 64 | | | 48 | | 64 | | | 48 | | | 32 | | | 32 | 16 | | 16 | | |
| Crop density | | | | 5 | 100 | | 80 | | | 60 | | 80 | | | 60 | | | 40 | | | 40 | 20 | | 20 | | |
| Row spacing | | | | 5 | 100 | | 80 | | | 60 | | 80 | | | 60 | | | 40 | | | 40 | 20 | | 20 | | |
| Row orientation | | | | 2 | 40 | | 32 | | | 24 | | 32 | | | 24 | | | 16 | | | 16 | 8 | | 8 | | |
| Sowing time | | | | 4 | 80 | | 64 | | | 48 | | 64 | | | 48 | | | 32 | | | 32 | 16 | | 16 | | |
| Depth of sowing | | | | 2 | 40 | | 32 | | | 24 | | 32 | | | 24 | | | 16 | | | 16 | 8 | | 8 | | |
| Nutrition | | | | 3 | 60 | | 48 | | | 36 | | 48 | | | 36 | | | 24 | | | 24 | 12 | | 12 | | |
| Soil characteristics (Sites) | | | | 3 | 60 | | 48 | | | 36 | | 48 | | | 36 | | | 24 | | | 24 | 12 | | 12 | | |
| Rainfall (Seasons) | | | | 3 | 60 | | 48 | | | 36 | | 48 | | | 36 | | | 24 | | | 24 | 12 | | 12 | | |
| **(B)** | |  | | | |  | |  | | |  | |  | | |  | |  | |  | | |  | |  | |
| **Factor** | |  | | | | Wheat | | Barley | | | Oats | | Canola | | | Lupins | | Field Peas | | Chickpeas | | | Faba beans | | Triticale | |
| Crop species | |  | | | | 80 | | 80 | | | 30 | | 50 | | | 30 | | 20 | | 20 | | | 0 | | 10 | |
| Cultivar | |  | | | | 60 | | 60 | | | 0 | | 0 | | | 40 | | 0 | | 0 | | | 0 | | 0 | |
| Crop density | |  | | | | 90 | | 90 | | | 20 | | 20 | | | 10 | | 0 | | 0 | | | 0 | | 0 | |
| Row spacing | |  | | | | 90 | | 90 | | | 10 | | 50 | | | 70 | | 50 | | 10 | | | 0 | | 0 | |
| Row orientation | |  | | | | 80 | | 80 | | | 0 | | 60 | | | 60 | | 40 | | 0 | | | 0 | | 0 | |
| Sowing time | |  | | | | 30 | | 20 | | | 0 | | 0 | | | 20 | | 0 | | 0 | | | 0 | | 0 | |
| Depth of sowing | |  | | | | 0 | | 0 | | | 0 | | 0 | | | 0 | | 0 | | 0 | | | 0 | | 0 | |
| Nutrition | |  | | | | 30 | | 20 | | | 0 | | 0 | | | 20 | | 0 | | 0 | | | 0 | | 0 | |
| Soil characteristics (Sites) | | | | | | 30 | | 20 | | | 0 | | 0 | | | 20 | | 0 | | 0 | | | 0 | | 0 | |
| Rainfall (Seasons) |  | | | | | 50 | | 40 | | | 0 | | 10 | | | 10 | | 10 | | 0 | | | 0 | | 0 | |
|  | | |  | | |  | | |  | |  | | |  | | |  |  |  | | | |  | |  |
| **(C)** | | |  | | |  | | |  | |  | | |  | | |  |  |  | | | |  | |  |
| **Factor** | | |  | | | Wheat | | | Barley | | Oats | | | Canola | | | Lupins | Field Peas | Chickpeas | | | | Faba beans | | Triticale |
| Crop species | | |  | | | OK | | | OK | | ! | | | ! | | | ! | OK | OK | | | | OK | | OK |
| Cultivar | | |  | | | OK | | | OK | | ! | | | !! | | | OK | ! | ! | | | | OK | | OK |
| Crop density | | |  | | | OK | | | OK | | ! | | | !! | | | ! | ! | ! | | | | OK | | OK |
| Row spacing | | |  | | | OK | | | OK | | ! | | | ! | | | OK | OK | ! | | | | OK | | OK |
| Row orientation | | |  | | | \* | | | \* | | OK | | | \* | | | \* | OK | OK | | | | OK | | OK |
| Sowing time | | |  | | | ! | | | ! | | ! | | | !! | | | ! | ! | ! | | | | OK | | OK |
| Depth of sowing | | |  | | | ! | | | ! | | OK | | | ! | | | OK | OK | OK | | | | OK | | OK |
| Nutrition | | |  | | | ! | | | ! | | ! | | | ! | | | OK | OK | OK | | | | OK | | OK |
| Soil characteristics (Sites) | | | | | | ! | | | ! | | ! | | | ! | | | OK | OK | OK | | | | OK | | OK |
| Rainfall (Seasons) |  | | | | | OK | | | OK | | ! | | | ! | | | ! | OK | OK | | | | OK | | OK |

Table . Crop competition knowledge gaps for the southern region as identified by (A) relative importance of each crop by crop competition factor out of 100 (each crop and crop competition factor were rated on a 1-5 scale, were 5 is highest importance), (B) intuitive percentage of coverage of crop by crop competition factor, (0% - nothing available, 100% - completely covered) to calculate (C) identified priority levels where !=literature doesn't meet priorities, \*=literature meets or exceeds priorities, OK=literature meets priorities. More symbols indicate greater emphasis (i.e. !! is a higher research priority than !).

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| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **(A)** |  |  | |  | |  | |  | |  | |  | |  | |  | | |  | | |  | | |  | | |  | | |  | | |
| **Factor** |  | Wheat | | Barley | | Oats | | Canola | | Lupins | | Field Peas | | Chickpeas | | Faba beans | | | Triticale | | | Rye | | | Lentils | | | Maize | | | Soybean | | |
|  |  | 5 | | 4 | | 3 | | 4 | | 3 | | 3 | | 3 | | 3 | | | 1 | | | 1 | | | 3 | | | 1 | | | 1 | | |
| Crop species | **5** | 100 | | 80 | | 60 | | 80 | | 60 | | 60 | | 60 | | 60 | | | 20 | | | 20 | | | 60 | | | 20 | | | 20 | | |
| Cultivar | 4 | 80 | | 64 | | 48 | | 64 | | 48 | | 48 | | 48 | | 48 | | | 16 | | | 16 | | | 48 | | | 16 | | | 16 | | |
| Crop density | 5 | 100 | | 80 | | 60 | | 80 | | 60 | | 60 | | 60 | | 60 | | | 20 | | | 20 | | | 60 | | | 20 | | | 20 | | |
| Row spacing | 5 | 100 | | 80 | | 60 | | 80 | | 60 | | 60 | | 60 | | 60 | | | 20 | | | 20 | | | 60 | | | 20 | | | 20 | | |
| Row orientation | 2 | 40 | | 32 | | 24 | | 32 | | 24 | | 24 | | 24 | | 24 | | | 8 | | | 8 | | | 24 | | | 8 | | | 8 | | |
| Sowing time | 4 | 80 | | 64 | | 48 | | 64 | | 48 | | 48 | | 48 | | 48 | | | 16 | | | 16 | | | 48 | | | 16 | | | 16 | | |
| Depth of sowing | 3 | 60 | | 48 | | 36 | | 48 | | 36 | | 36 | | 36 | | 36 | | | 12 | | | 12 | | | 36 | | | 12 | | | 12 | | |
| Nutrition | 4 | 80 | | 64 | | 48 | | 64 | | 48 | | 48 | | 48 | | 48 | | | 16 | | | 16 | | | 48 | | | 16 | | | 16 | | |
| Soil characteristics (Sites) | 3 | 60 | | 48 | | 36 | | 48 | | 36 | | 36 | | 36 | | 36 | | | 12 | | | 12 | | | 36 | | | 12 | | | 12 | | |
| Rainfall zones (Seasons) | 4 | 80 | | 64 | | 48 | | 64 | | 48 | | 48 | | 48 | | 48 | | | 16 | | | 16 | | | 48 | | | 16 | | | 16 | | |
|  |  | |  | |  | |  | |  | |  | |  | |  | |  | | |  | | |  | | |  | | |  | | |
| **(B)** |  | |  | |  | |  | |  | |  | |  | |  | |  | | |  | | |  | | |  | | |  | | |
| **Factor** | Wheat | | Barley | | Oats | | Canola | | Lupins | | Field Peas | | Chickpeas | | Faba beans | | Triticale | | | Rye | | | Lentils | | | Maize | | | Soybean | | |
| Crop species | 95 | | 20 | | 20 | | 20 | | 0 | | 0 | | 0 | | 0 | | 0 | | | 0 | | | 0 | | | 0 | | | 0 | | |
| Cultivar | 100 | | 60 | | 40 | | 95 | | 0 | | 40 | | 0 | | 0 | | 0 | | | 0 | | | 10 | | | 0 | | | 0 | | |
| Crop density | 100 | | 40 | | 20 | | 80 | | 0 | | 20 | | 0 | | 0 | | 0 | | | 0 | | | 20 | | | 0 | | | 0 | | |
| Row spacing | 70 | | 20 | | 20 | | 20 | | 0 | | 10 | | 0 | | 0 | | 0 | | | 0 | | | 0 | | | 0 | | | 0 | | |
| Row orientation | 0 | | 0 | | 0 | | 0 | | 0 | | 0 | | 0 | | 0 | | 0 | | | 0 | | | 0 | | | 0 | | | 0 | | |
| Sowing time | 100 | | 0 | | 20 | | 0 | | 0 | | 0 | | 0 | | 0 | | 0 | | | 0 | | | 0 | | | 0 | | | 0 | | |
| Depth of sowing | 0 | | 0 | | 0 | | 0 | | 0 | | 0 | | 0 | | 0 | | 0 | | | 0 | | | 0 | | | 0 | | | 0 | | |
| Nutrition | 100 | | 20 | | 20 | | 20 | | 0 | | 0 | | 0 | | 0 | | 0 | | | 0 | | | 0 | | | 0 | | | 0 | | |
| Soil characteristics (Sites) | 40 | | 0 | | 0 | | 0 | | 0 | | 0 | | 0 | | 0 | | 0 | | | 0 | | | 0 | | | 0 | | | 0 | | |
| Rainfall zones (Seasons) | 80 | | 0 | | 0 | | 0 | | 0 | | 0 | | 0 | | 0 | | 0 | | | 0 | | | 0 | | | 0 | | | 0 | | |
|  |  | |  | |  | |  | |  | |  | |  | |  | | |  | | |  | | |  | | |  | | |  | | |
| **(C)** |  | |  | |  | |  | |  | |  | |  | |  | | |  | | |  | | |  | | |  | | |  | | |
| **Factor** | Wheat | | Barley | | Oats | | Canola | | Lupins | | Field Peas | | Chickpeas | | Faba beans | | | Triticale | | | Rye | | | Lentils | | | Maize | | | Soybean | | |
| Crop species | OK | | !! | | ! | | !! | | !! | | !! | | !! | | !! | | | OK | | | OK | | | !! | | | OK | | | OK | | |
| Cultivar | OK | | OK | | OK | | \* | | ! | | OK | | ! | | ! | | | OK | | | OK | | | ! | | | OK | | | OK | | |
| Crop density | OK | | ! | | ! | | OK | | !! | | ! | | !! | | !! | | | OK | | | OK | | | ! | | | OK | | | OK | | |
| Row spacing | ! | | !! | | ! | | !! | | !! | | ! | | !! | | !! | | | OK | | | OK | | | !! | | | OK | | | OK | | |
| Row orientation | ! | | ! | | OK | | ! | | OK | | OK | | OK | | OK | | | OK | | | OK | | | OK | | | OK | | | OK | | |
| Sowing time | OK | | !! | | ! | | !! | | ! | | ! | | ! | | ! | | | OK | | | OK | | | ! | | | OK | | | OK | | |
| Depth of sowing | !! | | ! | | ! | | ! | | ! | | ! | | ! | | ! | | | OK | | | OK | | | ! | | | OK | | | OK | | |
| Nutrition | OK | | ! | | ! | | ! | | ! | | ! | | ! | | ! | | | OK | | | OK | | | ! | | | OK | | | OK | | |
| Soil characteristics (Sites) | OK | | ! | | ! | | ! | | ! | | ! | | ! | | ! | | | OK | | | OK | | | ! | | | OK | | | OK | | |
| Rainfall zones (Seasons) | OK | | !! | | ! | | !! | | ! | | ! | | ! | | ! | | | OK | | | OK | | | ! | | | OK | | | OK | | |

Table . Crop competition knowledge gaps for the northern region as identified by (A) relative importance of each crop by crop competition factor out of 100 (each crop and crop competition factor were rated on a 1-5 scale, where 5 is highest importance), (B) intuitive percentage of coverage of crop by crop competition factor, (0% - nothing available, 100% - completely covered) to calculate (C) identified priority levels where !=literature doesn't meet priorities, \*=literature meets or exceeds priorities, OK=literature meets priorities. More symbols indicate greater emphasis (i.e. !! is a higher research priority than !).

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **(A)** |  | |  | | |  | | |  | | |  | | |  | | |  | | |  | | |  | | |  | | |  | |  | | |  | | |  | | |  | | |
| **Factor** |  | | Wheat | | | Barley | | | Oats | | | Canola | | | Lupins | | | Field Peas | | | Chickpeas | | | Faba beans | | | Triticale | | | Maize | | Sorghum | | | Sunflower | | | Mungbean | | | Soybean | | |
|  |  | | 5 | | | 4 | | | 2 | | | 2 | | | 1 | | | 2 | | | 5 | | | 3 | | | 1 | | | 3 | | 5 | | | 3 | | | 3 | | | 2 | | |
| Crop species | 5 | | 100 | | | 80 | | | 40 | | | 40 | | | 20 | | | 40 | | | 100 | | | 60 | | | 20 | | | 60 | | 100 | | | 60 | | | 60 | | | 40 | | |
| Cultivar | 4 | | 80 | | | 64 | | | 32 | | | 32 | | | 16 | | | 32 | | | 80 | | | 48 | | | 16 | | | 48 | | 80 | | | 48 | | | 48 | | | 32 | | |
| Crop density | 5 | | 100 | | | 80 | | | 40 | | | 40 | | | 20 | | | 40 | | | 100 | | | 60 | | | 20 | | | 60 | | 100 | | | 60 | | | 60 | | | 40 | | |
| Row spacing | 5 | | 100 | | | 80 | | | 40 | | | 40 | | | 20 | | | 40 | | | 100 | | | 60 | | | 20 | | | 60 | | 100 | | | 60 | | | 60 | | | 40 | | |
| Row orientation | 1 | | 20 | | | 16 | | | 8 | | | 8 | | | 4 | | | 8 | | | 20 | | | 12 | | | 4 | | | 12 | | 20 | | | 12 | | | 12 | | | 8 | | |
| Sowing time | 3 | | 60 | | | 48 | | | 24 | | | 24 | | | 12 | | | 24 | | | 60 | | | 36 | | | 12 | | | 36 | | 60 | | | 36 | | | 36 | | | 24 | | |
| Depth of sowing | 3 | | 60 | | | 48 | | | 24 | | | 24 | | | 12 | | | 24 | | | 60 | | | 36 | | | 12 | | | 36 | | 60 | | | 36 | | | 36 | | | 24 | | |
| Nutrition | 3 | | 60 | | | 48 | | | 24 | | | 24 | | | 12 | | | 24 | | | 60 | | | 36 | | | 12 | | | 36 | | 60 | | | 36 | | | 36 | | | 24 | | |
| Soil characteristics (Sites) | 3 | | 60 | | | 48 | | | 24 | | | 24 | | | 12 | | | 24 | | | 60 | | | 36 | | | 12 | | | 36 | | 60 | | | 36 | | | 36 | | | 24 | | |
| Rainfall zones (Seasons) | 4 | | 80 | | | 64 | | | 32 | | | 32 | | | 16 | | | 32 | | | 80 | | | 48 | | | 16 | | | 48 | | 80 | | | 48 | | | 48 | | | 32 | | |
|  |  | | |  | | |  | | |  | | |  | | |  | | | |  | | |  | | |  | | |  | | | |  | | |  | | |  | | |  | | |
| **(B)** |  | | |  | | |  | | |  | | |  | | |  | | | |  | | |  | | |  | | |  | | | |  | | |  | | |  | | |  | | |
| **Factor** | Wheat | | | Barley | | | Oats | | | Canola | | | Lupins | | | Field Peas | | | | Chickpeas | | | Faba beans | | | Triticale | | | Maize | | | | Sorghum | | | Sunflower | | | Mungbean | | | Soybean | | |
| Crop species | 40 | | | 15 | | | 0 | | | 5 | | | 0 | | | 0 | | | | 25 | | | 5 | | | 0 | | | 0 | | | | 60 | | | 50 | | | 0 | | | 10 | | |
| Cultivar | 5 | | | 5 | | | 0 | | | 0 | | | 0 | | | 0 | | | | 0 | | | 0 | | | 0 | | | 0 | | | | 40 | | | 15 | | | 0 | | | 0 | | |
| Crop density | 80 | | | 50 | | | 0 | | | 0 | | | 0 | | | 0 | | | | 10 | | | 0 | | | 0 | | | 0 | | | | 80 | | | 80 | | | 0 | | | 10 | | |
| Row spacing | 70 | | | 20 | | | 0 | | | 10 | | | 0 | | | 0 | | | | 50 | | | 10 | | | 0 | | | 0 | | | | 80 | | | 80 | | | 0 | | | 10 | | |
| Row orientation | 10 | | | 10 | | | 0 | | | 0 | | | 0 | | | 0 | | | | 0 | | | 0 | | | 0 | | | 0 | | | | 5 | | | 0 | | | 0 | | | 0 | | |
| Sowing time | 0 | | | 0 | | | 0 | | | 0 | | | 0 | | | 0 | | | | 0 | | | 0 | | | 0 | | | 0 | | | | 0 | | | 0 | | | 0 | | | 0 | | |
| Depth of sowing | 0 | | | 0 | | | 0 | | | 0 | | | 0 | | | 0 | | | | 0 | | | 0 | | | 0 | | | 0 | | | | 0 | | | 0 | | | 0 | | | 0 | | |
| Nutrition | 0 | | | 0 | | | 0 | | | 0 | | | 0 | | | 0 | | | | 0 | | | 0 | | | 0 | | | 0 | | | | 0 | | | 0 | | | 0 | | | 0 | | |
| Soil characteristics (Sites) | 60 | | | 20 | | | 0 | | | 0 | | | 0 | | | 0 | | | | 30 | | | 0 | | | 0 | | | 0 | | | | 60 | | | 30 | | | 0 | | | 10 | | |
| Rainfall zones (Seasons) | 60 | | | 20 | | | 0 | | | 0 | | | 0 | | | 0 | | | | 30 | | | 0 | | | 0 | | | 0 | | | | 60 | | | 30 | | | 0 | | | 10 | | |
|  | |  | | |  | | |  | | |  | | |  | | |  | |  | | |  | | |  | | |  | | |  | | |  | | |  | | |  | | |
| **(C)** | |  | | |  | | |  | | |  | | |  | | |  | |  | | |  | | |  | | |  | | |  | | |  | | |  | | |  | | |
| **Factor** | | Wheat | | | Barley | | | Oats | | | Canola | | | Lupins | | | Field Peas | | Chickpeas | | | Faba beans | | | Triticale | | | Maize | | | Sorghum | | | Sunflower | | | Mungbean | | | Soybean | | |
| Crop species | | !! | | | !! | | | ! | | | ! | | | OK | | | ! | | !! | | | !! | | | OK | | | !! | | | ! | | | OK | | | !! | | | ! | | |
| Cultivar | | !! | | | !! | | | ! | | | ! | | | OK | | | ! | | !!! | | | ! | | | OK | | | ! | | | ! | | | ! | | | ! | | | ! | | |
| Crop density | | OK | | | ! | | | ! | | | ! | | | OK | | | ! | | !!! | | | !! | | | OK | | | !! | | | OK | | | OK | | | !! | | | ! | | |
| Row spacing | | ! | | | !! | | | ! | | | ! | | | OK | | | ! | | ! | | | ! | | | OK | | | !! | | | OK | | | OK | | | !! | | | ! | | |
| Row orientation | | OK | | | OK | | | OK | | | OK | | | OK | | | OK | | OK | | | OK | | | OK | | | OK | | | OK | | | OK | | | OK | | | OK | | |
| Sowing time | | !! | | | ! | | | OK | | | OK | | | OK | | | OK | | !! | | | ! | | | OK | | | ! | | | !! | | | ! | | | ! | | | OK | | |
| Depth of sowing | | !! | | | ! | | | OK | | | OK | | | OK | | | OK | | !! | | | ! | | | OK | | | ! | | | !! | | | ! | | | ! | | | OK | | |
| Nutrition | | !! | | | ! | | | OK | | | OK | | | OK | | | OK | | !! | | | ! | | | OK | | | ! | | | !! | | | ! | | | ! | | | OK | | |
| Soil characteristics (Sites) | | OK | | | ! | | | OK | | | OK | | | OK | | | OK | | ! | | | ! | | | OK | | | ! | | | OK | | | OK | | | ! | | | OK | | |
| Rainfall zones (Seasons) | | OK | | | ! | | | ! | | | ! | | | OK | | | ! | | ! | | | ! | | | OK | | | ! | | | OK | | | OK | | | ! | | | OK | | |

The team of experts ‘brainstormed’ the future needs for RD&E at both national and regional levels. A summary of identified needs is provided below. The process used to identify these needs is outlined in Section 8 (Knowledge Gap Analysis).

## 8.2 National RD&E Needs

* Breeding for and evaluation of competitive ability of the most important crops is required. Also, understanding of the traits and genetics that influence competitive ability (e.g. allelopathy, early vigour). Cultivars in NVT trials should be rated on early ground cover. This could be by using green seeker technology. Assessment will be needed across seasons to provide reliable averages.
* Can gains be made in the competitive ability of weakly competitive crops (e.g. pulses)? Such crops represent a weak phase in the crop rotation (in terms of crop competition) and therefore gains should be pursued. Need to encourage farmers and breeders to grow more competitive varieties.
* Varietal differences – although quite a bit of research has been done, there are new varieties being released periodically and therefore this type of research should continue as a routine process, maybe as part of National Variety Trials.
* Fertiliser rates and more efficient fertiliser placement (horizontally and vertically) to favour the crop over the weed, measuring impact of crop competitiveness ability on weed control. This type of work has generally been done in a weed free environment. There is scope to do more work here to give advantage to crop over weeds.
* There are insufficient data across all regions on key weed species. For example in the west, most research is on annual ryegrass and wild radish. Table 1 (Page 2) has identified other key weeds for which little data exists. This is a major issue across all regions.
* The effect of the timing of weed emergence on the efficacy of crop competition.
* Do specific crop rotations seem to out compete weeds compared to others? Using existing or new long-term experimental sites to evaluate change in weed populations.
* Farmers need more guidance and demonstration/extension as to how to use crop competition and how to best fit it in the farming system. How to integrate into an IWM system.
* If crop and cultivar competitiveness information is available it should be in crop production agronomy guides.
* It may be feasible to model different crop competition by crop interactions once there is sufficient uniform data. This information could be used in the extension of crop competition as a weed management tactic.

## 8.3 Western Region RD&E Needs

* Row spacing and density – need work on canola, grain legumes (lupin, chickpea and field pea)

## 8.4 Southern Region RD&E Needs

* Row spacing and density – need work on grain legumes (lupin, chickpea and field pea)
* Legumes – weakness in the rotation in terms of crop competition – need to look at breeding for competitive ability.
* Row spacing and crop density in pulses is less of a crop competition question and more a question of disease management.
* Need work on barley and oats.
* Row orientation - weed competition aspect.

## 8.5 Northern Region RD&E Needs

* Lack of information on row spacing and crop density for key weeds in key crops
* Sorghum vs maize competitiveness for key weed species
* Mungbeans – row spacing and density work
* Chickpeas – what gains can be made?

# 9. RECOMENDATIONS FOR OPTIMISING FUTURE RD&E

One of the key findings of this scoping study is the need for an improved and consistent approach to experimentation on crop competition. This need is evidenced by the large number of different weed growth measures used across studies (Table 20). The project team has developed an experimental protocol to guide future planning as outlined below.

Table . Different weed growth measures used to determine the effect of crop competition factors on weeds in the cropping regions of Australia. Numbers in parentheses are the number of different measures used for each region.

|  |  |  |  |
| --- | --- | --- | --- |
| **Crop competition factor** | **Western Region** | **Southern Region** | **Northern Region** |
| Varietal differences | Weed dry weight biomass (g/m2), weed seed heads per m2, weed seed head length (cm), weed tillers per m2 **(4)** | Weed plants per m2, weed dry weight biomass (g/m2), weed growth score (0-5), weed seed yield (g/m2), weed seed heads per m2, weed seed production per m2 **(6)** | Weed plants per m2, weed dry weight biomass (g/m2), weed Seed heads per m2, seed production per m2, height (cm), fresh weed biomass (g/m2) **(6)** |
| Crop density | Weed tillers per m2 **(1)** | Weed seed number per m2, weed leaf area index (LAI), weed dry weight biomass (g/m2) **(3)** | Weed plants per m2, weed seed number per m2, tillers per m2, weed dry weight biomass (g/m2), control rating (0-9), fresh weed biomass (g/m2), weed seed heads per m2, weed height (cm), weed seed yield (g/m2) **(9)** |
| Row spacing | Weed plants per m2, weed tillers per m2, weed dry weight biomass (g/m2), weed seed number per m2, weed seed heads per m2 **(5)** | Weed seed heads per m2, weed plants per m2, weed dry weight biomass (g/m2) **(3)** | Weed dry weight biomass (g/m2), plants per m2, control rating (0-9), seed yield (g/m2), seed production per m2, fresh weed biomass (g/m2) **(6)** |
| Row orientation | Weed seed number per m2, weed dry weight biomass (g/m2) **(2)** | Weed plants per m2 **(1)** | - |
| Sowing time | Weed dry weight biomass (g/m2), weed tillers per m2 **(2)** | - | - |

## 9.1 Experimental design protocol

***Planning***

* Weed : crop competition is complex. The research needs to be kept relatively ‘simple’ to tease out the main effects. Much of the existing work combines several crop competition and non-crop competition factors and clear messages are lost.
* Have clearly defined and achievable research questions and hypotheses with grower, advisor and researcher consultation.
* Literature review –
  + be aware of what data already exists.
  + read and understand the standard papers on competition research.
* How many sites and seasons are needed?
* Multiple sites will provide locally-relevant data -> better adoption.
* But, is it really necessary or valuable to repeat an experiment for a different region?
* Research-station based research – needed to sort out whether there is a real effect before taking out into the regions, for regional validation.
* On-farm ‘demonstrations’ can be unreplicated and will usually involve large plots using farmer-sized machinery. On-farm ‘experiments’ must meet the basic standards of randomisation, replication and control.
* Consider that other above-ground competition effects are likely to include an unseen contribution from ‘interference’ factors including allelopathy.
* If the proposed experiments are successful, will a peer-reviewed scientific paper be possible?

***Experimental design***

* Consult with biometrician before starting to determine optimal experimental design, ensuring sufficient power in the experiment.
* Experimental design needs to be able to account for spatial variability in weed populations.
* Try to keep factors (treatments) to a maximum of two, with multiple levels within each factor. Three-way factor interactions are almost impossible to interpret.
* Minimum replication should be 3; higher numbers (4, 5 ,6) will be required where the expected differences are small (e.g. <10% difference in crop yield) or weed numbers are low.
* On-farm experimentation - Do something that is ‘simple’ (only one factor/treatment – to tease out main effects), clear research question, use a straight-forward design, has to fit in with farmer operation, clear benefit to farmer, don’t introduce weeds onto farm.
* Multi-site and multi-season research needs to clearly quantify the efficacy of different crop competition factors (e.g. “treatment X significantly reduces weed biomass by 50%, and reduces weed seed production by 30% compared to the control”).
* To enable multi-site analysis, experiments must have some consistent treatment(s), and it is important to have the same terms of weed growth measurement (e.g. weed dry matter biomass).
* Use buffer plots.
* Make sure field plots are a sufficient size to reflect the distribution of the underlying weed seed population (generally with more spatial heterogeneity in the weed population larger plot sizes would be needed, but if the weed population is more uniform then smaller plots and more replicates would be better).

***The weed population***

* The ideal situation regarding weed population is:
  + Uniform density across site.
  + Weed density must reflect typical field situations.
  + Ideal weed density will vary depending upon weed species and time of emergence in relation to the crop (all in plants/m2):
    - Wild radish (5) – same for other large brassicas such as *Sinapis arvensis*, *Brassica tournifortii*, *Rapistrum rugosum* and *Sisymbrium thellungii*.
    - Annual ryegrass (100-200)
    - Wild oats and brome grass (50-100)
    - Barley grass (25-50)
    - Sowthistle (10-15)
    - Fleabane (10-15)
    - Much of this is unknown for other species
  + Can use either a natural or artificial weed population.
  + Natural weed populations will be mixed species.
* Working with natural weed populations is difficult – need sufficient resources ($ and time) to be able to have multiple sites to ensure sufficient weed populations, across sites.
* When would a mimic weed be used?
  + To understand the density dependant relationships,
  + To look at spatial variability (e.g. different types of weed patches),
  + Asking questions about the mechanism of competition (e.g. inter-row vs intra-row),
  + If weeds are difficult to germinate, then mimic weeds are a way to minimise variability.
  + Can overcome limitations with time and resources.
* If looking to use a mimic weed, the mimic needs to:
  + Be aggressive (needs early vigour).
  + Have a similar morphology and habit as the target weed species.
  + Not pose a biosecurity risk (needs to be treatable).
* Potential differences in allelopathy between the mimic and the target weed species will be an issue.

***What to measure***

* What is the paddock history?
  + Pre-sowing assessment of weed density and distribution to ensure site and weed density are appropriate for addressing the research question. This is commonly through weed density counts, however there may be opportunity to use new technologies including weed detector, drones, NDVI.
  + Alternatively, take a representative sample of the seed bank (through soil coring and germinations from those soil cores) – but expensive, time consuming and there is a need for sufficient number of cores to provide relevant data..
* What else needs to be measured?
  + Needs to be tailored to the crop x weed system that is being examined/tested.
  + Seed bank assessment (pre-trial) – only needed if looking at impact on seed banks/future weed populations.
  + Test crop and weed seed for germination percentage *in vitro* before sowing. Measure seed size before sowing. These may be useful covariates in analysis.
  + Weed emergence count (plants/m2) in crop to determine starting density.
    - The more variability, the more samples required.
  + Crop emergence and establishment – to define the parameters of the treatment (plants/m2) or metre row.
    - The more variability the more samples required.
  + Weed biomass (g/m2) – dry weight biomass – taken at crop anthesis, or early flowering for broadleaf crop.
  + Crop biomass (g/m2) – dry weight – taken at the same time as weed biomass.
  + Crop grain yield (kg/ha)
  + Weed seed production – at crop maturity – pre-harvest (seed number/m2).
  + Don’t use ratings (e.g. 0-5, 1-10) – they are too coarse, are subjective, and are not necessarily on a linear scale.
  + Measurements need to be taken with precision!
* Sampling protocol is very important – only one sample per plot doesn’t allow the variability due to the sampling process to be quantified. Sampling error may be larger than the treatment differences.
* Samples-within-samples introduce further unwanted variability (e.g. subsamples of bulky dry-matter cuts). Discuss with biometrician.
* If wanting to understand the mechanisms (e.g. to provide parameters for a crop:weed model), then measurements will need to be much more detailed.
* Site description metadata is essential (rainfall, temperature, soil tests).
* Record other external impacts which may affect weed/crop interactions (e.g. diseases, frost, water logging).

***Statistical analysis***

* Consult with a biometrician. Use appropriate software and analysis (including covariates and spatial adjustments where necessary). Make sure necessary data transformations are used. The analysis must be transparent and reproducible. Carefully preserve your raw data and your analysis code (script files).
* Correct interpretation of analysis.
  + Analyse raw data.
  + Don’t analyse % of control data.
  + If presenting % weed control, need to know what the weed density was in the standard/control.
  + Across sites analysis – don’t use ANOVA – which assumes that variance at each site is consistent. Use a procedure such as REML (restricted maximum likelihood) that can model necessary information for across site data.

***Reporting***

* Present actual measurement (biomass, plant number, seed number).
* Clearly describe experimental design.
* Ensure measure of error is included (e.g. LSD, SE, residual variance).
* Need to include significance (P values).
* What significant main effects and/or interactions do/don’t exist? Do not place emphasis on ‘trends’ that are not significant.
* Consider the economic impact.
* People should be encouraged to publish in scientific journals.

# 10. RECOMMENDATIONS

Herbicide resistance is becoming increasingly important as a constraint across conservation agriculture systems of Australia.

To enable a 20% increase in grower adoption of crop competition by 2020, there is a need for both agronomic research (short-term) and plant breeding research (long-term) to improve the competitive ability of crops. We therefore make the following recommendations to GRDC:

1. Focus on the key weed species is important to develop the priority order to fill knowledge gaps.

* Common weeds across the regions are annual ryegrass, wild radish, wild oat and fleabane, while windmill grass and feathertop Rhodes grass are emerging problems.
* Weeds specific to regions include brome grass and prickly lettuce for western and southern regions, and sweet summer grass for the northern region.
* There is a more limited range of species in the western region reflecting the simpler rotations compared with the southern and northern regions.

1. Future crop competition research requires national funding, coordination and communication for:

* National breeding for competitive ability traits
* Regional packages for agronomy
* Research consistency to improve the quality of research outputs

We recommend that GRDC supports *A National Crop Competition Program* to improve communication, coordination and quality of RD&E on crop competition for the Grains industry of Australia.

1. We recommend a monograph (scientific refereed literature review) of this report be produced in conjunction with a short (4-8 page) extension document, to promote nationally, crop competition as a weed management tactic.
2. Specific Research Needs: While the principles underpinning agronomy of crop competition are well-understood, basic research on traits for breeding is needed. In addition, strategic and applied research on crops by competition factors at the regional level.

* **Breeding for and evaluation of competitive ability** of the most important crops is required. Also, an understanding of the traits and genetics that influence competitive ability (e.g. allelopathy and early vigour).
* **Agronomy packages for each region require the following information:**
  + **Nationally**
    - Can gains be made in the competitive ability of weakly competitive crops (eg pulses)? Such crops represent a weak phase in the crop rotation (in terms of crop competition) and therefore gains should be pursued. Need to encourage farmers and breeders to grow more competitive varieties.
    - Varietal differences – although quite a bit of research has been done, there are new varieties being released periodically and therefore this type of research should continue as a routine process, maybe as part of National Variety Trials. Explore the inclusion of an early vigour score for varieties.
    - Fertiliser rates and more efficient fertiliser placement (horizontally and vertically) to favour the crop over the weed, measuring impact of crop competitiveness ability on weed control. This type of work has generally been done in a weed free environment. There is scope to do more work here to give advantage to crop over weeds.
    - There are insufficient data across all regions on key weed species. For example in the west, most research is on annual ryegrass and wild radish. Table 1 (Page 2) has identified other key weeds for which little data exists. This is a major issue across all regions.
    - The effect of the timing of weed emergence on the efficacy of crop competition.
    - Do specific crop rotations seem to out compete weeds compared to others? Using existing or new long-term experimental sites to evaluate change in weed populations.
    - Farmers and farmer groups need more guidance and demonstration/extension as to how to use crop competition and how to best fit it in the farming system. How to integrate into an IWM system, particularly when using crop competition in conjunction with pre- or early post-emergent in-crop herbicides.
    - If crop and cultivar competitiveness information is available it should be in crop production agronomy guides.
  + **Western region**
    - Row spacing and density – need work on canola, oats, grain legumes (lupin, chickpea and field pea).
    - Canola across all crop competition factors.
    - Field pea for cultivar and crop density.
    - Chickpea for cultivar, crop density and row spacing.
    - Role of root pruning herbicides on crop competitive abiity.
  + **Southern region**
    - Row spacing and density – need work on grain legumes (lupin, chickpea and field pea)
    - Legumes – weakness in the rotation in terms of crop competition – need to look at breeding for competitive ability.
    - Row spacing and crop density in pulses is less of a crop competition question and more a question of disease management.
    - Need work on barley and oats.
    - Row orientation - weed competition aspect.
    - Lupins, faba beans, chickpea for cultivar, crop density and row spacing.
    - Canola for row spacing.
  + **Northern region**
    - Lack of information on row spacing and crop density for key weeds in key crops
    - Sorghum vs maize competitiveness for key weed species
    - Mungbeans – row spacing and density work
    - Chickpeas – what gains can be made?
    - Chickpea, faba beans, canola, mung beans and maize for cultivar, crop density and row spacing.
    - Wheat and barley for cultivar differences.

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# APPENDIX A META ANALYSIS GRAPHS

**WESTERN REGION**

G:\Delivery\R&DDel\PlantSc\WeedsMgt\A Cultural management review 2015\DATA\Meta analysis\Western\West_CropCultivar_Tillersm2(Cereal).emf

**Figure A1.** Comparison of western region research on cereal crop cultivar effect on annual ryegrass tillers per m2. Data labels indicate reference number in parentheses, location, date of research and statistical significance (Sign) or non-significance (NS). Where available, an LSD bar (P=0.05) has been added.

G:\Delivery\R&DDel\PlantSc\WeedsMgt\A Cultural management review 2015\DATA\Meta analysis\Western\West_CropCultivar_Headsm2(Cereal).emf

**Figure A2.** Comparison of western region research on cereal crop cultivar effect on annual ryegrass seed head production per m2. Data labels indicate reference number in parentheses, location, date of research and statistical significance (Sign) or non-significance (NS). Where available, an LSD bar (P=0.05) has been added.

G:\Delivery\R&DDel\PlantSc\WeedsMgt\A Cultural management review 2015\DATA\Meta analysis\Western\West_CropCultivar_HeadLength(Cereal).emf

**Figure A3.** Comparison of western region research on cereal crop cultivar effect on annual ryegrass seed head length (cm). Data labels indicate reference number in parentheses, location, date of research and statistical significance (Sign) or non-significance (NS). Where available, an LSD bar (P=0.05) has been added.

G:\Delivery\R&DDel\PlantSc\WeedsMgt\A Cultural management review 2015\DATA\Meta analysis\Western\West_CropCultivar_Biomass(Lupin).emf

**Figure A4.** Comparison of western region research on lupin crop cultivar effect on wild radish dry weight biomass (g/m2). Data labels indicate reference number in parentheses, location, date of research and statistical significance (Sign) or non-significance (NS). Where available, an LSD bar (P=0.05) has been added.

G:\Delivery\R&DDel\PlantSc\WeedsMgt\A Cultural management review 2015\DATA\Meta analysis\Western\West_CropCultivar_Biomass(Cereal).emf

**Figure A5.** Comparison of western region research on cereal crop cultivar effect on annual ryegrass dry weight biomass (g/m2). Data labels indicate reference number in parentheses, location, date of research and statistical significance (Sign) or non-significance (NS). Where available, an LSD bar (P=0.05) has been added.

G:\Delivery\R&DDel\PlantSc\WeedsMgt\A Cultural management review 2015\DATA\Meta analysis\Western\West_CropDensity_Tillersm2.emf

**Figure A6.** Comparison of western region research on barley crop density effect on annual ryegrass tillers per m2. Data labels indicate reference number in parentheses, location, date of research and statistical significance (Sign) or non-significance (NS). Where available, an LSD bar (P=0.05) has been added.

G:\Delivery\R&DDel\PlantSc\WeedsMgt\A Cultural management review 2015\DATA\Meta analysis\Western\West_RowSpacing_Tillersm2.emf

**Figure A7.** Comparison of western region research on wheat crop row spacing effect on annual ryegrass tillers per m2. Data labels indicate reference number in parentheses, location, date of research and statistical significance (Sign) or non-significance (NS). Where available, an LSD bar (P=0.05) has been added.

G:\Delivery\R&DDel\PlantSc\WeedsMgt\A Cultural management review 2015\DATA\Meta analysis\Western\West_RowSpacing_Seedsm2.emf

**Figure A8.** Comparison of western region research on wheat and canola crop row spacing effect on annual ryegrass seed number per m2. Data labels indicate reference number in parentheses, location, date of research and statistical significance (Sign) or non-significance (NS). Where available, an LSD bar (P=0.05) has been added.

G:\Delivery\R&DDel\PlantSc\WeedsMgt\A Cultural management review 2015\DATA\Meta analysis\Western\West_RowSpacing_Plantsm2.emf

**Figure A9.** Comparison of western region research on crop row spacing effect across crop species on annual ryegrass and wild radish plants per m2. Data labels indicate reference number in parentheses, location, date of research and statistical significance (Sign) or non-significance (NS). Where available, an LSD bar (P=0.05) has been added.

G:\Delivery\R&DDel\PlantSc\WeedsMgt\A Cultural management review 2015\DATA\Meta analysis\Western\West_RowSpacing_Headsm2.emf

**Figure A10.** Comparison of western region research on wheat crop row spacing effect on seed head production per m2 ofannual ryegrass and unknown spectrum of weed species. Data labels indicate reference number in parentheses, location, date of research and statistical significance (Sign) or non-significance (NS). Where available, an LSD bar (P=0.05) has been added.

G:\Delivery\R&DDel\PlantSc\WeedsMgt\A Cultural management review 2015\DATA\Meta analysis\Western\West_RowSpacing_Biomass.emf

**Figure A11.** Comparison of western region research in barley on crop row spacing effect on annual ryegrass dry weight biomass (g/m2). Data labels indicate reference number in parentheses, location, date of research and statistical significance (Sign) or non-significance (NS). Where available, an LSD bar (P=0.05) has been added.

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**Figure A12.** Comparison of western region research on crop row orientation effect across crop species on annual ryegrass and wild radish dry weight biomass (g/m2). Data labels indicate reference number in parentheses, location, date of research and statistical significance (Sign) or non-significance (NS). Where available, an LSD bar (P=0.05) has been added.

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**Figure A13.** Comparison of western region research on crop row orientation effect in wheat and barley on annual ryegrass seed number per m2. Data labels indicate reference number in parentheses, location, date of research and statistical significance (Sign) or non-significance (NS). Where available, an LSD bar (P=0.05) has been added.

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**Figure A14**. Comparison of western region research on crop sowing time effect for barley on annual ryegrass tillers per m2. Data labels indicate reference number in parentheses, location, date of research and statistical significance (Sign) or non-significance (NS) where known. Where available, an LSD bar (P=0.05) has been added.

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**Figure A15.** Comparison of western region research on lupin crop sowing time effect on annual ryegrass dry weight biomass (g/m2). Data labels indicate reference number in parentheses, location, date of research and statistical significance (Sign) or non-significance (NS). Where available, an LSD bar (P=0.05) has been added.

**SOUTHERN REGION**

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**Figure A16.** Comparison of southern region research on field pea crop cultivar effect on wheat (as a mimic weed) seed yield (g/m2). Data labels indicate reference number in parentheses, location, date of research and statistical significance (Sign) or non-significance (NS). Where available, an LSD bar (P=0.05) has been added.

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**Figure A17.** Comparison of southern region research on field pea crop cultivar effect on wheat (as a mimic weed) seed yield (g/m2). Data labels indicate reference number in parentheses, location, date of research and statistical significance (Sign) or non-significance (NS). Where available, an LSD bar (P=0.05) has been added.

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**Figure A18.** Comparison of southern region research on barley crop cultivar effect on oat (as a mimic weed) seed yield (g/m2). Data labels indicate reference number in parentheses, location, date of research and statistical significance (Sign) or non-significance (NS). Where available, an LSD bar (P=0.05) has been added.

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**Figure A19.** Comparison of southern region research on wheat crop cultivar effect across weed species on weed seed production per m2. Data labels indicate reference number in parentheses, location, date of research and statistical significance (Sign) or non-significance (NS). Where available, an LSD bar (P=0.05) has been added.

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**Figure A20.** Comparison of southern region research on wheat crop cultivar effect on annual ryegrass plants per m2. Data labels indicate reference number in parentheses, location, date of research and statistical significance (Sign) or non-significance (NS). Where available, an LSD bar (P=0.05) has been added.

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**Figure A21.** Comparison of southern region research on barley crop cultivar effect on brome grass plants per m2. Data labels indicate reference number in parentheses, location, date of research and statistical significance (Sign) or non-significance (NS). Where available, an LSD bar (P=0.05) has been added.

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**Figure A22.** Comparison of southern region research on barley crop cultivar effect on brome grass seed heads per m2. Data labels indicate reference number in parentheses, location, date of research and statistical significance (Sign) or non-significance (NS). Where available, an LSD bar (P=0.05) has been added.

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**Figure A23.** Comparison of southern region research on field pea crop cultivar categories and their effect on annual ryegrass and wheat (as a mimic weed) growth score (0-5). Data labels indicate reference number in parentheses, location, date of research and statistical significance (Sign) or non-significance (NS). Where available, an LSD bar (P=0.05) has been added.

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**Figure A24.** Comparison of southern region research on field pea crop cultivar effect on annual ryegrass and wheat (as a mimic weed) growth score (0-5). Data labels indicate reference number in parentheses, location, date of research and statistical significance (Sign) or non-significance (NS). Where available, an LSD bar (P=0.05) has been added.

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**Figure A25.** Comparison of southern region research on wheat crop cultivar effect on annual ryegrass dry weight biomass (g/m2). Data labels indicate reference number in parentheses, location, date of research and statistical significance (Sign) or non-significance (NS). Where available, an LSD bar (P=0.05) has been added.

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**Figure A26.** Comparison of southern region research on lupin crop cultivar effect on canola (as mimic weed) dry weight biomass (g/m2). Data labels indicate reference number in parentheses, location, date of research and statistical significance (Sign) or non-significance (NS). Where available, an LSD bar (P=0.05) has been added.

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**Figure A27.** Comparison of southern region research on canola crop cultivar effect on annual ryegrass and wheat (as a mimic weed) dry weight biomass (g/m2). Data labels indicate reference number in parentheses, location, date of research and statistical significance (Sign) or non-significance (NS). Where available, an LSD bar (P=0.05) has been added.

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**Figure A28.** Comparison of southern region research on wheat crop density effect on wild radish seed numbers per m2. Data labels indicate reference number in parentheses, location, date of research and statistical significance (Sign) or non-significance (NS). Where available, an LSD bar (P=0.05) has been added.

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**Figure A29.** Comparison of southern region research on wheat crop density effect on wild radish leaf area index (LAI). Data labels indicate reference number in parentheses, location, date of research and statistical significance (Sign) or non-significance (NS). Where available, an LSD bar (P=0.05) has been added.

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**Figure A30.** Comparison of southern region research on wheat crop density effect on wild radish dry weight biomass (g/m2). Data labels indicate reference number in parentheses, location, date of research and statistical significance (Sign) or non-significance (NS). Where available, an LSD bar (P=0.05) has been added.

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**Figure A31.** Comparison of southern region research on barley crop row spacing effect on brome grass plants per m2. Data labels indicate reference number in parentheses, location, date of research and statistical significance (Sign) or non-significance (NS). Where available, an LSD bar (P=0.05) has been added.

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**Figure A32.** Comparison of southern region research on barley crop row spacing effect on brome grass seed head production per m2. Data labels indicate reference number in parentheses, location, date of research and statistical significance (Sign) or non-significance (NS). Where available, an LSD bar (P=0.05) has been added.

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**Figure A33.** Comparison of southern region research on wheat and barley crop row spacing effect on grass weed species (combined) dry weight biomass (g/m2). Data labels indicate reference number in parentheses, location, date of research and statistical significance (Sign) or non-significance (NS). Where available, an LSD bar (P=0.05) has been added.

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**Figure A34.** Comparison of southern region research on wheat crop row orientation effect on barley grass and wild turnip plants per m2. Data labels indicate reference number in parentheses, location, date of research and statistical significance (Sign) or non-significance (NS). Where available, an LSD bar (P=0.05) has been added.

**NORTHERN REGION**

**C:\Users\widderm\Desktop\A Cultural management review 2015\DATA\Meta analysis\Northern\North_CropCultivar_SeedYield(Barley).emf**

**Figure A35.** Comparison of northern region research on barley crop cultivar effect on oats (as a mimic weed) seed yield (g/m2). Data labels indicate reference number in parentheses, location, date of research and statistical significance (Sign) or non-significance (NS). Where available, an LSD bar (P=0.05) has been added.

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**Figure A36.** Comparison of northern region research on sorghum crop cultivar effect on millet (as a mimic weed) seed production per m2. Data labels indicate reference number in parentheses, location, date of research and statistical significance (Sign) or non-significance (NS). Where available, an LSD bar (P=0.05) has been added.

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**Figure A37.** Comparison of northern region research on sorghum crop cultivar effect on millet (as a mimic weed) plants per m2. Data labels indicate reference number in parentheses, location, date of research and statistical significance (Sign) or non-significance (NS). Where available, an LSD bar (P=0.05) has been added.

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**Figure A38.** Comparison of northern region research on sorghum crop cultivar effect on millet (as a mimic weed) height (cm). Data labels indicate reference number in parentheses, location, date of research and statistical significance (Sign) or non-significance (NS). Where available, an LSD bar (P=0.05) has been added.

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**Figure A39.** Comparison of northern region research on sorghum crop cultivar effect on millet (as a mimic weed) seed heads per m2. Data labels indicate reference number in parentheses, location, date of research and statistical significance (Sign) or non-significance (NS). Where available, an LSD bar (P=0.05) has been added.

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**Figure A40.** Comparison of northern region research on sorghum crop cultivar effect on millet (as a mimic weed) fresh biomass (g/m2). Data labels indicate reference number in parentheses, location, date of research and statistical significance (Sign) or non-significance (NS). Where available, an LSD bar (P=0.05) has been added.

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**Figure A41.** Comparison of northern region research on wheat crop cultivar effect on canola (as a mimic weed) dry weight biomass (g/m2). Data labels indicate reference number in parentheses, location, date of research and statistical significance (Sign) or non-significance (NS). Where available, an LSD bar (P=0.05) has been added.

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**Figure A42.** Comparison of northern region research on sorghum crop cultivar effect on millet (as a mimic weed) dry weight biomass (g/m2). Data labels indicate reference number in parentheses, location, date of research and statistical significance (Sign) or non-significance (NS). Where available, an LSD bar (P=0.05) has been added.

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**Figure A43.** Comparison of northern region research on barley crop cultivar effect on canola (as a mimic weed) dry weight biomass (g/m2). Data labels indicate reference number in parentheses, location, date of research and statistical significance (Sign) or non-significance (NS). Where available, an LSD bar (P=0.05) has been added.

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**Figure A44.** Comparison of northern region research on crop density effect across crop species on plant per m2 for various weed species. Data labels indicate reference number in parentheses, location, date of research and statistical significance (Sign) or non-significance (NS). Where available, an LSD bar (P=0.05) has been added.

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**Figure A45.** Comparison of northern region research on sorghum crop density effect on millet (as a mimic weed) height (cm). Data labels indicate reference number in parentheses, location, date of research and statistical significance (Sign) or non-significance (NS). Where available, an LSD bar (P=0.05) has been added.

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**Figure A46.** Comparison of northern region research on sorghum crop density effect on millet (as a mimic weed) seed heads per m2. Data labels indicate reference number in parentheses, location, date of research and statistical significance (Sign) or non-significance (NS). Where available, an LSD bar (P=0.05) has been added.

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**Figure A47.** Comparison of northern region research on sorghum crop density effect on millet (as a mimic weed) fresh biomass (g/m2). Data labels indicate reference number in parentheses, location, date of research and statistical significance (Sign) or non-significance (NS). Where available, an LSD bar (P=0.05) has been added.

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**Figure A48.** Comparison of northern region research on wheat and barley (combined) crop density effect on control rating (0-9, where 0=0-10%, 9=90-100%) of an unknown spectrum of weed species. Data labels indicate reference number in parentheses, location, date of research and statistical significance (Sign) or non-significance (NS). Where available, an LSD bar (P=0.05) has been added.

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**Figure A49.** Comparison of northern region research on crop density effect across crop species on multiple weed species dry weight biomass (g/m2). Data labels indicate reference number in parentheses, location, date of research and statistical significance (Sign) or non-significance (NS). Where available, an LSD bar (P=0.05) has been added.

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**Figure A50.** Comparison of northern region research on barley and wheat crop density effect on seed yield (g/m2) of various weed species. Data labels indicate reference number in parentheses, location, date of research and statistical significance (Sign) or non-significance (NS). Where available, an LSD bar (P=0.05) has been added.

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**Figure A51.** Comparison of northern region research on sorghum and wheat crop density effect on weed seed number per m2 for various weed species. Data labels indicate reference number in parentheses, location, date of research and statistical significance (Sign) or non-significance (NS). Where available, an LSD bar (P=0.05) has been added.

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**Figure A52.** Comparison of northern region research on wheat crop sowing rate effect on wild oat tillers per m2. Data labels indicate reference number in parentheses, location, date of research and statistical significance (Sign) or non-significance (NS). Where available, an LSD bar (P=0.05) has been added.

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**Figure A53.** Comparison of northern region research on wheat crop sowing rate on wild oat plants per m2. Data labels indicate reference number in parentheses, location, date of research and statistical significance (Sign) or non-significance (NS). Where available, an LSD bar (P=0.05) has been added.

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**Figure A54.** Comparison of northern region research on wheat crop sowing rate effect on wild oat dry weight biomass (g/m2). Data labels indicate reference number in parentheses, location, date of research and statistical significance (Sign) or non-significance (NS). Where available, an LSD bar (P=0.05) has been added.

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**Figure A55.** Comparison of northern region research on wheat crop row spacing (cm) effect on chickpea (as a mimic weed) on seed yield (g/m2). Data labels indicate reference number in parentheses, location, date of research and statistical significance (Sign) or non-significance (NS). Where available, an LSD bar (P=0.05) has been added.

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**Figure A56.** Comparison of northern region research on crop row spacing (cm) effect across crop species on plants per m2 of various weed species. Data labels indicate reference number in parentheses, location, date of research and statistical significance (Sign) or non-significance (NS). Where available, an LSD bar (P=0.05) has been added.

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**Figure A57.** Comparison of northern region research on wheat and barley (combined) crop row spacing (cm) effect on control rating (0-9, where 0=0-10%, 9=90-100%) of an unknown spectrum of weed species. Data labels indicate reference number in parentheses, location, date of research and statistical significance (Sign) or non-significance (NS). Where available, an LSD bar (P=0.05) has been added.

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**Figure A58.** Comparison of northern region research on crop row spacing (cm) effect across crop species on dry weight biomass (g/m2) of various weed species. Data labels indicate reference number in parentheses, location, date of research and statistical significance (Sign) or non-significance (NS). Where available, an LSD bar (P=0.05) has been added.

**C:\Users\widderm\Desktop\A Cultural management review 2015\DATA\Meta analysis\Northern\North_SkipRow_Seedm2(JapMillet).emf**

**Figure A59.** Comparison of northern region research on sorghum crop skip row effect on Japanese millet (as a mimic weed) seed production per m2. Data labels indicate reference number in parentheses, location, date of research and statistical significance (Sign) or non-significance (NS). Where available, an LSD bar (P=0.05) has been added.

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**Figure A60.** Comparison of northern region research on sorghum crop skip row effect on sweet summer grass plants per m2. Data labels indicate reference number in parentheses, location, date of research and statistical significance (Sign) or non-significance (NS). Where available, an LSD bar (P=0.05) has been added.

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**Figure A61.** Comparison of northern region research on sorghum crop skip row effect on Japanese millet (as a mimic weed) fresh biomass (g/m2). Data labels indicate reference number in parentheses, location, date of research and statistical significance (Sign) or non-significance (NS). Where available, an LSD bar (P=0.05) has been added.

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**Figure A62.** Comparison of northern region research on sorghum crop skip row effect on mungbean (as a mimic weed) dry weight biomass (g/m2). Data labels indicate reference number in parentheses, location, date of research and statistical significance (Sign) or non-significance (NS). Where available, an LSD bar (P=0.05) has been added.

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**Figure A63.** Comparison of northern region research on sorghum crop skip row effect on Japanese millet (as a mimic weed) dry weight biomass (g/m2). Data labels indicate reference number in parentheses, location, date of research and statistical significance (Sign) or non-significance (NS). Where available, an LSD bar (P=0.05) has been added.

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**Figure A64.** Comparison of northern region research on barley and wheat crop row orientation effect on canola (as a mimic weed) dry weight biomass (g/m2). Data labels indicate reference number in parentheses, location, date of research and statistical significance (Sign) or non-significance (NS). Where available, an LSD bar (P=0.05) has been added.