Final Report

DAN 2004

Improved management of weeds in cotton and grains farming systems

1 Nov 2019 – 30 June 2023

Executive Summary

The Australian cotton industry is considered a global leader in sustainable agriculture. However, herbicide resistance and problem weeds threaten the productivity and profitability of the cotton industry and the farming system. Over time, the industry is increasingly moving back to relying on residual herbicides to manage herbicide resistant weeds in cotton, in rotation crops and in fallows, with glyphosate now ineffective for controlling some grass and broadleaf weeds, and resistance to the grass herbicides (Group 1) and paraquat also becoming increasingly common.

With the increasing use of residual herbicides, comes the problem of crop safety to the following crop, an even more difficult issue in dryland cropping, where rotations are often determined by planting opportunities, but selection of a residual herbicide applied in the fallow may restrict these options. The issues are further complicated by the increasing range of herbicides available for fallow use, with multiple herbicides potentially applied and multiple applications within a fallow period common. On top of this, camera sprayers are becoming standard in the industry and it is common to apply higher than normal rates through these rigs. There is a big need to explore the potential for these herbicides and herbicide combinations and rates to damage following cotton and other rotation crops.

The primary research focus of this project was on the impact of residual herbicides applied to rotation crops and in fallows on the following cotton crops. Research was carried out over a series of seasons (replicated in time), on replicated, randomised field experiments, some with split-plot designs, in fields grown under typical commercial conditions. Components were tested at Warwick (Southern Qld), Narrabri (Northern NSW) and Leeton (Southern NSW). The experiments were on solid plant, irrigated cotton, picked with modified commercial pickers, and ginned to determine lint yield. Excessively wet conditions delaying herbicide applications and flooding in spring 2022 were challenging for some experiments.

Our research has highlighted: that a) residual herbicides used in rotation crops, fallows, and through camera sprayers have the potential to seriously impact following cotton crops, reducing seedling vigour and lint yield, and b) combinations of herbicides can be more damaging than expected, such that label crop-safety information may underestimate the potential damage from combinations.

However, the limitation of this work was that it could not test every potential herbicide, herbicide combination and application scenario. The largest of the experiments (at Narrabri) examined eight in-crop herbicides in two rotation crops (wheat and chickpea) and 9 fallow herbicide combinations, a total of 80 treatments, with four replications. While the findings from the results from this work are extremely valuable to industry, a common scenario in the cotton system would be two in-crop herbicides and two or more fallow herbicides, increasing the potential herbicide combinations four-fold or more (as herbicides other than the ones we used could have been included).

Future research should focus on the impacts of some of the more common multiple-herbicide strategies. The current work, for example, showed that the standard cotton herbicides are not causing issues for the following rotation crops. However, only single herbicides were considered, applied at cotton planting. The potential impact of multiple herbicides, some applied pre-crop and others in-crop is yet to be examined, but is likely to be damaging to rotation crops.

Further work is also needed to correlate herbicide soil and plant concentrations to crop damage as we note that with more residual damage occurring in the industry and increasing concern around damage from residual herbicides, there is currently no information that can

relate herbicide concentrations in soils or plants to damage. Where a grower sees damaged plants, it is becoming increasingly common to test for herbicide residues. When a herbicide is detected from a laboratory sample, it is assumed that the detected herbicide has caused the damage. However, this may not be the case, and conversely, when no herbicide is detected, this does not necessarily indicate that a given herbicide is not causing the damage. We simply have no data to relate laboratory test results to plant damage and this needs to be addressed.

Herbicide screening showed that samples of awnless barnyard grass, feathertop Rhodes and windmill grass had some level of resistance to glyphosate, the Group 1 grass herbicides, paraquat and glufosinate. Theses levels of resistance have big implications for managing weeds. The resistance to glufosinate is surprising and unexpected and will diminish the value of this relatively new mode of action herbicide to the cotton system, especially if resistance occurs amongst broadleaf weeds.

The studies on emerging weeds highlighted the challenges of managing some of these weeds, especially as they develop herbicide resistance. Cotton growers and consultants need to be aware of these issues with these weeds and develop management strategies for fields where they become problematic.

This research has generated a bulk of experimental results that will be published in information sheets, articles and scientific papers, and delivered to industry through the CottonInfo network.

Already from this project there have been a series of scientific publications, articles, conference presentations, many presentations at grower meetings and conversations with growers and consultants. More presentations and articles will follow.

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Milestones 1.1 & 1.4 – Explore issues with residual herbicides used in cotton, wheat, chickpeas and fallows, monitoring damage and crop responses in cotton and rotation crops

Background

The evolution of glyphosate tolerance and resistance in weeds in cotton cropping systems has changed the way growers manage weeds. Before Roundup Ready technology was introduced, growers largely relied on residual herbicide programs, cultivation and chipping to manage weeds in cotton, and glyphosate and 2,4-D to control weeds in fallows. With the evolution of glyphosate tolerant and resistant weeds, growers are increasingly being forced back to using residual herbicides in crops and fallows, often with multiple residual herbicides used over the year. However, there is very limited understanding of how these herbicides and combinations may interact and may affect following crops.

Milestone 1.1 & 1.4 aimed to investigate the effects of residual herbicides used in cotton crops or winter crops and fallow on the following crops. This information will identify potential issues in the system.

The experiment was conducted at the Australian Cotton Research Institute at Narrabri and split into two parts: A) cotton herbicides preceding winter crops, and B) winter crop and fallow residual herbicide combinations preceding cotton.

A) Cotton herbicides preceding winter crops

Methods and materials

Cotton herbicide treatments were applied at planting in irrigated cotton as split plots within a randomised complete block design with 4 replicates, with herbicides (sub-plots) applied within cotton main-plots which were later sown to wheat or chickpea (main plots), with each sub-plot 4 m x 20 m. The experiment consisted of 8 sub-plot treatments as below:

Treatment	Herbicide	Herbicide rate (x/ha)
Main plots	Wheat Chickpea	
Sub plots		
1	Diuron	2 kg
2	Fluometuron	4 kg
3	Metolachlor	1 L
4	Prometryn	2.5 kg
5	Pendimethalin	3 L
6	Terbyn	1.4 kg
7	Trifluralin	2.3 L
8	Untreated	

The winter crops were planted at the end of July in 2020, 2021 and 2022 and irrigated as required, in line with normal practices. Samples were taken from 1 m of row and 10 plants selected for measurements. Plant stand, height, number of leaves, leaf area, and biomass were measured. At the end of the season, crops were harvested with a small plot header to determine yield. Treatments were applied with a high-clearance sprayer using TTI 110015 nozzles at 30 psi and 100 L/ha water.

Results and Discussion

The data will be fully analysed next year with the intention of publishing in a scientific journal. Preliminary results are as follows, with results from the three seasons combined.

Effect of residual herbicide applied in cotton on the following wheat crop.

Herbicide	**Plant stand**		**Height**		**Biomass**		**Yield**	
	(No./m)	**s.e.**	**(cm)**	**s.e.**	**(g/m)**	**s.e.**	**(kg/ha)**	**s.e.**
Diuron	30.5	1.5	30.7	2.5	42.7	8.4	2287	255
Fluometuron	30.0	1.5	30.7	2.7	44.1	9.4	2179	242
Metolachlor	32.6	1.4	31.5	2.8	42.7	9.3	1875	288
Prometryn	31.6	1.2	30.5	2.5	45.0	9.3	2100	180
Pendimethalin	32.7	1.3	29.9	2.5	42.3	9.7	2388	272
Terbyn	33.5	1.3	30.7	2.6	42.2	8.8	2183	257
Trifluralin	33.3	1.7	30.3	2.7	41.1	8.7	2318	165
Untreated	32.5	0.9	31.1	1.4	43.0	5.1	2097	117

Note. Values in red **in all tables** are less than the untreated value by more than twice the standard error of that value.
Note. Results in all tables are compared with the respective Untreated plots.

Effect of residual herbicide applied in cotton on the following chickpea crop.

Herbicide	**Plant stand**		**Height**		**Biomass**		**Yield**	
	(No./m)	**s.e.**	**(cm)**	**s.e.**	**(g/m)**	**s.e.**	**(kg/ha)**	**s.e.**
Diuron	11.9	1.2	21.3	2.2	11.2	2.7	752	124
Fluometuron	12.1	1.3	21.7	2.2	11.2	2.7	757	106
Metolachlor	12.5	1.3	21.6	2.0	11.5	2.5	868	119
Prometryn	13	1.4	23.4	2.6	11.2	2.2	783	145
Pendimethalin	13.5	1.5	22.7	2.1	11.8	2.4	789	111
Terbyn	13	1.3	23.5	2.3	13.5	2.5	715	122
Trifluralin	12.9	1.4	22.0	2.0	11.3	2.5	838	159
Untreated	13.5	0.8	22.3	1.2	11.1	1.2	789	67

Residual herbicides applied to cotton at-planting had some detrimental early-season effects on the following wheat and chickpea crops but these effects did not consistently result in yield reductions.

The wheat plant stand was reduced by 5 – 8% by diuron and fluometuron applications in the preceding cotton crops, but there were no yield reductions.

Chickpea was more sensitive to the residual herbicides applied in cotton, but the damage was not consistent over years. In the first season, the chickpea plant stand was reduced by 15 – 22% by diuron, fluometuron and prometryn. This translated to a 26% yield reduction on the plots where prometryn had been applied. In the second season, plant stand reductions of 22 – 26% were recorded from diuron, fluometuron and metolachlor, with a yield reduction of

39% from diuron. In the third season there were no plant stand effects, but yield was reduced by 39% on the Terbyn treatment. However, these effects were not consistent over time except for the reduction in plant stand from diuron, that averaged 12% over the three seasons.

These effects may have been greater had the herbicides been applied as combinations or been applied later in the cotton season as herbicide half-lives are impacted by rainfall and conditions influencing herbicide breakdown. Nevertheless, the results suggest there are no major issues for these rotation crops from residuals applied prior to or at planting in cotton.

B) <u>Winter crop and fallow residual herbicide combinations preceding cotton</u>

Methods and materials

The experiment was established as a split plot within a randomised complete block with 4 replicates. The experiment was run over four seasons, with winter crops in 2019, 2020 and 2021, followed by fallows and cotton crops in 2020-21, 2021-22, and 2022-23. Results are presented for the data set combined over years.

Main plots (field length) were treatments applied in wheat or prior to chickpea emergence (Balance and simazine), and fallow treatments were applied along the main plots. Each sub-plot was 4 m x 20 m and conducted under irrigation as per typical industry practice. Weeds were controlled using glyphosate applied as necessary. The experiment consisted of eight main plot treatments, as below:

Treatment	Crop	Herbicide	Herbicide rate (x/ha)	Plant back To cotton
1	Wheat	Atlantis	330 ml	12 months
2	Chickpea	Balance	100 g	7 months
3	Wheat	Hussar	100 g	12 months
4	Wheat	Precept	2 L	12 months
5	Chickpea	Simazine	1.1 kg	12 months
6	Wheat	Starane	900 ml	1 month
7	Wheat	Velocity	1 L	14 months
8	Wheat	Untreated		

The in-fallow sub-plot treatments were:

Treatment	Herbicide	Herbicide rate (x/ha)	Plant back To cotton
1	Balance	100 g	7 months
2	Flame	200 ml	24 months
3	Grazon Extra	400 ml	?
4	Sakura	118 g	5 months
5	Sharpen	272 g	6 weeks
6	Starane	900 ml	1 month
7	2,4-D amine	1.6 L	21 days
8	2,4-D amine x8	12.8 L	?
9	Untreated		

Note. The usage of Flame in these experiments is outside the label recommendation.

The eight times rate of 2,4-D was included as a camera-spray treatment comparison, with two untreated plots in each main-plot. Treatments were applied as per label directions using a high-clearance sprayer with TTI 110015 nozzles at 30 psi and 100 L/ha water.

Destructive samples were taken twice early in the cotton growing season. Five plants were taken from each plot and plant stand, plant height, node and leaf counts, leaf area and dry weight were measured for each treatment and replication. Leaf area measurements were taken using a leaf area meter. The cotton was defoliated and picked using a single-row plot picker and ginned to determine gin turn-out.

Results and discussion

The data will be fully analysed next year with the intention of publishing in a scientific journal. Preliminary results are as follows, with results from the three seasons combined.

In-crop herbicides with no following fallow residual herbicides:

Herbicide	**Plant stand**		**Height**		**Biomass**		**Yield**	
	(No./m)	**s.e.**	**(cm)**	**s.e.**	**(g/m)**	**s.e.**	**(Bales/ha)**	**s.e.**
Atlantis	9.1	0.4	26.9	2.9	49.2	10.7	10.3	0.4
Balance	9.1	0.2	31.3	3.2	70.9	14.7	10.9	0.4
Hussar	9.3	0.3	25.0	2.6	55.4	11.9	10.8	0.4
Precept	9.0	0.2	27.5	2.8	53.8	12.0	10.6	0.4
Simazine	9.2	0.3	28.8	3.0	57.8	12.3	10.3	0.7
Starane	9.7	0.3	27.5	2.8	70.8	14.3	11.2	0.4
Velocity	9.3	0.3	26.9	2.7	55.9	11.8	11.2	0.6
Untreated	9.3	0.3	28.7	3.0	65.6	14.2	10.7	0.6

None of the herbicides applied in-crop detrimentally affected the following cotton crop.

In-fallow herbicides with no herbicides applied in the previous crop:

Herbicide	**Plant stand**		**Height**		**Biomass**		**Yield**	
	(No./m)	**s.e.**	**(cm)**	**s.e.**	**(g/m)**	**s.e.**	**(Bales/ha)**	**s.e.**
2,4-D amine	8.8	0.3	25.7	3.7	44.6	14.8	11.5	0.7
2,4-D amine x8	9.3	0.3	26.8	3.7	61.7	18.6	10.5	0.6
Balance	9.2	0.3	26.3	3.5	56.3	16.1	11.9	0.8
Flame	8.2	0.4	16.8	2.8	30.1	12.8	9.0	0.9
Grazon Extra	7.9	0.6	19.3	3.1	32.6	11.5	9.1	0.9
Sakura	8.8	0.5	22.4	3.0	44.2	13.5	11.1	0.6
Sharpen	8.5	0.5	20.4	2.8	37.8	12.2	11.5	0.5
Starane	9.1	0.4	25.9	3.6	52.6	16.8	11.4	0.6
Untreated	9.3	0.3	28.7	3.0	65.6	14.2	10.7	0.6

When considered alone, with no residual herbicides applied in the previous crop, in-fallow applications of Flame, Grazon Extra and Sharpen reduced the cotton plant stand by 8 –

14%. Early-season crop height was reduced by 22 - 41% by Flame, Grazon Extra, Sakura and Sharpen. Flame and Grazon Extra also reduced crop biomass by 50% and 54%, respectively. The cotton recovered from this early-season damage from Sakura and Sharpen, but 15% yield reductions were recorded for Flame and Grazon Extra.

These results become far more complex and interesting when the interactions of in-crop and fallow herbicides are considered. The complexity would be even more challenging in the real world where multiple herbicides may be used in crop and it would be common to apply multiple residual herbicides over the fallow period. Seasonal conditions have a big influence on the breakdown of these herbicides and the effects would be likely to be more pronounced in dryer seasons, compared with these results from a series of wetter than normal years.

In-crop herbicides averaged over fallow herbicides:

Herbicide	**Plant stand**		**Height**		**Biomass**		**Yield**	
	(No./m)	**s.e.**	**(cm)**	**s.e.**	**(g/m)**	**s.e.**	**(Bales/ha)**	**s.e.**
Atlantis	8.6	0.2	23.8	1.2	47.8	5.0	10.1	0.3
Balance	8.8	0.1	26.2	1.2	53.8	5.5	10.8	0.3
Hussar	8.5	0.2	21.8	1.1	45.1	4.8	9.9	0.3
Precept	8.7	0.1	23.3	1.1	45.7	4.7	10.2	0.2
Simazine	8.6	0.2	24.5	1.2	46.2	4.7	10.8	0.3
Starane	8.5	0.2	23.8	1.2	49.5	5.1	10.2	0.3
Velocity	8.9	0.2	23.3	1.1	44.8	4.5	10.7	0.3
Untreated	8.8	0.1	24.0	1.1	48.6	5.0	10.8	0.2

When averaged over the fallow treatments, the in-crop applications of Hussar and Starane reduced the cotton plant stand by 3 – 4%. None of the herbicides reduced early-season growth as measured by crop height or crop above-ground biomass. Plants recovered from the early-season damage from Starane, but there was an 8% reduction in cotton yield following Hussar.

In-fallow herbicides averaged over in-crop herbicides:

Herbicide	**Plant stand**		**Height**		**Biomass**		**Yield**	
	(No./m)	**s.e.**	**(cm)**	**s.e.**	**(g/m)**	**s.e.**	**(Bales/ha)**	**s.e.**
2,4-D amine	9.2	0.1	25.8	1.3	50.7	5.7	11.1	0.3
2,4-D amine x8	9.3	0.1	25.2	1.3	51.9	5.6	10.9	0.3
Balance	9.0	0.1	25.0	1.3	49.0	5.4	11.2	0.3
Flame	7.4	0.2	15.2	1.0	24.4	4.2	7.6	0.4
Grazon Extra	7.7	0.2	22.1	1.3	42.0	4.9	9.2	0.3
Sakura	8.4	0.2	22.9	1.3	45.2	5.2	10.9	0.3
Sharpen	8.8	0.1	22.7	1.2	43.7	4.8	11.1	0.3
Starane	8.7	0.2	25.0	1.3	53.3	6.0	11.0	0.3
Untreated	9.2	0.1	27.8	1.0	60.0	4.5	10.8	0.2

When averaged over the in-crop herbicides, all in-fallow herbicides other than 2,4-D amine reduced the cotton plant stand, with reductions of 3 – 20%. All applications reduced early-season crop height, with reductions of 7 – 46%, and most reduced crop biomass (16 – 59%). The cotton generally recovered from this early-season damage, with yield reductions of 29% and 15% apparent only from Flame and Grazon Extra, respectively.

The following tables present the results for each in-crop and in-fallow herbicide combination.

In-fallow herbicides following Atlantis applied in wheat:

Herbicide	Plant stand		Height		Biomass		Yield	
	(No./m)	s.e.	(cm)	s.e.	(g/m)	s.e.	(Bales/ha)	s.e.
2,4-D amine	9.0	0.3	25.7	3.7	56.6	17.9	11.6	1.0
2,4-D amine x8	9.5	0.4	25.4	3.4	54.7	17.7	10.0	0.7
Balance	8.9	0.3	25.2	3.9	53.2	17.2	10.7	0.5
Flame	7.3	0.6	14.9	2.9	26.1	14.1	7.2	1.2
Grazon Extra	8.2	0.6	23.1	3.8	46.2	13.6	9.2	1.1
Sakura	7.6	0.6	21.1	3.3	43.8	14.0	11.2	0.8
Sharpen	9.3	0.3	23.8	3.3	42.0	13.6	10.9	0.5
Starane	8.2	0.5	26.1	3.7	57.2	19.9	9.8	0.9
Untreated	9.1	0.4	26.9	2.9	49.2	10.7	10.3	0.4

The in-crop application of Atlantis followed by in-fallow applications of Flame, Grazon Extra, Sakura and Starane reduced the cotton plant stand by 10 – 21%. Flame and Sakura also reduced early-season crop height by 45% and 22% respectively, and Flame reduced crop biomass by 47%. Plants were able to compensate for the early-season damage by Sakura, but damage from Flame and Grazon Extra resulted in 30% and 11% reductions in cotton lint yield, respectively.

In-fallow herbicides following Balance applied in chickpea:

Herbicide	Plant stand		Height		Biomass		Yield	
	(No./m)	s.e.	(cm)	s.e.	(g/m)	s.e.	(Bales/ha)	s.e.
2,4-D amine	9.6	0.5	28.1	3.9	61.2	19.1	11.3	0.8
2,4-D amine x8	9.3	0.3	27.9	3.9	59.0	16.9	11.4	0.3
Balance	9.2	0.4	27.2	3.8	63.2	19.6	11.9	0.5
Flame	6.9	0.6	14.2	2.8	11.5	8.0	7.4	1.6
Grazon Extra	7.6	0.4	25.0	3.8	37.2	13.4	9.6	1.1
Sakura	8.6	0.4	25.2	3.9	52.8	16.4	11.3	0.6
Sharpen	9.5	0.3	26.3	3.5	55.3	16.2	11.4	0.6
Starane	8.8	0.5	26.7	4.1	57.5	19.1	11.9	0.9
Untreated	9.1	0.2	31.3	3.2	70.9	14.7	10.9	0.4

The in-crop application of Balance followed by in-fallow applications of Flame, Grazon Extra and Sakura reduced the cotton plant stand by 5 – 24%. Flame also reduced early-season height by 55%. Flame and Grazon Extra reduced crop biomass by 84% and 48%, respectively. Plants were able to compensate for the early-season damage by Sakura, but damage from Flame and Grazon Extra resulted in 33% and 13% reductions in cotton lint yield, respectively.

In-fallow herbicides following Hussar applied in wheat:

Herbicide	Plant stand		Height		Biomass		Yield	
	(No./m)	s.e.	(cm)	s.e.	(g/m)	s.e.	(Bales/ha)	s.e.
2,4-D amine	9.4	0.3	22.9	3.7	41.8	14.5	9.9	0.8
2,4-D amine x8	7.9	0.6	21.5	3.7	54.6	17.9	10.3	1.1
Balance	9.1	0.3	24.2	4.0	50.4	16.4	10.1	0.7
Flame	7.4	0.5	14.0	2.4	21.4	10.0	7.1	1.2
Grazon Extra	7.3	0.7	21.1	3.8	45.4	16.5	8.0	1.0
Sakura	8.6	0.4	22.3	3.8	44.2	14.1	10.8	0.9
Sharpen	8.3	0.5	19.2	3.1	37.9	12.2	11.6	0.9
Starane	8.8	0.5	23.5	3.8	47.1	15.9	10.0	1.1
Untreated	9.3	0.3	25.0	2.6	55.4	11.9	10.8	0.4

The in-crop application of Hussar followed by in-fallow applications of Flame, Grazon Extra, Sakura and Sharpen reduced the cotton plant stand by 8 – 22%. Flame and Sharpen also reduced early-season crop height by 44% and 23%, respectively. Flame reduced crop biomass by 61%. Plants were able to compensate for the early-season damage by Sharpen, but damage from Flame and Grazon Extra resulted in 34% and 26% reductions in cotton lint yield, respectively.

In-fallow herbicides following Precept applied in wheat:

Herbicide	Plant stand		Height		Biomass		Yield	
	(No./m)	s.e.	(cm)	s.e.	(g/m)	s.e.	(Bales/ha)	s.e.
2,4-D amine	9.2	0.4	23.9	3.6	55.3	18.4	10.4	0.6
2,4-D amine x8	9.4	0.3	24.0	3.4	49.7	14.5	10.7	0.6
Balance	8.8	0.5	23.2	3.7	42.9	13.9	11.7	0.4
Flame	7.3	0.6	15.0	2.9	30.4	13.2	7.3	1.2
Grazon Extra	8.4	0.4	22.7	3.6	44.3	14.1	10.6	0.7
Sakura	8.8	0.3	24.0	3.7	33.3	10.5	9.9	0.5
Sharpen	8.6	0.3	24.7	3.6	48.1	13.5	10.5	0.6
Starane	8.3	0.6	21.8	3.6	47.8	16.3	9.8	0.9
Untreated	9.0	0.2	27.5	2.8	53.8	12.0	10.6	0.4

The in-crop application of Precept followed by in-fallow applications of Flame, Grazon Extra and Starane reduced the cotton plant stand by 6 – 18%. Flame and Starane also reduced early-season crop height by 46% and 21%, respectively. Plants were able to compensate for the early-season damage by Starane, but damage from Flame resulted in a 31% reduction in cotton lint yield.

In-fallow herbicides following simazine applied in chickpea:

Herbicide	Plant stand		Height		Biomass		Yield	
	(No./m)	s.e.	(cm)	s.e.	(g/m)	s.e.	(Bales/ha)	s.e.
2,4-D amine	9.4	0.4	27.0	3.6	46.0	14.3	11.0	0.7
2,4-D amine x8	9.8	0.4	26.6	3.5	47.4	14.2	11.7	0.6
Balance	8.9	0.4	25.6	3.8	46.5	14.6	11.8	0.7
Flame	7.3	0.5	15.5	3.2	22.3	14.3	8.3	1.5
Grazon Extra	6.9	0.6	21.5	3.6	37.5	12.9	9.2	1.1
Sakura	8.4	0.4	23.2	3.7	49.9	15.0	10.8	0.6
Sharpen	8.6	0.3	22.2	3.3	44.8	15.4	12.3	0.9
Starane	8.8	0.4	26.9	3.7	53.4	15.9	12.0	0.6
Untreated	9.2	0.3	28.8	3.0	57.8	12.3	10.3	0.7

The in-crop application of simazine followed by in-fallow applications of Flame, Grazon Extra and Sakura reduced the cotton plant stand by 9 – 26%. Flame, Grazon Extra and Starane also reduced early-season crop height by 23 – 46%. Flame reduced crop biomass by 61%. Plants were able to compensate for the early-season damage by Grazon Extra, Sakura and Starane, but damage from Flame resulted in a 19% reduction in cotton lint yield.

In-fallow herbicides following Starane applied in wheat:

Herbicide	Plant stand		Height		Biomass		Yield	
	(No./m)	s.e.	(cm)	s.e.	(g/m)	s.e.	(Bales/ha)	s.e.
2,4-D amine	8.8	0.3	26.9	3.7	53.9	16.1	11.4	0.9
2,4-D amine x8	9.0	0.4	25.4	3.7	44.5	14.0	11.3	0.7
Balance	8.8	0.5	24.7	3.7	43.1	13.4	9.9	1.0
Flame	6.6	0.5	14.1	2.9	23.3	9.7	6.8	1.1
Grazon Extra	7.5	0.6	23.1	3.7	44.9	15.0	9.1	1.2
Sakura	8.1	0.4	23.7	3.6	42.0	17.7	10.9	0.5
Sharpen	8.3	0.4	21.7	3.2	44.7	14.6	9.8	0.8
Starane	8.5	0.5	24.6	3.7	62.3	18.4	10.4	0.8
Untreated	9.7	0.3	27.5	2.8	70.8	14.3	11.2	0.4

The in-crop application of Starane followed by in-fallow applications of any of the fallow herbicides reduced the cotton plant stand by 7 – 32%. Flame and Sharpen reduced early-season crop height by 49% and 21%, respectively, and crop biomass by 67% and 37%, respectively. Plants were able to compensate for the early-season damage by 2,4-D amine, Sakura and Starane, but damage from Balance, Flame, Grazon Extra and Sharpen reduced cotton lint yield 13 – 40%.

In-fallow herbicides following Velocity applied in wheat:

Herbicide	Plant stand		Height		Biomass		Yield	
	(No./m)	s.e.	(cm)	s.e.	(g/m)	s.e.	(Bales/ha)	s.e.
2,4-D amine	9.5	0.4	25.9	3.9	45.1	14.3	11.2	0.8
2,4-D amine x8	10.0	0.4	23.9	3.2	43.6	13.0	11.2	0.7
Balance	8.9	0.3	23.4	3.2	36.9	11.0	11.4	0.9
Flame	8.1	0.5	16.7	3.2	28.6	11.3	7.6	1.1
Grazon Extra	7.4	0.7	21.3	3.7	47.4	14.9	8.5	1.3
Sakura	8.3	0.6	21.0	3.8	50.6	17.7	11.3	1.0
Sharpen	9.0	0.4	23.5	3.5	38.8	11.6	11.0	0.6
Starane	8.9	0.4	24.4	3.5	48.7	14.5	12.5	0.5
Untreated	9.3	0.3	26.9	2.7	55.9	11.8	11.2	0.6

The in-crop application of Velocity followed by in-fallow applications of Flame, Grazon Extra or Sakura reduced the cotton plant stand by 11 – 20%. These herbicides reduced early-season crop height by 21 – 38% and Flame reduced crop biomass by 49%. Plants were able to compensate for the early-season damage by Sakura, but damage from Flame and Grazon Extra reduced cotton lint yield by 32% and 24%, respectively.

These results highlighted both the potential for residual herbicides used in preceding crops and fallows to damage cotton crops, and also the complexity of the interactions that can occur between herbicides.

Conclusions

In-crop herbicides did not damage the following cotton crops, but may accentuate damage from fallow herbicides.

Starane used in wheat contributed to the most consistent damage from fallow-herbicides in the following cotton.

Flame used in the fallow always caused a reduction in cotton yields. Growers should follow the label recommendation of a 24 month plant-back to cotton and not apply Flame to a fallow in the season prior to cotton.

Grazon Extra used in the fallow always caused some early-season damage to cotton, reducing the plant stand or seedling growth and caused reductions in cotton yield when following in-crop applications of Atlantis, Balance, Hussar, Starane or Velocity. Growers should avoid using Grazon Extra in a fallow prior to a cotton crop.

Sakura used in the fallow resulted in plant-stand or seedling damage following all in-crop herbicides except Precept, but plants recovered from the damage, with no yield reductions in the cotton. Growers should be cautious when using Sakura in a fallow prior to cotton.

Sharpen used in the fallow caused some plant-stand or seedling damage, depending on the preceding in-crop herbicide. Sharpen reduced cotton yields when following Starane used in the preceding crop. Growers should be cautious when using Sharpen in a fallow prior to cotton.

Starane used in the fallow caused some plant-stand or seedling damage, depending on the preceding in-crop herbicide, but this early-season damage didn’t lead to a reduction in the crop yield. Growers should be cautious when using Starane in a fallow prior to cotton.

Balance used in the fallow caused plant-stand and seedling damage and a reduction in the crop yield when following the application of Starane in the preceding crop. Growers should be cautious when using Balance if Starane has been or will be applied.

Residues of 2,4-D amine have caused crop growth and yield issues for numerous cotton growers over many years. Nevertheless, in this research, 2,4-D amine applied in the fallow caused no issues to the following cotton crop, even when applied at a rate eight times the label rate, except when it followed an application of Starane in the wheat crop. These results strongly suggest that crop safety from Starane used in a preceding crop or fallow is of real concern, and far more likely to cause damage than will 2,4-D amine. The symptoms of damage from Starane may be difficult to identify, with the herbicide generally just reducing the plant stand and plant vigour. Growers should be very cautious in their use of Starane in the 18 months prior to cotton.

These results highlight the complexity of interactions that may occur when multiple herbicides are applied to crops and fallows preceding cotton. Cotton growers need to be aware that the crop plant-back safety information on a herbicide label relates to the use of a single application of the herbicide with no other herbicides and may not be an accurate guide to crop safety when using multiple herbicides. The implication of these results needs to be applied to not just the herbicides used in these experiments, but also to other residual herbicides that may be used in the farming system. These herbicides may have similar or greater issues than the herbicides reported here.

Milestone 1.2. – Explore selected residual options in dryland fields

Background

The evolution of glyphosate resistance in several weeds in cotton cropping systems has changed the way growers need to manage weeds since the introduction of Roundup Ready cotton. Before Roundup Ready technology was introduced, growers relied on full residual programs to manage weeds. Since its adoption, growers tended to rely heavily on glyphosate. In nearly two decades of reliance on glyphosate, a new generation of growers and consultants have had limited experience with the fit of residuals in cotton systems.

This milestone aims to investigate the effects of residual herbicides used in fallow and cotton on the following respective cotton and winter cereals. This information will enable us to determine which herbicides are likely to cause damage to following crops and which herbicides have little or no impact.

Results from Qld

Methods and materials

The experiment was conducted at Hermitage Research Facility, Warwick and split into two parts: A) fallow residual herbicides preceding cotton, and B) cotton herbicides preceding winter cereals.

Part A

Part A was established as a randomised complete block with 4 replicates. Each plot was 3 m x 10 m. The width of these plot was determined so that when cotton was planted with 2 rows 1 m apart along the middle of the plot, the whole trial resembled a single-skip configuration. The experiment consisted of eight treatments, outlined below:

Treatment	Herbicide	Herbicide rate (mL or g/ha)
1	Untreated	
2	Balance	100
3	Imazapic	200
4	Valor	210
5	Grazon Extra	400
6	2,4-D	1100
7	2,4-D x8	8800
8	Starane	900

The 2,4-D and Starane treatments were included to simulate fallow sprays that may be conducted with optical sprayer technology (OST), in particular, the eight times rate of 2,4-D treatment. All treatments were applied with a tractor mounted sprayer with a 2 m shrouded boom using TTI110015 nozzles at 30 psi and 100 L/ha water. Treatments 2-5 were applied in late June, with the remaining treatments applied in August. Sicot 746B3F was used in both years. In the first year, cotton was planted in late November and irrigated the day after planting. No further irrigation was required with adequate rainfall received for the remainder of the season. The repeat experiment in the second year was conducted in a different field.

Cotton was planted in mid-December due to continuous rain preventing the soil from drying out enough to plant earlier.

Destructive samples were taken 3 times early in the cotton growing season commencing when the 2nd set of true leaves emerged, then every 2 – 3 weeks after. Five plants were taken from each of the two rows and plant height, node and leaf counts, leaf area and dry weight (biomass) were measured and grouped for each treatment and replication. Leaf area measurements were taken using a leaf area meter.

In the first year, cotton was defoliated and picked using a plot picker and ginned in a small gin to determine gin turn-out. The trial in the second year was considerably damaged due to continuous rainfall. As a result, the cotton was unable to be defoliated and machine picked. Approximate yield was determined by selecting a 1 m section of each plot, cutting the bolls of each plant, and then manually pulling out the lint. Gin turn-out was assumed to be 43% of the original lint and seed weight, as this was the average for year 1.

Part B

This part of the experiment was established as a randomise complete block design with 3 replicates. Each plot was 3 m x 24 m. The plots were this length to plant the 4 winter cereals (wheat, durum, barley and chickpea) at right-angles to the way the herbicide treatments were applied. This then allowed for a 6 m wide planting of each cereal, with measurements coming from the middle 2 metres. The experiment consisted of 6 treatments outlined below:

Treatment	**Herbicide**	**Herbicide rate (mL or g/ha)**
1	Untreated	
2	Diuron	2000
3	Prometryn	2500
4	Trifluralin	2300
5	Pendimethalin	3400
6	Valor	90

Treatments were applied 1 day prior to cotton planting, with trifluralin and pendimethalin mechanically incorporated within 4 hours. Cotton was then planted through the plots at the same time as Part A. In the first year, cotton was picked at the same time as Part A and then the trial slashed and prepared for planting the winter cereals. The cereals were planted at the end of July. Sampling was conducted 3 times commencing at approximately 2 leaves for the cereals, and 4 nodes for the chickpeas. Samples were then taken at 2 and 4 weeks later. Samples were taken from 1 m of row and 10 plants selected for measurements. Plant height, number of leaves, leaf area, biomass was measured. At the end of the season crops were hand harvested from 1 m of row and threshed to obtain yield measurements.

In the second year, due to wet conditions, planting didn't occur until August, and only one sampling time was able to be conducted. This occurred just prior to booting. The wet conditions and intermittent water logging resulted in the death of the chickpeas, therefore no data was obtained. The other winter cereals were harvested in the same manner as the first year.

Results and discussion

Part A

In the first year of the experiment (2020/21), Imazapic significantly reduced cotton height, leaf number and the dry weight at the first sampling time (Figure 1). Imazapic continued to effect cotton growth for the remainder of the experiment, with the effects also being seen in leaf area. As the season progressed, the effects of Balance were also significant for cotton height, leaf number, leaf area, and dry weight particularly for the sampling time three (approximately 14 nodes). Imazapic was the only herbicide to produce a significant reduction in cotton yield. Yield in the Imazapic treatment was 1.2 bales/ha, as opposed to 5.7 bales/ha in the untreated plots. The yield in the Balance, Grazon Extra, 2,4-D and Starane treatments were lower than the untreated (approximately 4 bales/ha), however this effect was not significant. The high rate of 2,4-D had no effect on cotton growth and yield in this experiment. There were also no effects of the herbicide treatments on the gin turn-out, which was approximately 43%.The repeat experiment was affected by considerable rainfall with approximately 290 mm between applying the herbicide treatments and planting the cotton. There was also approximately 690 mm of in season rain. As a result, the trial was underwater twice, with considerable wash across the plots. No effects on cotton height were observed. No effects on any of the parameters measured were observed for the first two sampling times. Starane had the highest values for leaves, leaf area and biomass. This was followed by Balance, Grazon Extra and 2,4-D. The Imazapic and untreated plots had the lowest values for these parameters. These effects did not translate to the yield results. Yield was less than the previous year and ranged from 3.4 bales/ha in the untreated plots down to 1.1 bales/ha for the Imazapic treatment. The reduction in yield in the 2,4-D treatment was also significant at 1.6 bales/ha. However, the 2,4-D x8 treatment had a statistically similar yield to the untreated at 2.9 bales/ha. It is unclear as to why the lower 2,4-D rate had a greater impact on the cotton than the higher rate.

Results from the repeat experiment are likely to have been affected by high rainfall and subsequent water movement across the trial. However, the effects of Imazapic on cotton growth and yield were evident in both years. Imazapic is highly water soluble, it is proposed that initial rain moved the herbicide layer down in the profile deep enough not to be moved around with soil/water. The other herbicides bind more to the soil, and therefore may have moved with soil when the trial was underwater. The effect of the other herbicides was less evident. The phenoxy herbicides applied in the fallow had no significant effect on cotton yield, apart from 2,4-D in the repeat experiment. Even the high rate of 2,4-D designed to simulate OST applications had no effect. Reasons for this are unclear.

Part B

The maximum plant back to winter cereals for the cotton herbicides used is Diuron, with a plant back of 2 years. This is followed by trifluralin at 12 months and Prometryn at 6 months. The remaining herbicides have virtually no plant back concerns for winter cereals. These plant backs were reflected in the first seasons results with no significant effects of the herbicides on chickpea, wheat and barley (Figures 5-8). The only significant reductions occurred on the yield of durum in response to Diuron (0.8 t/ha) and Valor (1 t/ha) compared to the untreated plots (1.6 t/ha).

The repeat experiment in 2022 was affected by wet conditions. None of the herbicides applied at the time of cotton planting had significant effects on the growth and development of the winter cereals. The waterlogging conditions resulted in the death of the chickpeas, however, did not seem to affect the winter cereals.

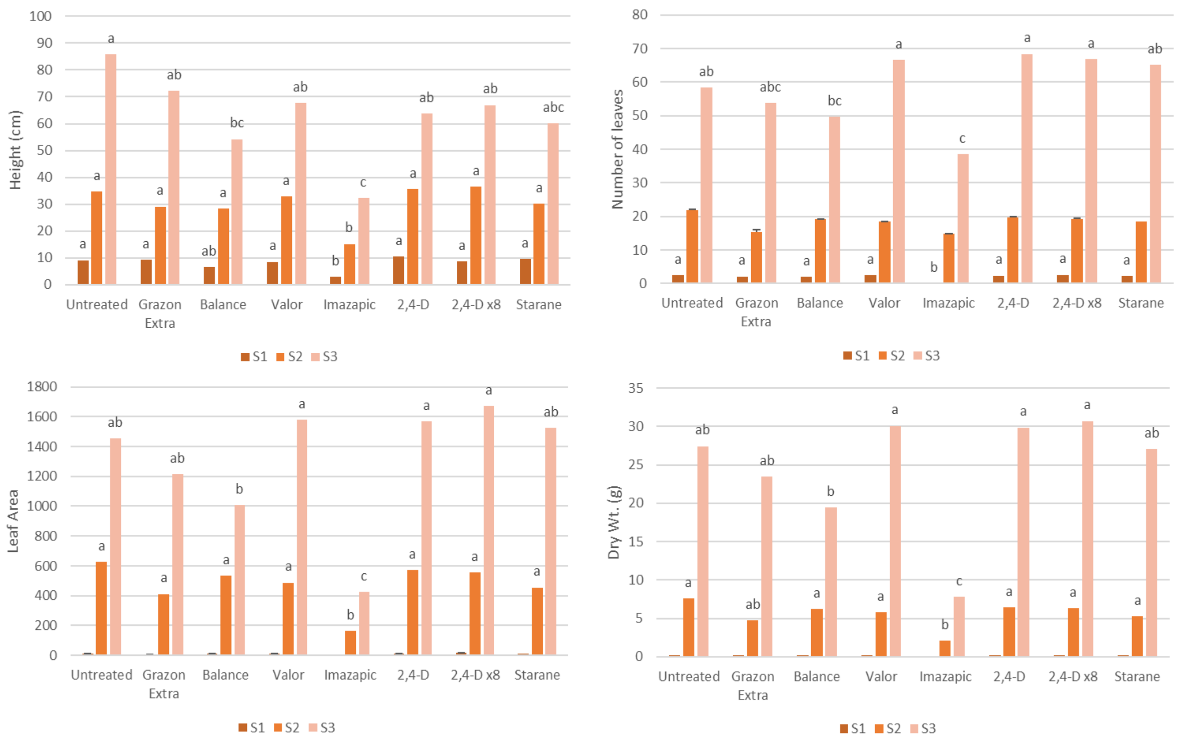


Figure 1. 2020/21 cotton height, leaves, leaf area and biomass with respect to herbicide treatment. The legend denotes sampling times. S1 – time one, S2 – time two, and S3 – time three. Bars with different letters for each respective sampling time are significantly different (p < 0.05).

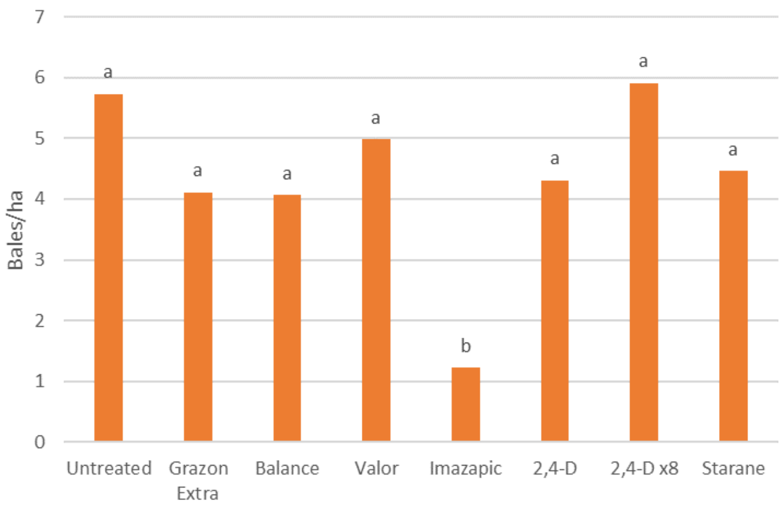


Figure 2. 2020/21 Cotton yield with respect to herbicide treatment. Bars with different letters are significantly different (p < 0.05).

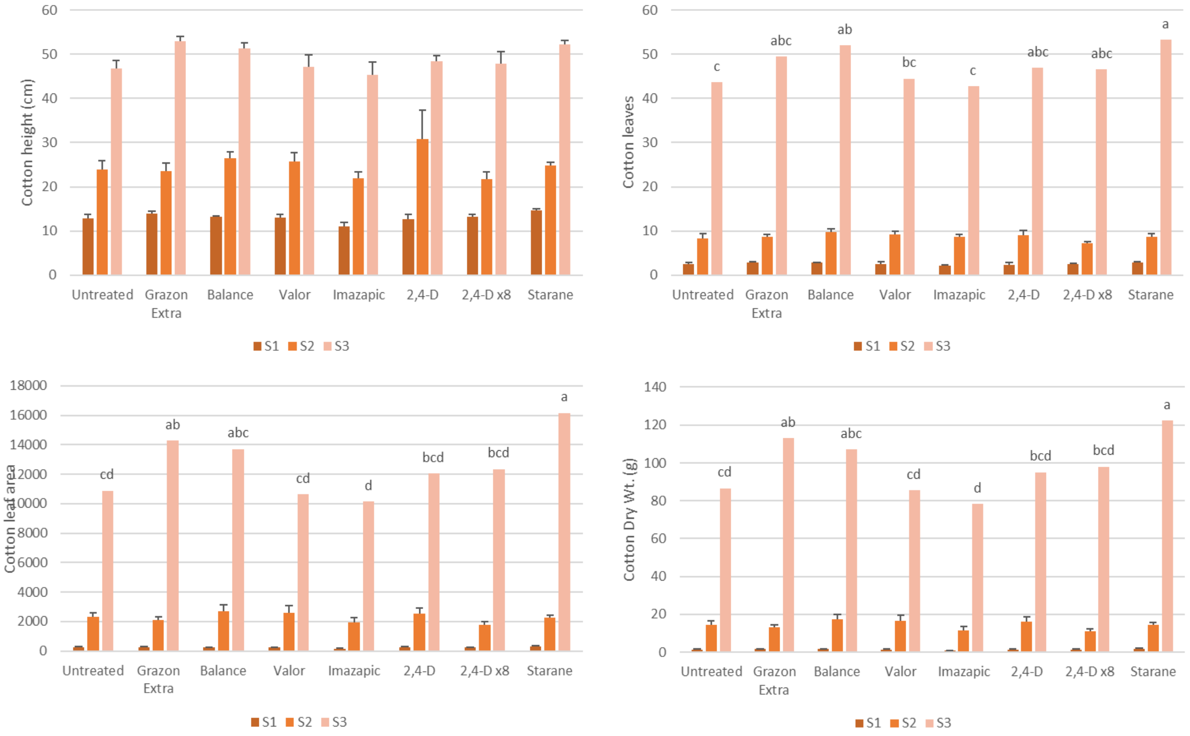


Figure 3. 2021/22 cotton height, leaves, leaf area and biomass with respect to herbicide treatment. The legend denotes sampling times. S1 – time one, S2 – time two, and S3 – time three. Bars with different letters for each respective sampling time are significantly different ($p < 0.05$). The effect of each herbicide on cotton height was not significant, error bars represent the standard error.

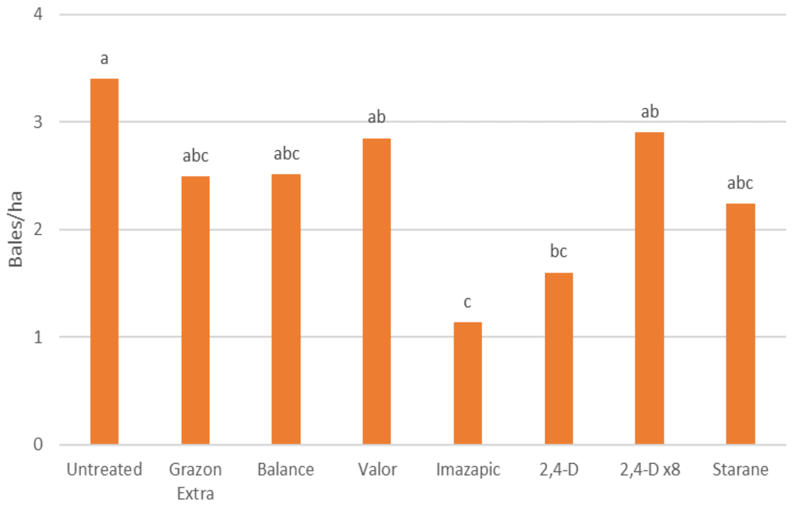


Figure 4. 2021/22 Cotton yield with respect to herbicide treatment. Bars with different letters are significantly different ($p < 0.05$).

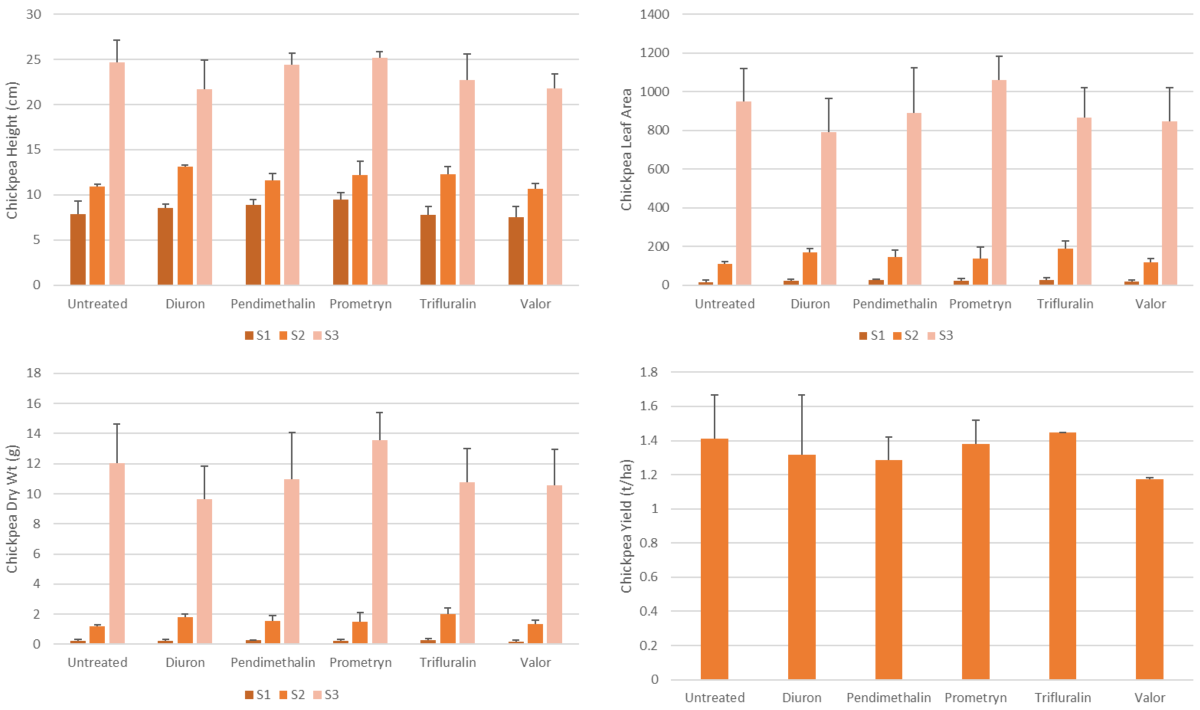


Figure 5. 2021 Chickpea height, leaf area, biomass and yield with respect to herbicide treatments. The legend denotes sampling times. S1 – time one, S2 – time two, and S3 – time three. Error bars indicate standard error of the mean.

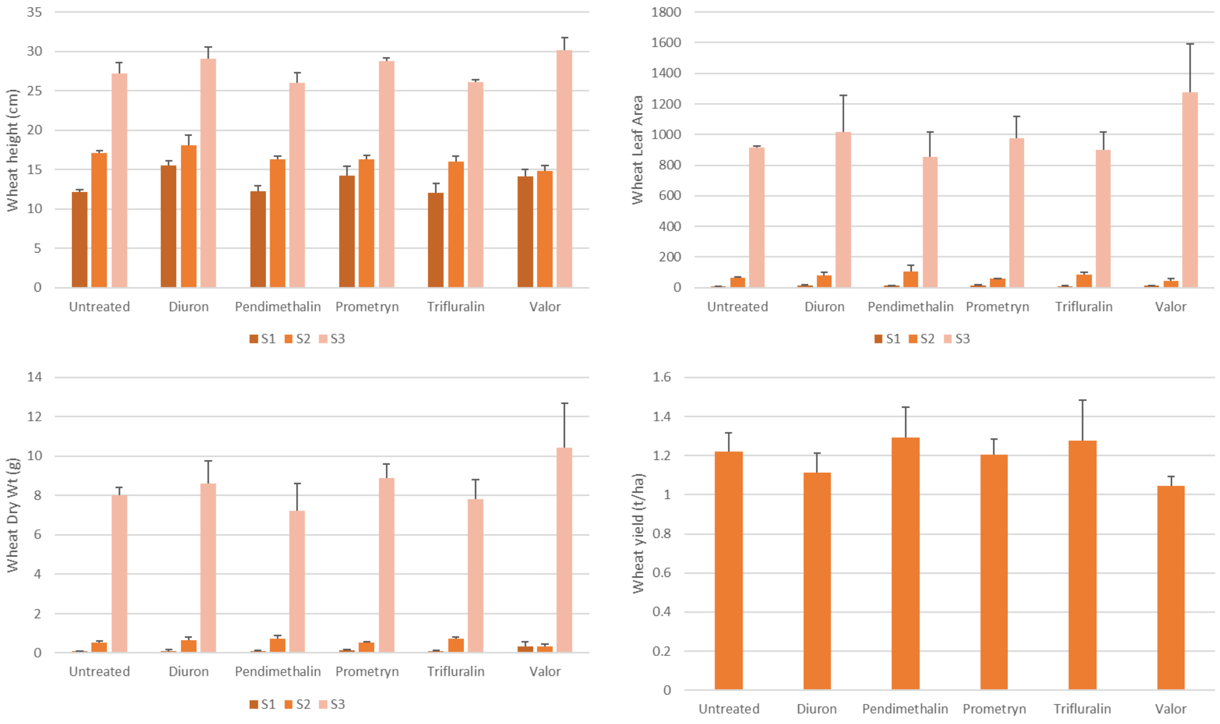


Figure 6. 2021 Wheat height, leaf area, biomass and yield with respect to herbicide treatments. The legend denotes sampling times. S1 – time one, S2 – time two, and S3 – time three. Error bars indicate standard error of the mean.

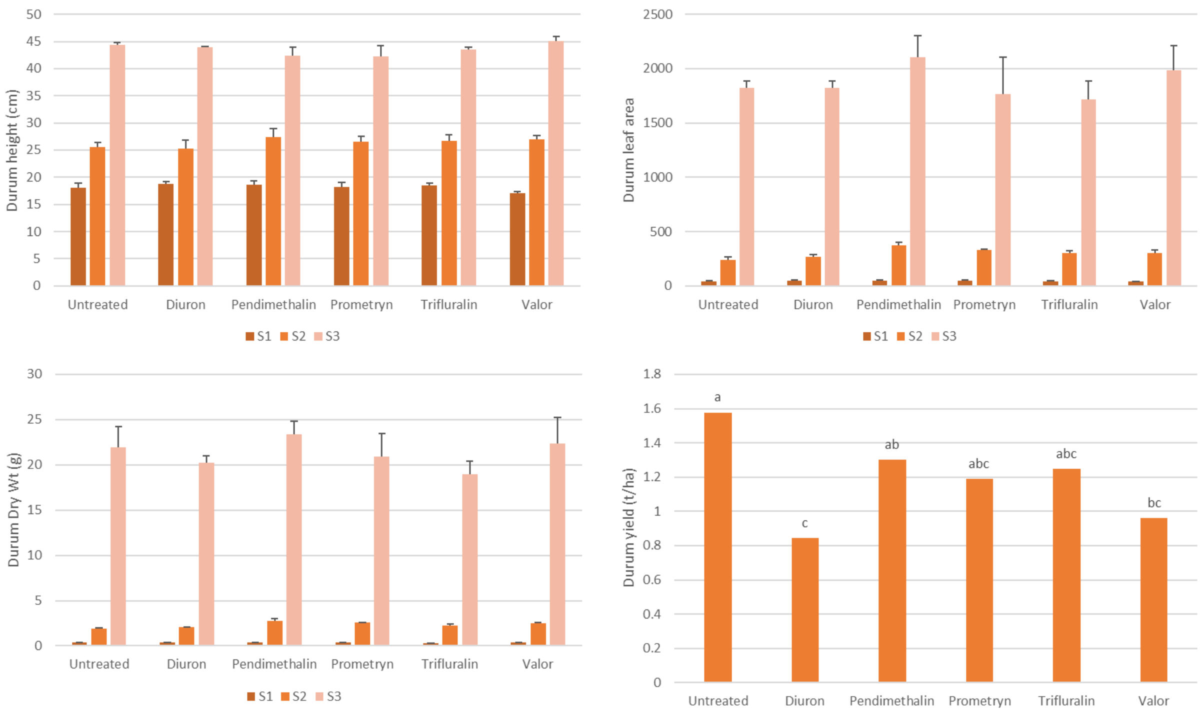


Figure 7. 2021 Durum height, leaf area, biomass and yield with respect to herbicide treatments. The legend denotes sampling times. S1 – time one, S2 – time two, and S3 – time three. Error bars indicate standard error of the mean. For Durum yield, bars with different letters are significantly different (P>0.05).

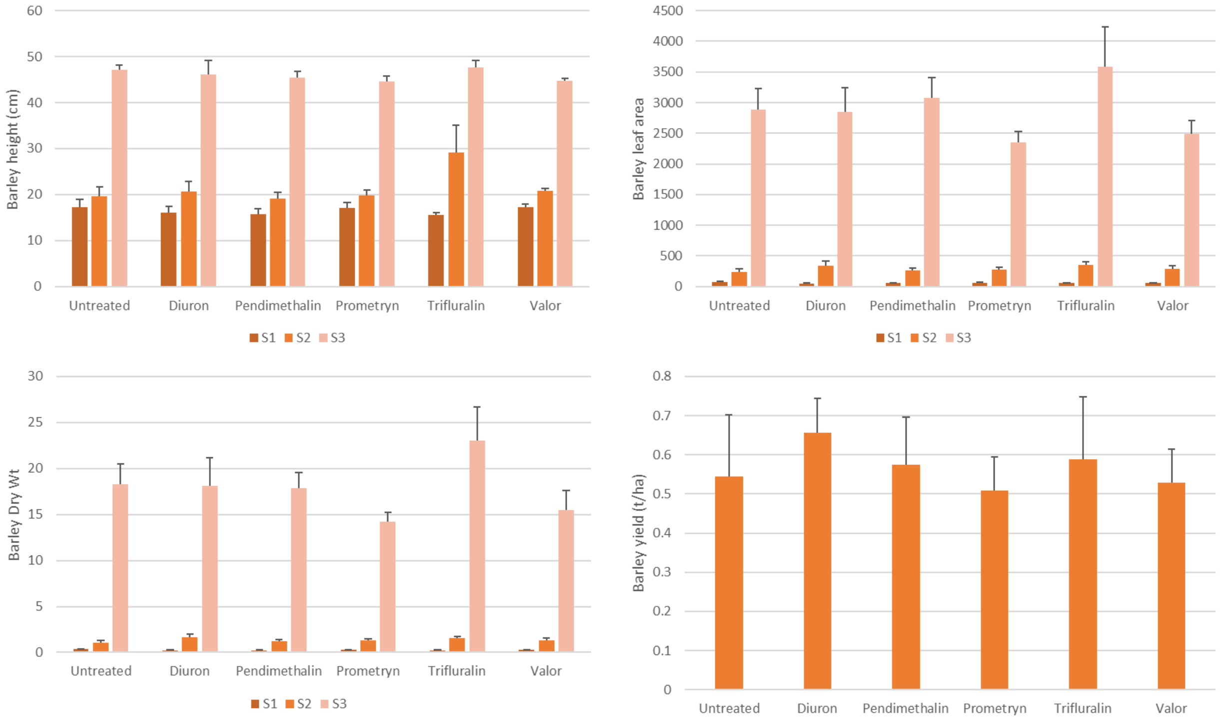


Figure 8. 2021 Barley height, leaf area, biomass and yield with respect to herbicide treatments. The legend denotes sampling times. S1 – time one, S2 – time two, and S3 – time three. Error bars indicate standard error of the mean.

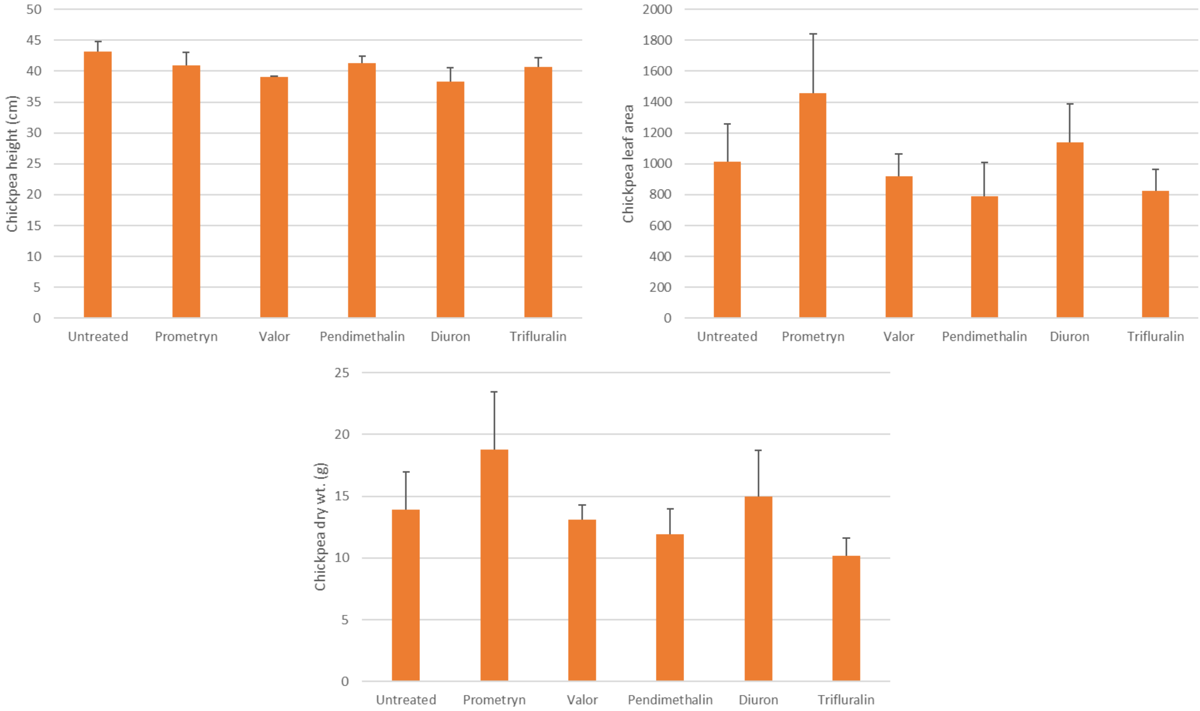


Figure 9. 2022 Chickpea height, leaf area and biomass with respect to herbicide treatments. Error bars indicate standard error of the mean.

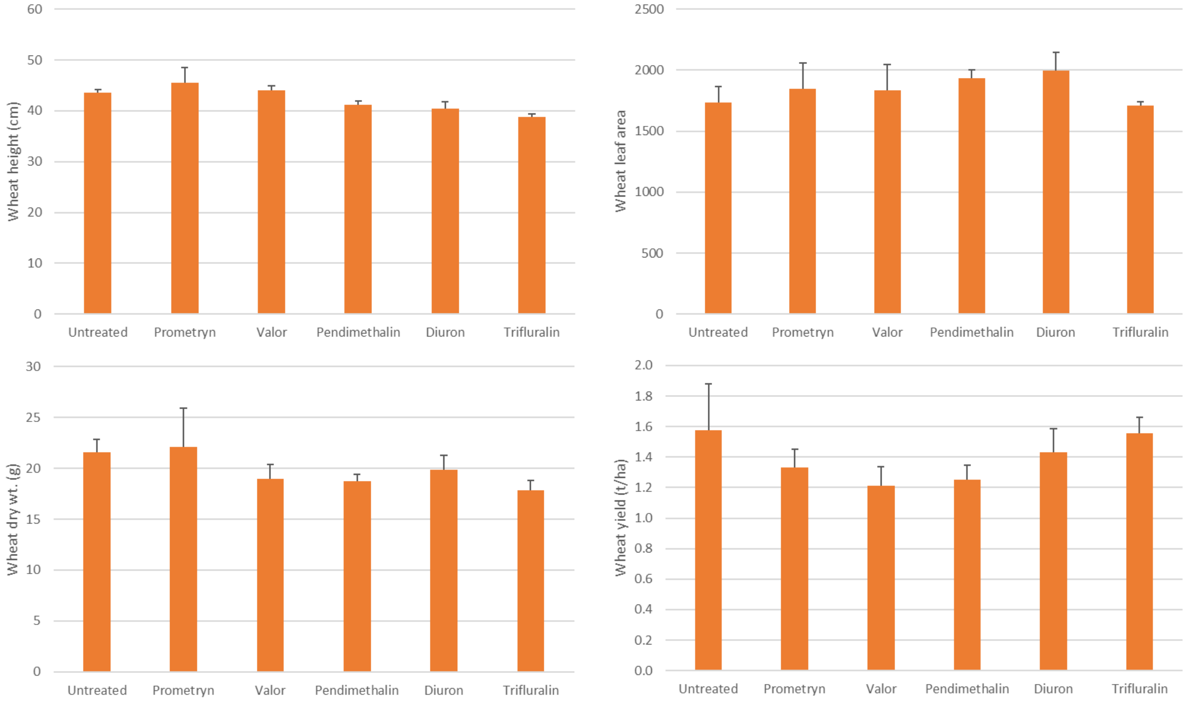


Figure 10. 2022 Wheat height, leaf area, biomass and yield with respect to herbicide treatments. Error bars indicate standard error of the mean.

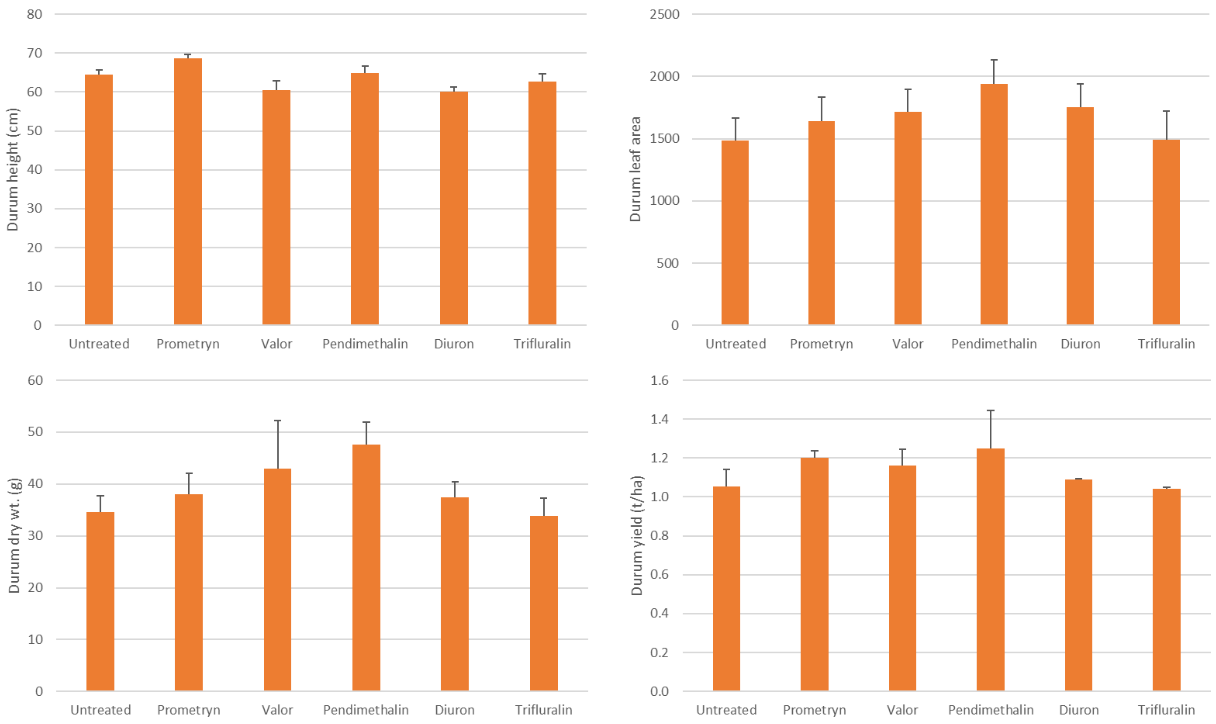


Figure 11. 2022 Durum height, leaf area, biomass and yield with respect to herbicide treatments. Error bars indicate standard error of the mean.

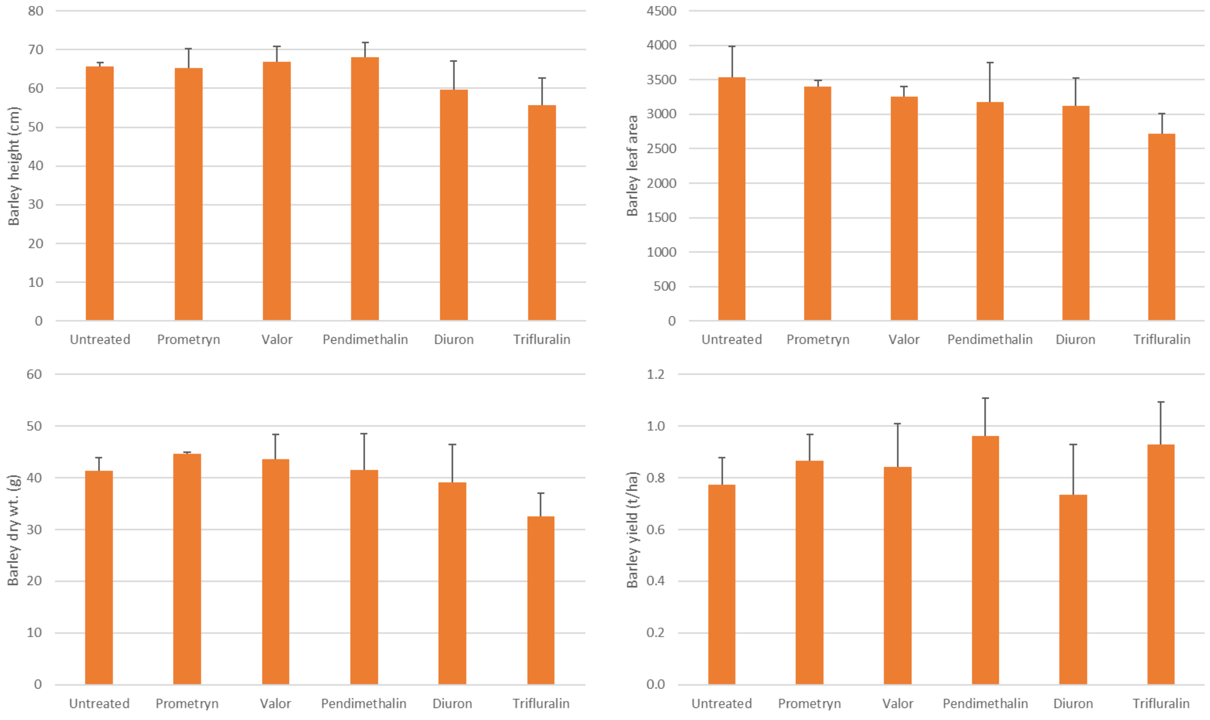


Figure 12. 2022 Barley height, leaf area, biomass and yield with respect to herbicide treatments. Error bars indicate standard error of the mean.

Results for Southern-NSW

The two planting dates of September 16 and October 5 were selected based on local best practice and results from 2019. There was no reduction in crop emergence between herbicide treatments. However, when averaged across all herbicide treatments establishment was higher from the late planting date, an indication that soil temperatures need to be on a rising trend. In crop weed counts showed pre-emergent herbicides reduced weed numbers compared to the control by > 95%. Plant biomass was measured at boll maturity with significant reductions in crop biomass from the control (weedy) and glyphosate only treatments. The field was weed free at planting and after watering up weeds emerged with the cotton. The delay in the application of the first in-crop glyphosate reduced crop biomass by up to 37% compared to residual herbicide treatments.

Plant height was reduced in the early planting time and where there were high weed numbers early in crop development (Treatment 1 & 2). Several cold shock events early in the crop’s development might also have contributed to the reduced height from TOS 1. There was no significant interaction between herbicide and node numbers per plant. There was a trend toward more nodes on the later planting date.

Cotton yield was greatest from the October 5 plant date which averaged 1bale/ha more than September 16 plant date. The highest yield (16.5 b/ha) was from treatment 3; Pendimethalin + glyphosate at plant, followed by Metolachlor + glyphosate OTT and a late glyphosate prior to canopy closure. In comparison the control had a yield reduction of 42% (9.7 b/ha) with a range from 5.5 to 11 b/ha across the replicates.

A small experiment in collaboration with Bayer was conducted to evaluate glufosinate and glyphosate application with two timings, one at midday and the second at sunset with three water rates; 50, 100 and 150L/ha. A glufosinate double knock is a robust strategy for control of a wide range of weeds. Control improved with higher humidity and as water rates were increased.

A farming systems experiment using evaluating the efficacy of the suite of Xtend herbicides was repeated at Leeton Research Station. The higher rates of Dicamba in the registered product provided up to 3 weeks of residual control of sowthistle compared to the control. A double knock of glufosinate provided >90% control of a range of grass and broadleaf weeds. The efficacy of the glufosinate as improved with early morning (higher humidity conditions) compared to the afternoon applications and there was a significant increase in activity when the water rates increased from 50L/ha to 100L/ha. There was no significant difference between 100L and 150L/ha water rates.

Milestones 1.3 & 1.5 – Explore potential issues with residual use from camera sprayers (high rates) and band-sprayers behind header tracts where weed seeds are concentrated

Background

The advent of camera sprayers has enabled growers to manage scattered large weeds in fallows by using relatively low rates of applied herbicide per ha and spot-applying herbicide just to these weeds. Permits and registrations for the use of higher than normal label rates of some herbicides has facilitated management of these large weeds using camera sprayers where such weeds would not be killed by a normal herbicide rate. Camera sprayers are typically set up to apply maximum rates, assuming application through a single nozzle. However, large weeds may trigger more than one nozzle, such that the rate of herbicide applied to a large weed could be twice the calibrated rate or more. Consequently, some herbicides may be being applied to small areas of a field at very high rates and the tolerance of cotton to these applications is not well understood. While generally only a small proportion of a fallow is sprayed with these high rates (say 5 – 20% of the field), it is still important to understand the level of damage that might be occurring to a following cotton crop.

Similarly, where crop residues are tram-tracked behind a header, it is common to use higher rates of herbicide to manage the flush of weeds that often occurs in these tracks. These experiments aim to measure the tolerance of cotton to potentially higher than normal rates of some residual herbicides. The design used rates of X, 2X, 4X and 8X the standard rates to cover the full range of herbicide rates that might occur.

Methods and materials

Residual herbicide treatments were applied in the fallow preceding an irrigated cotton crop using a randomise complete block design with 4 replicates. The experiment consisted of 6 herbicides, with each herbicide at 1X, 2X, 4X and 8X the standard rates, as shown below:

Treatment	Herbicide	Herbicide rate (x/ha)	Plant back To cotton
1	Balance	100 g	7 months
2	Sharpen	272 g	6 weeks
3	Starane	900 ml	1 month
4	Valor	140 g	
5	Voraxor	240 ml	9 months
6	2,4-D amine	1.6 L	21 days
7	Untreated		

Note. Cotton was planted within the plant-back window for Balance and Voraxor, and as such, damage to the cotton could be expected at a normal application rate of these herbicides.

The experiment was conducted over two seasons. The experiment has been expanded and continued under new CRDC funding and has been planted for a third season in 2023-24. Hence the results presented below are a summary of two season’s work and do not represent the final results from this experiment.

The herbicides were applied on the 26 July 2021 and 22 June 2022, and the cotton planted on 10 Oct 2021 and 10 Nov 2022, 76 and 141 days after spraying, respectively. Treatments were applied as per label directions using a high-clearance sprayer with TTI 110015 nozzles at 30 psi and 100 L/ha water. The crops were grown in line with normal practices. Destructive samples were taken twice early in the cotton growing season. Five plants were taken from each plot and plant stand, plant height, node and leaf counts, leaf area and dry weight were measured for each treatment and replication. Leaf area measurements were taken using a leaf area meter. The cotton was defoliated and picked using a single-row plot picker and ginned to determine gin turn-out.

Results and discussion

Preliminary results are as follows, with results from the two seasons combined.

Herbicide	Plant stand		Height		Biomass		Yield	
	(No./m)	s.e.	(cm)	s.e.	(g/m)	s.e.	(kg/ha)	s.e.
Balance	10.6	0.6	19.0	2.5	15.1	3.8	10.7	0.4
2X Balance	10.5	0.7	20.7	2.6	16.0	3.7	10.9	0.5
4X Balance	9.6	1.3	16.5	2.7	13.7	5.2	11.8	1.0
8X Balance	7.4	1.8	12.0	3.2	12.9	5.4	7.3	2.1
Sharpen	8.9	0.5	19.4	2.8	14.0	3.6	11.2	1.1
2X Sharpen	8.9	0.8	16.8	3.0	13.8	4.4	10.8	0.7
4X Sharpen	7.4	1.4	14.8	3.0	9.3	3.8	10.0	1.7
8X Sharpen	5.4	1.3	9.2	1.8	4.6	1.9	4.6	1.7
Starane	10.1	0.7	21.5	2.7	16.0	4.0	11.6	0.8
2X Starane	9.1	0.9	19.5	2.8	17.4	5.5	12.0	0.5
4X Starane	7.2	1.4	15.4	2.9	10.1	2.9	10.2	1.3
8X Starane	5.5	1.4	11.7	3.3	10.1	4.2	8.9	2.0
Valor	10.2	0.9	19.9	2.6	15.5	3.0	10.9	1.0
2X Valor	8.8	0.8	20.1	2.9	14.6	4.3	10.7	0.5
4X Valor	8.4	0.9	17.4	2.4	11.2	3.4	12.2	0.4
8X Valor	9.1	0.9	16.8	2.3	11.1	3.0	11.2	0.9
Voraxor	8.5	1.0	15.2	2.5	10.8	3.5	11.7	0.5
2X Voraxor	5.2	1.5	10.5	3.1	8.7	4.6	7.5	2.1
4X Voraxor	3.8	1.3	6.3	2.1	3.4	1.9	4.6	2.1
8X Voraxor	0.5	0.4	0.9	0.6	0.2	0.2	0.4	0.4
2,4-D	9.6	0.8	18.1	2.7	13.4	3.6	10.8	0.6
2X 2,4-D	11.5	1.6	21.5	2.8	19.8	5.4	11.6	0.8
4X 2,4-D	8.9	0.5	20.1	2.8	14.1	3.2	11.1	0.3
8X 2,4-D	8.9	0.7	20.4	2.6	16.0	4.3	11.7	0.6
Untreated	9.2	0.5	19.5	1.5	13.5	1.8	9.9	0.5

Note. Values in red are less than the untreated value by more than twice the standard error.

In-fallow applications of higher rates of Balance, Sharpen, Starane and Voraxor all damaged the following cotton crop, with the 8X rates of Balance and Sharpen and the 2X rate and higher rates of Voraxor reduced cotton lint yield.

When considered over the two seasons, damage from Balance was only observed at the 8X rate, with no damage apparent from a 4X rate of Balance. The 8X rate of Balance reduced the plant stand by 19%, early-season crop height 38% and lint yield 26%. However, Balance is an unusual herbicide, with a very short half-life in the field, but extremely low solubility.

Consequently, the break-down rate of Balance is very strongly affected by rainfall following application – each rainfall event dissolves some of the product which then rapidly breaks down. Balance has very limited breakdown under dry conditions. Closer examination of the data reveals damage at the 4X and 8X rates of Balance in the first season, where cotton was planted 76 days after spraying following what was a relatively dry winter. No damage was apparent in the second season, where cotton was planted 141 days after the herbicide application in a very wet winter. Both the extra time between the herbicide application and the time of cotton planting, and the wet conditions, would have been conducive to break-down of the Balance. Hence, damage from Balance would not be expected in this second season. In the first season, the 8X rate of Balance reduced the plant stand by 74%, early-season crop height and biomass by 72% and 67%, respectively, and lint yield by 56%.

4X and 8X rates of Sharpen reduced the plant stand by 20% and 42%, early-season crop height by 24% and 53%, and early-season biomass by 31% and 66%, respectively. Cotton recovered from the 4X rate of Sharpen, with no reduction in lint yield, but the 8X rate gave a 54% reduction in lint yield, with an 85% reduction in lint yield in the first season.

4X and 8X rates of Starane reduced the plant stand by 22% and 40%, and early-season crop height by 21% and 40%, respectively. Cotton recovered from the Starane damage, with no reduction in lint yield (when averaged over the two seasons). However, again the damage occurred primarily in the first season, with the 4X and 8X rates of Starane reducing the plant stand by 64% and 94%, respectively, and the 8X rate resulting in a 67% reduction in lint yield in this season.

All rates of Voraxor caused some damage to the cotton. 2X, 4X and 8X rate reduced the plant stand by 44%, 59% and 95%, early season crop height 46%, 68% and 95%, early-season biomass 36%, 75%, and 99%, and cotton lint yield by 24%, 54% and 96%, respectively, with yield reductions from the 4X and 8X rates occurring in both seasons.

Interestingly, in both this experiment and the previous work (Milestone 1.1), 2,4-D amine at rates of up to 8X did not negatively affect cotton establishment, growth or lint yield in either season, although as previously stated, 2,4-D damage has been documented in other research and there have been numerous examples of crop damage from 2,4-D residues reported by the industry.

This research shows both the impact of time and seasonal conditions on herbicide breakdown, and also the danger to cotton crops from residual herbicides applied in preceding fallows, especially where the herbicides may be applied at higher than normal rates, as can occur through camera spray systems. Growers should be very cautious when applying Balance, Sharpen, Starane or Voraxor through camera sprayers in fallows preceding cotton crops.

Milestones 2.1 – Evaluate non-chemical weed control options developed in grain industry. Evaluate potential introduction into non-cropping phase of cotton

Background

Weeds remain the bane of farming systems. Systems based on single crops inevitably select out weeds that tolerate the system. Minimum tillage systems, for example, become dominated by perennial weeds that are favoured by the lack of tillage and systems also including retained stubble favour surface germinating and wind spread species. Farmers generally respond to these issues by introducing an additional single herbicide tactic to manage the problem. This approach is unsustainable as the new tactic rapidly selects for weeds that tolerate this new input, then requiring inclusion of another new tactic, that again selects for resistance, requiring inclusion of yet another new tactic, and so on.

Rather than solving a problem by including a single new tactic, cotton growers need to return to more complex systems including multiple herbicide modes of action as well as cultivation and cropping rotations that allow the introduction of differing herbicides and control windows, but this also bring complexities with herbicide residues.

The grains industry has for many years now been dealing with the challenge of systems that primarily are single crops (wheat), minimum tillage, and are being challenged by several weeds (especially ryegrass and wild radish) that have resistance to most of the available herbicides. Some of the tools that have been adopted by the grains industry to deal with their problematic weeds are:

1) Harvest weed seed destruction,
2) Long fallows with full weed control,
3) Strategic cultivation,
4) Targeted weed removal,
5) Cropping rotations,
6) Crop competition,
7) Cover crops,
8) Delayed sowing,
9) Autumn tickle,
10) Robotic weeders, and
11) Drone sprayers.

1) Harvest weed seed destruction (HWSD)

HWSD can be undertaken using a variety of techniques that focus on the management of weed seeds in the chaff fraction coming from a header at harvest. HWSD techniques range from mechanical destruction of the seed or collection and burning of the chaff, to dropping chaff and seeds into tram-tracks behind the header that can then be targeted for burning or herbicides. The option for using this approach has been explored in the cotton system but has limited value. Few of the winter weeds that could be captured by a header are sufficiently problematic in cotton to justify the expense of HWSD. Application of this approach to cotton pickers is not effective as relatively few weeds retain their mature seed until picking, although in reality, most fields are relatively clean at picking, with few weeds present at this time. In addition, the HWSD approach has its own challenges and for managing annual ryegrass, HWSD is failing over time. Ryegrass plants are adapting to this selection pressure (developed resistance) by shedding their seed before harvest, steadily diminishing the value of HWSD. So, while this approach can have value, in the long-term, it can’t be relied on as a primary tool for weed management.

2) Long fallows with full weed control

Long-term fallows have been an effective tool in the south for greatly diminishing the seed bank of problematic weeds. Problematic paddocks might be left bare for 1 to 2 years to exhaust the seedbank, with weeds such as annual ryegrass having a seedbank life of little more than 1 year. This approach can have great value in cotton systems, but in reality, is already a standard component of most cotton farming systems, which generally include a summer fallow following cereal crops, may include a winter fallow after a sorghum crop or cotton crop, depending on autumn rain, and a long fallow from a cereal crop back to cotton. Additionally, many of the problematic weeds of the cotton system have longer seedbank lives, such that their seedbanks aren't exhausted by a 1 or 2 year fallow, and in some cases, such as cowvine, thornapple and Noogoora burr, a 2 year fallow will do little to diminish the seedbank.

3) Strategic cultivation

Strategic cultivation is an important tool that should be part of the cotton system, used to target problematic weeds, such as perennial weeds that persist through routine shallow cultivation, and to bury surface germinating seeds of species such as sow thistle and fleabane. Strategic cultivation should be a component of all dryland cotton systems, used as necessary to manage problematic weeds. However, in the furrow irrigated cotton system, although cultivation may not be used specifically to manage weeds, it remains a standard practice used to maintain the flow of irrigation water along furrows, and is often used when applying fertilizer. Hence, for the majority of the cotton industry, the system is one of permanent beds and minimum tillage, with light tillage remaining an important component of the system.

One of the more recent changes to the cotton system was the removal of the mandatory requirement for a pupae busting cultivation pass after crop harvest. This change in practice raised the question as to how much the pupae busting pass may be contributing to weed control in the cotton system. An experiment was established at Narrabri in 2014 by Dr. Sudeesh Manallil to determine the effect of cultivation following picking on the weed pressure in a continuous cotton system. The experiment was a split plot, with cultivation as the main-plot, imposed soon after picking or prior to planting. Main plots were 70 m by 4 m and replicated 4 times. Main plot treatments were:

Fallow tillage	**Timing**	
Lilliston (light cultivation)	Following picking	(Early Lilliston)
	Prior to planting	(Late Lilliston)
Go-Devil (heavier disc cultivation)	Following picking	(Early Go-Devil)
	Prior to planting	(Late Go-Devil)
Centre-busting & sweeps	Prior to planting	(Centre bust)
Nil	-	(Nil)

Across this design was imposed weed control approaches, with plots 10 m by 4 m, replicated twice within each main plot (8 replications). The treatments were:

At-planting	**In-crop**
	Glyphosate
Fluometuron	Glyphosate
Fluometuron	Glyphosate + hand chipping

Plots were also inter-row cultivated such that all weeds were controlled in crop.

This design was maintained for the 2014-15 and 2015-16 seasons. The experiment became part of the current project in 2016-17 and the weed control component of the design was changed, with slight modifications of the existing treatments and inclusion of three additional treatments, reducing each sub-plot treatment to 4 replications, as shown below. Inter-row cultivation was only used when necessary to maintain the irrigation furrows. These changes were introduced as the original design had resulted in weed-free plots, not allowing the impact of the cultivation treatments to be assessed. The modified design resulted in heavy weed infestations on some treatments, challenging the impact of fallow-cultivation strategies.

	At-planting		**In-crop**	
1	Fluometuron + pendimethalin	(Pre-residual)		
2	Fluometuron + pendimethalin	(Pre-residual)	Metolachlor + Envoke	(Residual)
3			Glyphosate	(Glyphosate)
4	Fluometuron + pendimethalin	(Pre-residual)	Glyphosate	(Glyphosate)
5			Metolachlor + Envoke + glyphosate	(Residual + glyphosate)
6	Fluometuron + pendimethalin	(Pre-residual)	Metolachlor + Envoke + glyphosate	Residual + glyphosate)

Note. Envoke is trifloxysulfuron-sodium.

The original main-plot cultivation treatments remained unchanged under the new design and the experiment was continued for nine season through to the 2022-23 season and the modified weed control design for seven seasons. Weed biomass was assessed mid-season each year.

Results and discussion

There were variations in the results over time, however, analysis showed few consistent differences and few trends. A comparison of the cultivation treatments is shown below, averaged over the past 7 seasons.

	Herbicides		**Cultivation**	**Weeds**		**Lint yield**	
	At-planting	**In-crop**		**(g/m^2)**	**s.e.**	**(bales/ha)**	**s.e.**
1	Pre-residuals	-	Nil	250.3	52.0	9.0	0.5
2	Pre-residuals	-	Early Lilliston	169.6	43.6	10.8	0.4
3	Pre-residuals	-	Early Go-Devil	192.1	40.1	10.6	0.6
4	Pre-residuals	-	Late Lilliston	192.5	42.5	11.2	0.4
5	Pre-residuals	-	Late Go-Devil	219.7	47.1	10.9	0.7
6	Pre-residuals	-	Centre bust	225.1	45.5	9.9	0.5
7	Pre-residuals	Residuals	Nil	232.3	55.4	10.0	0.4
8	Pre-residuals	Residuals	Early Lilliston	180.4	39.4	10.4	0.6
9	Pre-residuals	Residuals	Early Go-Devil	161.9	40.4	10.0	0.5
10	Pre-residuals	Residuals	Late Lilliston	175.6	42.8	11.1	0.5
11	Pre-residuals	Residuals	Late Go-Devil	176.0	50.3	9.9	0.5
12	Pre-residuals	Residuals	Centre bust	116.0	36.1	10.8	0.5
13		Glyphosate	Nil	57.8	14.2	9.4	0.6
14		Glyphosate	Early Lilliston	39.8	14.6	10.0	0.6
15		Glyphosate	Early Go-Devil	78.9	21.1	9.9	0.7

16		Glyphosate	Late Lilliston	51.6	15.0	10.6	0.5
17		Glyphosate	Late Go-Devil	60.8	16.8	10.2	0.8
18		Glyphosate	Centre bust	77.3	22.9	9.7	0.7
19	Pre-residuals	Glyphosate	Nil	21.7	8.8	10.7	0.4
20	Pre-residuals	Glyphosate	Early Lilliston	21.7	9.6	11.7	0.5
21	Pre-residuals	Glyphosate	Early Go-Devil	32.7	11.9	11.0	0.4
22	Pre-residuals	Glyphosate	Late Lilliston	42.4	16.5	11.2	0.6
23	Pre-residuals	Glyphosate	Late Go-Devil	23.5	10.2	11.6	0.4
24	Pre-residuals	Glyphosate	Centre bust	37.2	17.8	11.2	0.4
25		Residuals + glyphosate	Nil	29.9	14.3	10.6	0.5
26		Residuals + glyphosate	Early Lilliston	10.5	4.2	10.6	0.5
27		Residuals + glyphosate	Early Go-Devil	16.6	6.0	10.1	0.6
28		Residuals + glyphosate	Late Lilliston	10.7	3.4	10.0	0.5
29		Residuals + glyphosate	Late Go-Devil	11.9	3.8	10.4	0.6
30		Residuals + glyphosate	Centre bust	11.6	4.3	10.5	0.8
31	Pre-residuals	Residuals + glyphosate	Nil	27.6	8.7	10.5	0.4
32	Pre-residuals	Residuals + glyphosate	Early Lilliston	7.2	2.8	10.8	0.6
33	Pre-residuals	Residuals + glyphosate	Early Go-Devil	10.0	3.1	10.4	0.5
34	Pre-residuals	Residuals + glyphosate	Late Lilliston	14.8	6.6	11.0	0.4
35	Pre-residuals	Residuals + glyphosate	Late Go-Devil	8.4	2.9	11.5	0.5
36	Pre-residuals	Residuals + glyphosate	Centre bust	6.1	2.1	9.9	0.6

Note. Values in red are less than the untreated value by more than twice the standard error.

When comparing cultivation treatments within a weed management tactic, there was a tendency for weed biomass to be higher where there was no cultivation treatment following picking. This effect was most apparent where there was a higher level of weed control (treatments 25 to 36) where the weed biomass was around 3-times greater on the Nil treatments, but there were no apparent differences due to the intensity or timing of the cultivation. There were also no consistent trends in yield, with similar yields on all treatments.

The results averaged over weed control tactics are shown below.

Cultivation	**Weeds**		**Lint yield**	
	(g/m^2)	**s.e.**	**(bales/ha)**	**s.e.**
Nil	103.3	15.8	10.0	0.2
Early Lilliston	71.6	12.1	10.7	0.2
Early Go-Devil	82.0	12.1	10.3	0.2
Late Lilliston	81.3	12.6	10.9	0.2
Late Go-Devil	83.4	14.0	10.8	0.3
Centre bust	78.9	12.7	10.3	0.2

When compared across weed control tactics, the results showed consistently better weed control where a more diverse approach to weed management was used, as shown below. The trends in these results were consistent across all fallow cultivation tactics. Lint yield was similar on most treatments but was lower where there was no cultivation during the fallow phase. Although the trend was weak, there was evidence that a cultivation pass during the fallow phase improved weed control and lint yield.

The results averaged over cultivation tactics are shown below.

	Herbicides		**Weeds**		**Lint yield**	
	At-planting	**In-crop**	**(g/m^2)**	**s.e.**	**(bales/ha)**	**s.e.**
1	Pre-residuals		**208.2**	18.3	10.4	0.2
2	Pre-residuals	Residuals	**173.7**	18.1	10.4	0.2
3		Glyphosate	61.0	7.2	10.0	0.3
4	Pre-residuals	Glyphosate	29.9	5.2	**11.2**	0.2
5		Residuals + glyphosate	15.2	2.9	10.4	0.2
6	Pre-residuals	Residuals + glyphosate	12.4	2.1	10.7	0.2

Weed control was much poorer where in-crop glyphosate was not part of the system (Treatments 1 and 2) and these plots became dominated by nutgrass, thornapple and Noogoora burr, amongst other weeds. This contrasted with the first season where these treatments were imposed (2016-17), when the field was largely weed-free and an assessment showed few weeds and no differences between the treatments. By 2017-18, after just one season without in-crop glyphosate, high levels of weed biomass were recorded on these treatments. The level of weed pressure recorded in 2017-18 remained consistent over the next 5 seasons. However, one of the issues of the experimental design was that due to the small size of the sub-plots of only 10 m by 4 rows, weed seed was spread between plots and treatments by mulching and cultivation treatments. Hence mulching and cultivation tended to reduce the concentration of weeds on the more heavily infested plots, spreading weeds into clean plots. Without this effect, it seems likely that weed pressure would have been higher on these treatments by the end of the experiment.

A higher level of weed control was achieved where glyphosate was used in-crop (Treatment 3), and still better weed control where glyphosate was combined with residual herbicides (Treatments 4-6). The early-season, over-the-top in-crop application of metolachlor + Envoke was very effective in controlling weeds through much of the season, resulting in very low levels of weed pressure on these plots, however, Envoke is no-longer available in Australia.

It was anticipated that the Nil and light cultivation treatments would become dominated by perennial weeds over time, but this didn’t happen, except for nutgrass. Partly this was just the result of chance, as weed spectrum tends to vary between most fields and seasons. This field did not have a background population of perennial species. The nutgrass density did build over time on the treatments that didn’t include glyphosate but didn’t become unmanageable, probably because the nutgrass was being exposed to applications of glyphosate during the fallow period between each cotton crop. This was a further complication of the trial design, where glyphosate was necessarily applied over all treatments during the fallow phase to manage weeds during this time, as cultivation was not a tool available to control these weeds, since fallow cultivation was a main treatment. Again, had winter weed management been only imposed by the fallow cultivation treatments, the experiment would have given a different result, but would have also quickly become unmanageable. Instead, weeds were managed in the fallow using glyphosate, as is the normal practice in the industry.

Overall, the experimental area remained relatively clean of weeds throughout the trial period and cultivation and herbicide tactics had little impact on the cotton yield, with yields similar even on plots with higher weed pressure. The only treatment that stood out over the 7 seasons was the herbicide combination of at planting residual herbicides (pendimethalin and fluometuron) and in-crop glyphosate (Treatment 4), arguably an industry standard treatment. The average yield on Treatment 4 of 11.2 bales/ha was 0.8 bales higher than the treatments which achieved poorer weed control (Treatments 1 & 2).

Conclusion

Strategic cultivation is an important weed management tool that should be part of all cotton production systems. Cultivation should be used strategically as a double-knock to control herbicide resistant species, to manage hard-to-control perennial weeds, and to bury seeds of surface germinating species. A cultivation pass in-fallow between cotton crops will aid with weed control and may help maintain crop yields. Cotton growers should include a fallow cultivation pass in their system, ideally aiming to use the pass to restore irrigation furrows and incorporate fertilizer as well as help manage perennial and other weeds, ideally using the cultivation pass as a double-knock backup to a herbicide application.

4) Targeted weed removal

Spot spraying, hand hoeing and hand removal of low densities of herbicide resistant weeds has become a targeted approach in some grain systems to remove the last weeds from a field. This approach has proven valuable, especially for removing low densities of resistant wild radish from cereal crops, as the flowers of these weeds can easily spotted in the crop. These tactics were commonly used in the cotton industry prior to the introduction of glyphosate tolerant cotton varieties and remain a valuable backup for cotton growers to manage low densities of large and difficult to manage weeds. Targeted weed removal should continue to be a minor, but valuable tool in the weed control tool bag.

5) Cropping rotations

Rotation crops remain a valuable component of the cotton system, enabling a range of alternative herbicides to be used to control weeds, as well as other pests and diseases. Rotations can also create fallow opportunities to control weeds over both summer and winter. However, herbicides used in fallows and rotations can also have their own challenges with potential issues from herbicide residues, and weeds can be difficult to manage in some rotation crops, such as broad-leaf weeds in broad-leaf crops.

All things considered, the common cotton system practice of rotating cotton and wheat, creating a summer-fallow opportunity, continues to be a practical option for managing weeds in the system.

6) Crop Competition

Research over many years in the grain’s space has shown the value of narrower row configurations and increased crop density for increasing crop competition and thus supressing weeds. While these approaches are being increasingly used in the rotation crops in the cotton system, they have little direct application in cotton. Reducing row spacing, ultimately to ultra-narrow row configurations, has been tried in cotton but has not proven to be advantageous. Standard seeding rates, of 12-15 seeds/m are already above the optimum and further increases would not improve crop competitiveness.

Nevertheless, cotton growers do all that they can to promote early-season crop growth, closing the rows and achieving competitive crops as early as possible in the season. Cotton growers use precision planters, seed treatments etc. to minimise gaps in cotton rows, use water management, pesticides and fertilisers to promote crop growth, and delay planting until temperatures are suitable when possible to promote rapid crop emergence and establishment. All these practices are employed to promote crop growth and crop competitiveness. Generally, cotton varieties also produce a larger, more competitive plant later in the season than was the case in the past, but on the down side, many of the newer cotton varieties are small seeded, with poorer seedling vigour, sometimes contributing to less competitive crops with gappy stands and slower early-season growth.

7) Cover crops

A variation of the crop competition tactic for weed control is to use a cover crop, either in the fallow pre-cotton, or in the cotton crop. Cover crops are routinely used prior to cotton, if not directly, then by way of cereal crops grown prior to a cotton crop, with the standing stubble retained as long as possible, thus providing cover. This is not generally done for weed control, but the retention of cereal stubbles does give some advantage in weed control, as well as advantages including improved moisture retention and protection from sand blasting. Cover cropping prior to planting is being trialled in the NT and appears to bring many advantages.

Cover crops are not used within cotton crops, as they would compete too strongly with relatively uncompetitive cotton seedlings.

8) Delayed sowing

A valuable strategy for managing winter weeds in cereals has been to delay sowing – instead of sowing as soon as possible after the autumn rains, allowing the flush of weeds stimulated by these rains to be controlled before planting. This strategy should be applied in cotton production as much as possible, where the dirtiest fields are pre-irrigated and planting is delayed as long as possible to allow the subsequent flush of weeds to be controlled before crop emergence. In practice, the use of cotton varieties with the Roundup Ready Flex trait has allowed cotton growers to apply a glyphosate at or soon after crop emergence to remove the first flush of weeds, ensuring the crop establishes in a clean seedbed.

9) Autumn tickle

The autumn tickle is a modification of the delayed sowing tactic, where a cultivation pass following the rains of the autumn break stimulates a flush of weeds that can be controlled before planting occurs. This tactic may have value in the future cotton system where weeds such as herbicide-resistant feathertop Rhodes, windmill, awnless barnyard grass and annual ryegrass become increasingly troublesome. The tactic might involve pre-irrigating a field and controlling the emerged grass with one or even two light cultivation passes, maybe the second pass as part of the planting operation. It would be valuable to undertake research to determine if this approach could significantly reduce emerging populations of these grasses.

10) Robotic weeders

Robotic weeders certainly have a place in the cotton farming system of the future and are ideal for targeted weed removal. Robots should become far more common in the cotton system over the next decade. Robotic detection and management of larger weeds in fallows is being achieved, but detection of weeds in crops is very challenging and yet to be reliably accomplished, such that the use of robotic weeders is limited to fallows and the “bare” area between crop rows. Also, to date, these systems are still employing herbicides as the means of weed control. Consequently, their use is not assisting with managing herbicide resistant weeds and the use of high herbicide rates through robots to control large weeds can lead to issues with herbicide residues for following crops.

Work by others has explored the practicality of using these platforms to control weeds using other tools, including microwaves, steam and lasers, but these tools can require large inputs of energy, struggle to control large weeds, and are not effective for controlling most perennial species. The value of robotic platforms will remain limited until an effective non-herbicidal tool is developed to control weeds and green-on-green weed detection is established.

11) Drone sprayers

The use of drones to detect and manage weed infestations in cotton systems has much potential but suffers from the same limitations as robotic weeders, with the additional limitations of short flight times (when compared to cotton fields that may be hundreds of ha per field) and the challenge of “spot” herbicide applications, where the “spot” may be around 2 m in diameter of more. Drones will have a lot of potential in the cotton system when they can employ green-on-green detection technology and can be paired to robotic weeders, enabling these weeders to efficiently move from weed to weed.

Conclusion

Many of the weed management tactics used in the grains system have value for cotton production, and most of these are already being utilized in cotton, or preceding crops or fallows.

The main advances for the cotton system in the future are likely to be around robotics and drones with green-on-green detection, together with non-herbicidal weed-control tools. Research in this area continues, with robots and drones now proven technology, albeit with further advances to be expected over the next decade. Refinements can be expected in combining these technologies and fully-automating the technologies. Accurate green-on-green detection, coupled with an effective non-herbicidal means of weed control remains a big hurdle at this time and field application of this technology is still to be validated.

The potential use of cultivation to control herbicide resistant weeds after pre-irrigation should be further explored. Assuming that grasses resistant to glyphosate, paraquat, the grass herbicides (Group 1) and glufosinate become more widespread over the next decade, delayed planting and early-season removal of emerged seedlings by light cultivation may become a valuable tactic for reducing the numbers of these and other weeds. The potential to stimulate the emergence of these weeds through pre-irrigation and light cultivation should be explored.

Milestones 3.1 and 3.2 – Undertake targeted resistance surveys in weeds in the cotton farming system. + Screen weed seeds for resistance to glyphosate, glufosinate, paraquat and Group A chemistry

Background

Herbicide resistance has an increasing presence in the Australian cotton industry. Glyphosate resistance in awnless barnyard grass, and feathertop Rhodes grass is becoming commonplace in fields throughout the cotton growing regions. Resistance to other herbicides, particularly the group 1 (A) herbicides, is now starting to appear as growers look for other options besides glyphosate to control grasses. Glyphosate resistance has also placed increasing pressure on paraquat, the most common second knock partner in double knock applications. This is due to the likelihood that weed populations may contain biotypes that are resistant to glyphosate. As a result, paraquat is the only applied herbicide that can provide effective control as part of the double knock. Survivors of the paraquat application that are then able to produce seed, have an increased risk of developing resistance.

The aims of these milestones were to conduct targeted weed surveys across the cotton industry to collect samples that would then be screened for resistance to glyphosate paraquat, group 1 herbicides and glufosinate. This will enable us to determine how widespread resistance is to these herbicides.

Methods and materials

Source of seeds

Targeted weed surveys were conducted throughout the cotton growing regions of Queensland and New South Wales from 2019 to 2022. The QDAF team collected seed samples including feathertop Rhodes grass, awnless barnyard grass, windmill grass and sowthistle from the Darling Downs region in 2019 and 2020. Seeds of feathertop Rhodes grass and awnless barnyard grass populations from New South Wales were collected via the Cotton Info network in 2020 and samples from the Queensland border region, St George and Goondiwindi were collected by Andrew McKay in 2021. The QDAF team also collected samples of feathertop Rhodes grass, purpletop Rhodes grass (*Chloris inflata*) and awnless barnyard grass from the Theodore, Moura and Emerald cotton growing regions in March 2022.

Herbicide Screening

The screening of grasses for resistance to commonly used herbicides was conducted at the Leslie Research Facility in Toowoomba. Screening of broadleaf samples was conducted at Charles Sturt University in Wagga Wagga. The herbicides used are listed in Table 1.

All plants were sprayed using a research track cabinet sprayer using DG95015EVS nozzles at 30 psi delivering 114 L/ha of water. The herbicide rates were determined to deliver a discriminating dose that represented the herbicide label. As the timing of the herbicide application was at the 2-3 leaf stage, where relevant, the lower end of the label rate was used.

Table 1. Herbicides and rates used for resistance screening of summer grasses.

Herbicide	Active	Rate
Roundup UltraMax	Glyphosate (570 g/L)	1.44 L/ha
Gramoxone Pro 360	Paraquat (360 g/L)	1.1 L/ha
Verdict 520	Haloxyfop (520 g/L)	100 mL/ha
Sequence	Clethodim (240 g/L)	250 mL/ha
Basta	Glufosinate (200 g/L)	3.75 L/ha

Seeds from each population were placed into individual take-away food containers, containing approximately 100 ml of a 0.6% agar solution for germination. Containers were then placed into a growth room with a 30/20°C day/night temperature and 12hrs light. After approximately one week when the seedlings were between the cotyledon and 1-leaf stage, they were transplanted into larger trays filled with a mixture of potting mix and sand to ensure good contact of the mixture with the seedling's roots.

Each tray contained two populations scheduled to be sprayed with the same herbicide. There were up to 50 seedlings from each population transplanted, a total of up to100 seedlings per tray. The trays were then placed either in the glasshouse or growth room (in the winter months) with the moisture kept up so that trays were continually moist and not waterlogged. Once the seedlings had reached the 2-3 leaf stage (approximately two weeks later) the respective herbicide treatments were applied.

After herbicide application, trays were then placed back in the glasshouse/growth room. Survival counts were conducted 28 days after herbicide application.

Herbicide Assessment

Populations with over 30 seedlings established at the time of spraying, were able to be assessed for herbicide resistance. This methodology is used for resistance screening in other GRDC projects. Populations with fewer seedlings were still sprayed and survival data recorded. If there were between 20-30 seedlings sprayed, the data could still be recorded but not reported on unless sprayed on multiple occasions to confirm results. For less than 20 seedlings, data was not used in reporting.

The resistance status of each population was grouped into 3 classes: 1. 20% or more survivors – resistant; 2. 1-19% survivors – developing resistance; and 3. Less than 1% survivors – susceptible.

Results and discussion

A total of 100 grass samples were collected across the cotton regions. The samples consisted of 57 awnless barnyard grass, 40 feathertop Rhodes grass, 1 windmill grass and 2 purpletop Rhodes grass. Of these populations, 4 BYG and 1 FTR were not included in any resistance testing due to germination failure (Table 2).

A large proportion of the seed collected did not germinate in sufficient quantity to be included in the results. The highest failure with germinations was with the awnless barnyard grass populations were there was a 30-67% failure to germinate/survive transplant across the herbicide treatments. This is compared to a failure rate of 5-36% with the feathertop Rhodes grass populations.

Table 2: The total number of species and populations collected across the regions and included in the herbicide resistance tests.

Weed species	Darling Downs samples	NSW Cotton Info samples	Border Rivers samples	Central Qld samples
Awnless barnyard grass	4	40	7	2
Feathertop Rhodes grass	8	1	15	15
Purpletop Rhodes grass	0	0	0	2
Windmill grass	1	0	0	0

Of the 16 awnless barnyard grass populations tested for glyphosate, one population was resistant with another population developing resistance (Table 3). Four other populations indicated resistance to glyphosate however in these populations less than 30 plants were sprayed, and therefore require further testing. Most populations were susceptible to haloxyfop with three populations having some survivors. Clethodim had two populations that were resistant with one population having some survivors and the remainder susceptible.

Results with glufosinate and were less ideal than expected, with several populations either being resistant or developing resistance. Screening with glufosinate and paraquat was conducted with plants growing in the growth room over winter (to get through the populations). Both herbicides rely on photosynthesis and therefore light (photons) to rupture cells in the plant. The photosynthetically active radiation (PAR) in the growth rooms is approximately 400-500 µmol m^{-1} s^{-2} compared to 2000 µmol m^{-1} s^{-2} in full sunlight. As the likelihood of previous exposure to glufosinate of all populations in low, it is expected that control would be higher in full sunlight.

Table 3. Awnless barnyard grass populations screened to each herbicide and number of resistant (>20% survivors), developing resistance (1-19% survivors) and susceptible (no survivors) populations. Results show populations with ≥ 30 plants sprayed. Numbers in brackets show population where 20-30 plants were sprayed, and further testing is required to confirm status.

Herbicide	No. populations sprayed	No. populations with ≥20 plants	Resistant	Developing resistance	Susceptible
Glyphosate	49	16	1 (4)	1 (2)	3 (5)
Haloxyfop	44	31	0	2 (1)	17 (11)
Clethodim	47	24	2	1	7 (14)
Glufosinate	32	22	4 (2)	12	4
Paraquat	35	23	0	10 (2)	11 (1)

The incidence of glyphosate resistance in feathertop Rhodes grass was much higher than awnless barnyard grass with only one population testing susceptible (Table 4). Three populations tested resistant to haloxyfop with another population requiring further testing. An additional five populations were classed as developing resistance. Results from clethodim were also worse than expected, although it is important to note that the lower label rate of clethodim was used, and that the higher rate may have controlled more populations. However, results on previous experiments in CQ indicate that the effectiveness of clethodim on feathertop is questionable. The effectiveness of glufosinate and paraquat was also lower than expected, however these populations were also grown in the growth room, so the problems encountered with light also contributed. Some of these populations were retested and proved to be susceptible. It is considered unlikely that all of these populations would test as resistant, which indicates that the growing conditions have affected the results. Ideally with no time constraints we would like to retest all populations under external conditions.

Table 4. Feathertop Rhodes grass populations screened to each herbicide and number of resistant (>20% survivors), developing resistance (1-19% survivors) and susceptible (no survivors) populations. Results show populations with ≥ 30 plants sprayed. Numbers in brackets show population where 20-30 plants were sprayed, and further testing is required to confirm status.

Herbicide	No. populations sprayed	No. populations with ≥20 plants	Resistant	Developing resistance	Susceptible
Glyphosate	38	36	30 (4)	1	1
Haloxyfop	34	30	3 (1)	5 (2)	16 (3)
Clethodim	33	29	21 (3)	1 (1)	2 (1)
Glufosinate	28	23	10	3 (1)	9
Paraquat	33	25	10	13 (1)	0 (1)

The windmill grass population tested susceptible to the range of herbicides except for glufosinate and potentially developing resistance to paraquat (Table 5). Again, the growing conditions were mostly likely not conducive to those herbicides.

Table 5. Windmill grass populations screened to each herbicide and number of resistant (>20% survivors), developing resistance (1-19% survivors) and susceptible (no survivors) populations. Results show populations with ≥ 30 plants sprayed.

Herbicide	No. populations sprayed	Resistant	Developing resistance	Susceptible
Glyphosate	1	0	0	1
Haloxyfop	1	0	0	1
Clethodim	1	0	0	1
Glufosinate	1	1	0	0
Paraquat	1	0	1	0

The purpletop Rhodes grass collected tested generally susceptible to the range of herbicides with one population that had 20-30 plants sprayed indicating resistance to glyphosate. There were survivors from one population to glyphosate, haloxyfop and paraquat. The other population had survivors from clethodim.

The prevalence of glyphosate resistance in awnless barnyard grass and feathertop Rhodes grass appears to have increased. Our results indicate that all barnyard grass populations appear to be resistant to one herbicide. For feathertop Rhodes grass, there appears to be three populations from CQ that are resistant to both glyphosate and haloxyfop. The mixed results from glufosinate and paraquat confuse the issue somewhat. However, it is expected that these populations will be able to be controlled by those herbicides. The feathertop populations that survived clethodim had not died at the time of the assessment. However, they were stunted and did not appear to have any new growth after the clethodim application. Screening conducted by the GRDC project showed that at the higher rate of clethodim feathertop Rhodes grass populations were controlled.

We are starting to see increased pressure on the glyphosate alternatives throughout all regions. This also places increased pressure on double knock applications, as resistance means that the first application of glyphosate or group 1 herbicides is becoming largely ineffective. The result is increased pressure on paraquat and glufosinate as the follow-up herbicides. This is likely to result in an increase in the incidence of paraquat and glufosinate resistance on these species.

Table 6. Purpletop Rhodes grass populations screened to each herbicide and number of resistant (>20% survivors), developing resistance (1-19% survivors) and susceptible (no survivors) populations. Results show populations with ≥ 30 plants sprayed. Numbers in brackets show population where 20-30 plants were sprayed, and further testing is required to confirm status.

Herbicide	No. populations sprayed	No. populations with ≥20 plants	Resistant	Developing resistance	Susceptible
Glyphosate	2	1	0	1	0
Haloxyfop	2	2	0 (1)	0	0 (1)
Clethodim	2	2	0	0 (1)	1
Glufosinate	2	0	0	0	0
Paraquat	2	2	0	1	0 (1)

Southern work

Weed surveys were conducted through the CottonInfo network and liaising with consultants due to travel restrictions around Covid-19, and 123 samples were collected. Weed samples were sent to Wagga and the sowthistle, windmill grass and feathertop Rhodes grass (FTRG) samples tested.

Fifteen samples of windmill grass were screened for resistance to glyphosate and all were resistant. Six populations were resistant to haloxyfop and clethodim. Three populations of barnyard grass were tested for herbicide resistance and all were resistant to glyphosate, clethodim and haloxyfop. The feathertop Rhodes grass samples were all resistant to glyphosate and clethodim, however, in a promising sign only one population was resistant to haloxyfop. Potentially, we have some chemistry still available in the Group 1 mode of action that is working on some of the summer grasses. The low numbers of individual populations reflect poor germination from collected samples a reflection of the wet conditions during collection time.

The results from herbicide resistance testing have been extended to the cooperating REO's and agronomists. A comprehensive weed survey across all cotton valleys will be undertaken during the 2021-22 season.

Screening of sowthistle samples to glyphosate and 2-4,D was undertaken from the 10 individual populations collected in 2021-22 season. Four of the nine populations are resistant to glyphosate and five of the populations are resistant to 2-4,D with one population in each herbicide developing resistance.

A study was conducted on the effect of under dosing with glyphosate or 'hormesis' on barnyard grass and paraquat on tall fleabane populations. The low doses can stimulate biomass accumulation in resistant biotypes which leads to the development of herbicide resistance. Above ground biomass accumulation increased significantly in resistant populations of both weeds, meaning that the resistant populations have a fitness advantage and eventually will become dominant over the susceptible plants in the field.

Milestone 3.3 – Phenology studies on emerging weeds, identifying potential weaknesses to target control

Milestone 3.3.1 – Effect of moisture stress on the development and time to maturity for feathertop Rhodes grass (*Chloris virgata*)

Background

There is limited scientific information available on the effect soil moisture has on the growth and development of feathertop Rhodes grass (*Chloris virgata*). Anecdotal evidence suggests that feathertop matures quicker when under stressed conditions. An experiment was established under growth cabinet conditions to investigate research questions pertaining to this statement in relation to water stress.

In particular:

- Are there any significant differences in growth and development parameters of feathertop Rhodes grass (FTR) based on field/water capacity?
- How does FTR respond to water stress in relation to time to maturity?
- Is seed production and viability impacted by water stress?

Methods and materials

Growing conditions

The experiment was conducted in a growth chamber so that the temperature, water capacity and day length could be controlled. A temperature regime of 30/20 °C with a photoperiod of 12 hrs was chosen to mimic the growing conditions for feathertop Rhodes grass during the cotton growing season.

Seed collected from a population of feathertop Rhodes grass during a survey in April 2022 of central Queensland cotton farms was used in this experiment. Six field capacities (% FC) ranging from no stress to high stress were applied (100, 75, 50, 37.5, 25, 15) with 6 replicates for each treatment. Pots were randomised within each replicate, and replicates were randomised within the growth cabinet. Replicates were re-randomised around the cabinet every two weeks to account for temperature and humidity differentials in the cabinet.

Soil moisture calculations

An initial test was conducted to determine the field capacity of the soil being used in the experiment. Six pots (165 mm diameter x 175 mm deep) were filled with 2500 g of black cracking clay from the Hermitage Research Facility at Warwick. Pots were lined with paper towel prior to adding the soil to limit moisture loss. The soil in the pots was saturated with water and after draining for 24 hrs, weighed and then oven-dried at 50 °C for 3 days and reweighed. The measurements for the saturated soil and the dry soil were averaged and used to calculate field capacity for the Hermitage soil (Boyd & Van Acker 2003).

Calculations were then made to determine how much water had to be added to the experimental pots to bring each to the required field capacity.

Experimental procedure

Experimental pots were watered-up to their respective percent of field capacity and placed in the growth cabinet where they were monitored and weighed daily for a period of three days.

Seeds of feathertop Rhodes grass were pre-germinated in take-away containers containing approximately 100 ml of a 0.6% agar solution. Up to five healthy seedlings with root lengths greater than 1 cm were transplanted into the individual pots and the soil lightly moistened to ensure seedling survival. Water stress treatments were imposed 10 days after transplant with seedlings being culled back to one plant/pot and individual pots being brought up to their respective field capacity. During early plant growth pots were watered back to their respective field capacity three times/week (Mon, Wed, Fri) and as the plants developed, daily watering was required to maintain the desired field capacities.

The growth and development measurements recorded included:

- time to tillering, booting (the boot stage is the time the seedhead is enclosed within the sheath of the flag leaf), panicle production, pollen production and maturity
- tiller and panicle production
- dry weight biomass at maturity (above and below ground)
- seed production and seed viability

As the plants matured, seed was collected daily from individual plants and placed into relevant seed packets. Seed production was calculated by counting 1,000 seeds from three plants, weighing each and then calculating an average weight/1,000 seeds. Individual seed collections were weighed, divided by the calculated seed weight, then multiplied by 1,000 to obtain a seed production value.

Seed viability study

Seeds (100 seeds x 3 replicates) from each plant were then incubated at 30/20 °C on a 12 hr day/night regime. Seeds were placed in 9 cm Petri dishes with a layer of filter paper (No. 1: Whatman International, Maidstone, UK) and 3ml of deionised water. Up to 9 Petri dishes were placed into Ziplock bags to retain moisture and make daily counting of germinated seed easier.

Results

Growth and development

For all analyses the average number of days (time) for plants to reach each successive growth stage was calculated from the date of transplant.

The first development stage, the time taken for seedlings to commence tillering, was insignificant across all field capacity (FC) treatments ($p = 0.588$) and ranged from 17 to 29 days. The 15% FC treatment was included in this development analysis as all seedlings had produced tillers.

The average time for plants to commence booting was significant ($p<0.001$) as was the average number of tillers produced before booting ($p=0.002$) across the treatments (Fig 1a & 1b).

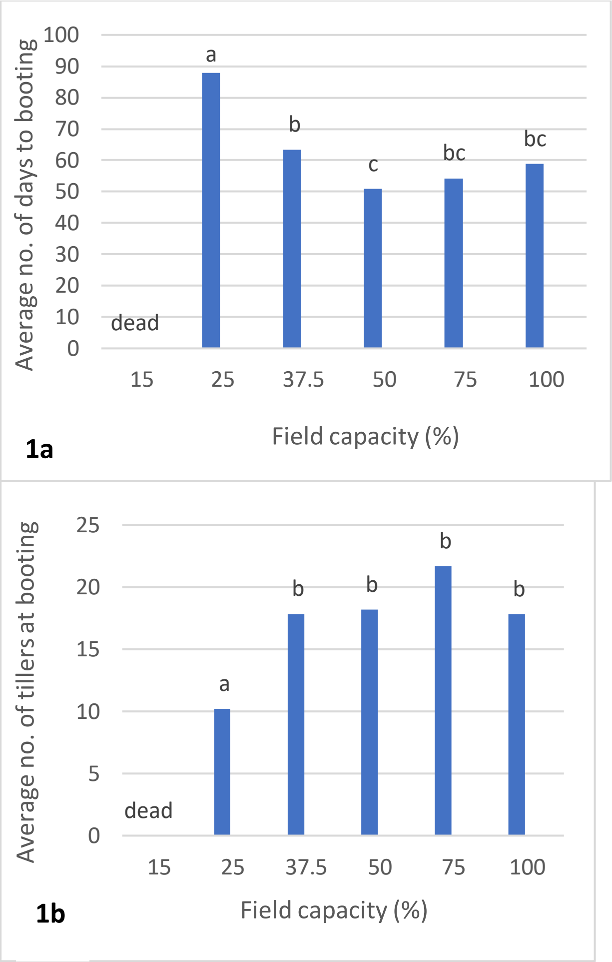


Figure 1. a) The average number of days for the seedlings to commence the booting stage of development for each field capacity treatment. b) The average number of tillers produced per plant up until the booting stage commenced across the field capacity treatments. Bars with different letters for each respective moisture regime are significantly different ($p < 0.05$).

At 25% FC plants took significantly longer to boot (88 days) compared to treatments with higher field capacities (51 – 63 days) (Fig 1a). Additionally, plants in this treatment produced significantly fewer tillers prior to booting compared to plants with higher water availability (Fig 1b).

Panicle production was measured as the time taken for the first panicle on each plant to emerge from the booting sheath. Both time to panicle production and time to pollen production were significant ($p<0.001$) across treatments (Fig 2a). The time taken to reach maturity was also significantly different across treatments ($p<0.001$) (Fig 2b).

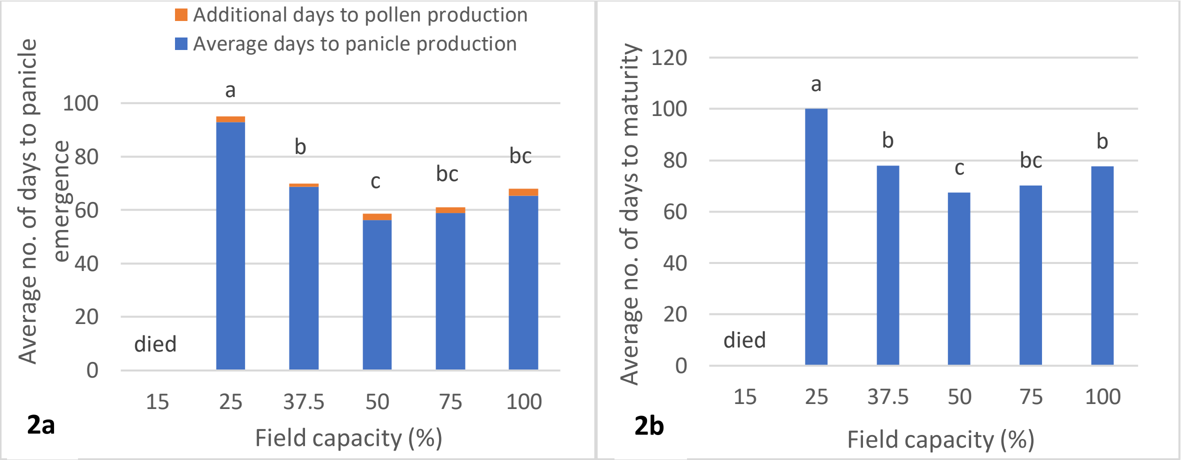


Figure 2. a) Average number of days to the onset of panicle production and additional days to pollen production across the field capacity treatments. b) Average number of days to the onset of maturity across the field capacity treatments. Bars with different letters for each respective moisture regime are significantly different ($p < 0.05$).

Plants grown at 50% FC produced panicles earlier and matured the earliest after an average of 56 and 67 days respectively. This was similar to the development of plants at 75% FC and 100% FC but significantly different from plants grown at 25% FC and 37.5% FC. Plants grown at 25% FC took the longest time to mature, on average 100 days.

Panicle production was also significantly different across treatments ($p<0.001$) (Fig 3). The data presented is back transformed.

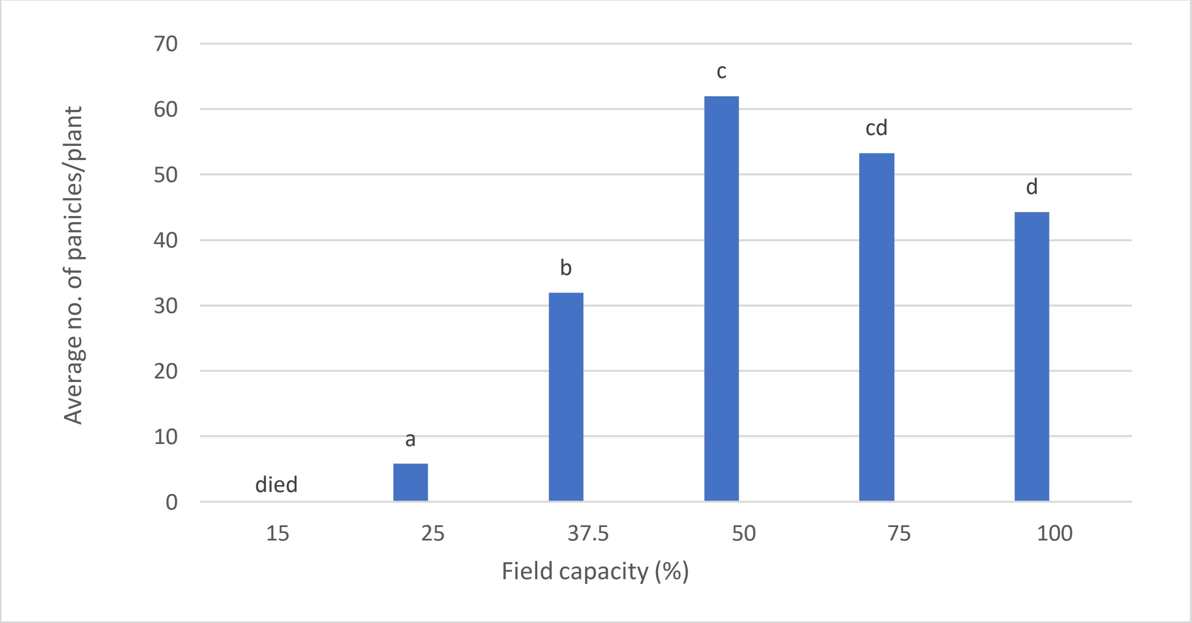


Figure 3: Average number of panicles produced per plant across the field capacity treatments (data presented is back transformed). Bars with different letters for each respective moisture regime are significantly different ($p < 0.05$).

Average panicle production/plant was highest in the 50% FC treatment (62) followed by, and similar to that in the 75% FC treatment (53). Panicle production in both the 25% FC and 37.5 FC treatments were significantly different from other treatments and had the lowest average production of 3 and 32 panicles respectively.

Dry weight biomass measurements were taken of both the plant (including roots) and just the root balls. Both measurements were significantly different across treatments ($p<0.001$) as was the average length of the roots (Figures 4 a,b,c).

Plants grown under the differing field capacities were all significantly different in relation to total plant biomass, but there were similarities in relation to root biomass (Figs 4a & b). Plants grown at 75% FC gained the largest amount of biomass at 8.7 g and also had a significantly higher root biomass at 1.6 g. Higher biomasses were also attained at 100% FC (7.3 g including 1.1 g roots) and 50% FC (5.7 g including 0.9 g roots). Plants grown at 75% and 100% FC produced the longest roots averaging 37.4cm and 36.5 cm respectively (Fig 4c). Plants that had died during the experiment were included in the analyses as they had tillered and produced biomass.

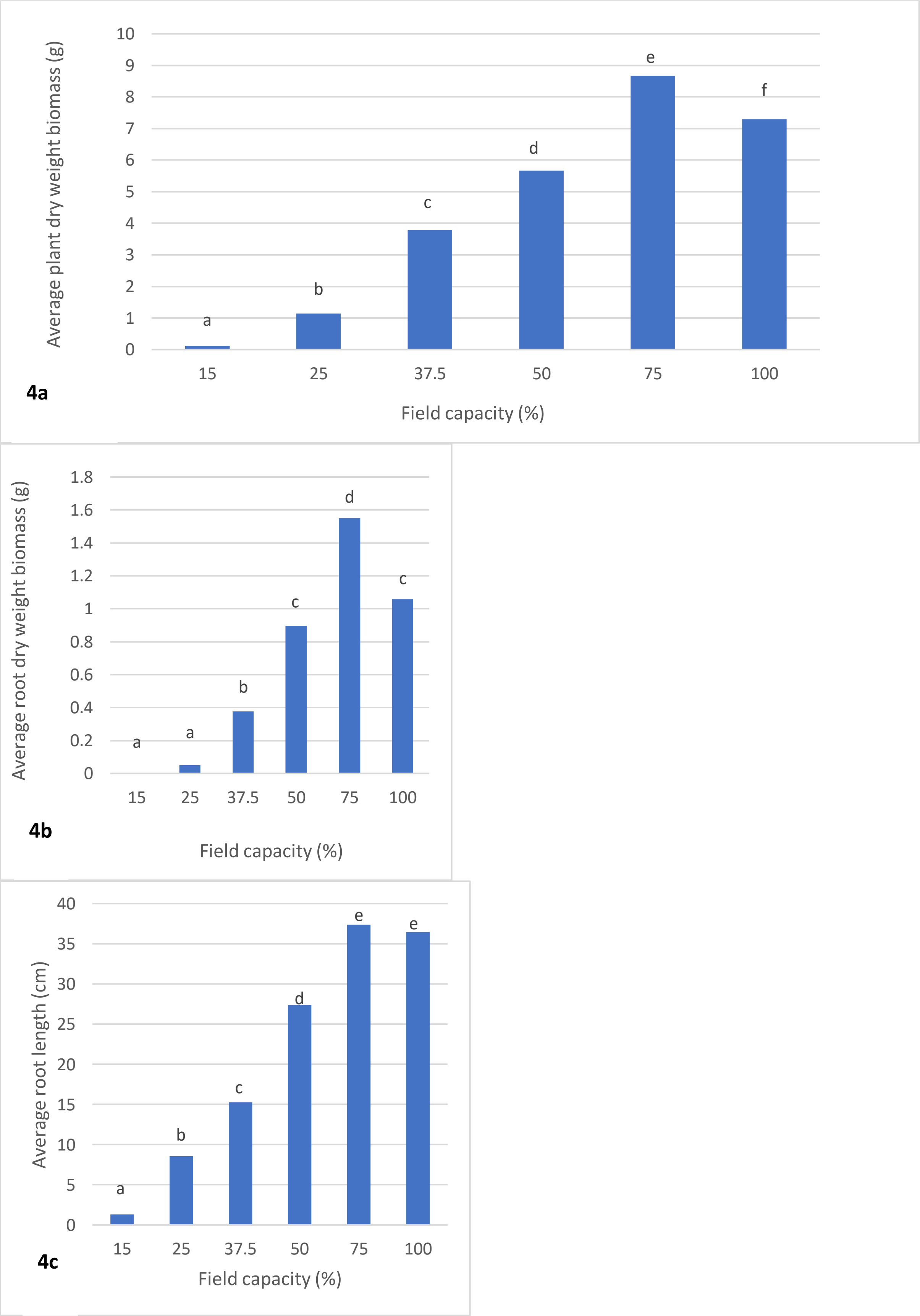


Figure 4. a) Average plant dry weight biomass (above and below-ground) across the field capacity treatments at the termination of experiment. b) Average dry weight biomass of plant root balls across the field capacity treatments at the termination of the experiment. c) Average root length of plants

across the field capacity treatments at the termination of the experiment. Bars with different letters for each respective moisture regime are significantly different ($p < 0.05$).

Seed production and viability

Average seed production and seed viability across the treatments has not been statistically analysed at this stage and germinations, as a measure of viability, are still being recorded (Table 1).

Table 1: Average seed production per plant, seed viability and calculated viable seed per plant across the field capacity treatments. Seed viability is based on emergences for a period of 21 days.

Field capacity	25%	37.5%	50%	75%	100%
Seed production	1,274	7,350	13,304	15,390	11,614
Viability (range)	34% (3-75%)	60% (54-65%)	68% (65-71%)	61% (49-70%)	57% (52-60%)
Viable seeds	433	4,410	9,047	9,388	6,620

Viable seed was produced across all field capacity treatments with plants grown at 50% FC and above producing more seed overall. Average seed viability was the highest (68%) for plants grown at 50% FC compared to plants with the lowest viability (34%) grown at 25% FC. However, some plants in the 25% FC treatment did produce seed with higher average viability (75%) than plants grown under higher field capacities.

Discussion

This initial research shows that the amount of soil water available to feathertop Rhodes grass seedlings has a significant effect on growth and development parameters.

Plants grown at 50% field capacity were the quickest to mature (67 days) and produced the most panicles, averaging 62 panicles/plant. While seed production was lower than that of plants grown at 75% field capacity, viability was slightly higher at 68% compared to 61%. However, in relation to plant biomass, plants in this treatment produced significantly less biomass when compared to plants grown with higher water availability. Results indicated that at 50% field capacity the plants were putting more effort into reproductive growth rather than biomass production. While plants subjected to the highest water stress (15% FC) died before maturity they did tiller and produce above-ground biomass.

With regard to root length, plants grown at 75% and 100% field capacities had the longest roots averaging 36 - 37cm, significantly longer than all treatments, including plants grown at 50% field capacity (27 cm). Across all treatments, the roots took advantage of what moisture was available in the soil and developed accordingly.

Regardless of the amount of soil moisture available, plants in treatments with a field capacity of 25% and above survived to produce viable seed. While plants grown at 50% and 75% field capacity produced on average over 9,000 viable seeds/plant, the viability decrease in seeds produced at 100% FC resulted in plants producing an average of 6,620 viable seeds.

This experiment has provided interesting information on how feathertop Rhodes grass responds to soil moisture stress. It appears that the plants optimal development occurs around 50% field capacity and decreases with lower and higher water availability. To further investigate the impact of soil moisture availability on feathertop, this experiment will be repeated in 2023 to confirm and expand on our existing knowledge.

Milestone 3.3.2 – 1) Determining base temperatures for red pigweed and dwarf amaranth. 2) Emergence and persistence of red pigweed seeds

Background

Understanding the triggers for emergence and growth of weeds is important to determine when they are likely to emerge in the field and identify potential weaknesses to target for control. Red pigweed (*Portulaca oleracea*) and dwarf amaranth (*Amaranthus macrocarpus*) have been present in cotton and grain fields for many years. However, numbers have been relatively low, but the presence of both species has been steadily increasing. Both species are prolific seed producers, producing small seeds, indicating that they are primarily surface germinators. However, both have hard seeds, indicating that they could be quite persistent, and their continued presence in-field is a strong indicator of this characteristic. Therefore, an understanding of the temperature requirements for germination and emergence, and their persistence relative to burial depth is important.

The base temperatures for red pigweed and dwarf amaranth were determined in addition to a separate experiment focused on assessing the impact of seed burial on seed bank emergence and persistence of red pigweed seed in the soil. The research question was the emergence patterns and persistence of red pigweed.

Red pigweed is an annual, succulent herb germinating late spring to summer, with flowering and seed set occurring in summer. Being a succulent type weed, control of larger plants is deemed to be difficult and there have been reports of reduced control using herbicides. Little is known about the ecology and seed-bank dynamics of red pigweed and this part of the study investigated the effect of seed burial on the emergence and persistence of red pigweed over time.

Methods and materials

Base temperature determination

Seeds (50 seeds x 3 replicates) of each species were incubated at eight different constant temperature regimes (5, 10, 15, 20, 25, 30, 35 and 38°C), and a 12-hr day/night regime. The highest temperature of 38°C was due to limitations in the incubator that prevented it reaching the desired maximum temperature of 40°C. Seeds were placed in 9 cm Petri dishes with two layers of filter paper (No. 1; Whatman International, Maidstone, UK) and 10 ml of deionised water. The number of germinated seeds was recorded daily for at least 28 days, and recordings stopped when no further germinations were observed for 7 days. The tests were run twice in different incubators for each temperature regime.

Minimum temperature thresholds, and the reciprocal time to 50% germination were estimated according to Steinmaus *et al*. (2000). Percentage germinations for each replicate were fitted to the logistic function:

$$Y = \min+(\max-\min)/(1+(x/T_{50})^{\wedge}(-\text{Hillslope})), \qquad (1)$$

where Y is the percentage of cumulative germination, X is the time (days), the germination rate (T_{50}) is the time taken for half of the seeds to germinate, and Hillslope is the steepness of the curves. This was calculated using R version 3.6.2 (The R Foundation for Statistical Computing).

A linear regression was then performed by plotting the inverse of the germination rates against each incubation temperature. The base temperature (T_b) was then determined by where the regression intercepted the temperature axis.

Emergence and persistence of red pigweed

An 18-month pot trial was established in a shade house (10% shade cloth) at the Leslie Research Facility, Toowoomba in July 2021 and designed to run until January 2023 investigating the impact of five burial depths (0, 1 ,2, 5 and 10 cm) and five exhumation times (3, 6, 9, 12 and 18 months) on emergence and persistence of red pigweed seeds. Seed used was collected in March 2020 from mature plants growing on the edge of cotton fields around Nandi, Queensland.

The experiment was designed as a randomised complete block with 3 replications. Pots were placed on 3 benches with each bench being a separate replicate. A total of 84 pots, including 9 control pots with no weed seed added, were filled with unsterilized heavy black cracking clay collected from Hermitage Research Facility, Warwick. The 9 control pots were included in the design to determine the possible background red pigweed population in the soil. The average emergence across these pots was less than one, indicating that the background population in the soil was negligible.

Using 200 mm pots (20 cm diameter x 17 cm depth), soil was added in such a way to create a soil/seed layer that could be exhumed for seed persistence measurements. Permanent marks were made on the interior of all pots at the soil surface level. Further measurements were taken from this level down into the pots to identify where seeds needed to be placed. Marks were made at the burial depth and at 2 cm below this depth (1, 2, 5 and 10 cm) and at 2 cm above the burial depth (5 and 10 cm only). No additional marks were required for the 0 cm pots.

Soil was added up to the 2 cm below mark in all pots, except the 0 cm treatments, and covered with a shade cloth disc to establish a soil/seed layer for future exhumations. An additional 2 cm of soil was placed on the disc to bring the soil surface up to the seed burial mark. A total of 150 red pigweed seeds were then spread over the soil surface in the centre of the pot. An additional 2 cm of soil was added over the seeds except for the 1 cm treatment where 1 cm of soil was added. In the 5 cm and 10 cm treatments another layer of shade cloth was added at the 2 cm above mark and then filled to the surface mark with the 0cm burial depth having seeds spread across the surface.

Existing irrigation lines were removed from the benches to ensure pots received rainfall without any impediment and that no additional watering occurred. Rainfall was recorded after each event using a rain gauge set up in the vicinity of the pots. Pots were checked for emergences on a regular basis, especially after a rainfall event and once recorded, all emergences were removed.

The number of seeds persisting in the soil at exhumation (3,6,9,12,18 months) was determined via recovery of the soil/seed layer. Due to the small size of the red pigweed seed (0.5 to 0.8 mm) seeds that failed to germinate were not recovered for further testing. The soil/seed layer from each pot was transferred into individual trays (35 x 28 cm), with the soil being spread evenly over a base of potting mix approximately 2 cm in depth. Trays were randomised and placed within existing reps in a growth room at 30/20°C (12-hour day/night cycle) for a period of 3 months to provide conditions suitable for seed germination. Emergences were recorded on a regular basis with seedlings removed from the trays once counted. Soil was dried out before being scratched up and re-watered to potentially bring buried seed closer to the surface and allow further flushes. This was not done with the 18-month trays due to time limitations. These trays were kept in the growth room for only 5 weeks and scratched up and re-watered on a weekly basis. After a week with no flushes the experiment was terminated.

In conjunction with the persistence experiment, an experiment was run to investigate how seed viability changes over time. This was assessed by measuring the change in viability of stored seed samples. Eighteen specimen bottles, each containing 150 red pigweed seeds, were prelabelled with an exhumation month (0, 3, 6, 9, 12, 18 months) and replicate number (1 to 3). The bottles were stored in a dark environment (paper bag inside of a shoe box) at ambient temperature, in this case a shed in the shade house.

The stored seed was assessed for viability via germination tests in conjunction with each 3-monthly pot exhumation. At each exhumation the stored seed was placed into 9 cm Petrie dishes with a layer of filter paper (No. 1: Whatman International, Maidstone, UK) and 3 ml of deionised water. The Petrie dishes were put into Ziplock bags and placed into the growth room with the trays. Germinations in the Petri dishes were counted for a period of 28 days in order to determine a comparison between the viability of the seeds in dry storage compared to seed in the pots at each exhumation time.

Results and discussion

Base temperature determination

Red Pigweed

Red pigweed was able to germinate at a wide range of temperatures (10^{o}C – 38^{o}C) (Figures 1 and 2). There were no germinations at 5^{o}C. The lowest germinations occurred at 10^{o}C (20%) and the highest at 25^{o}C (70% and 50% in runs 1 and 2 respectively). These maximum germinations occurred within 5-7 days of incubation, indicating that when exposed to moisture and the right temperature they are quick to germinate.

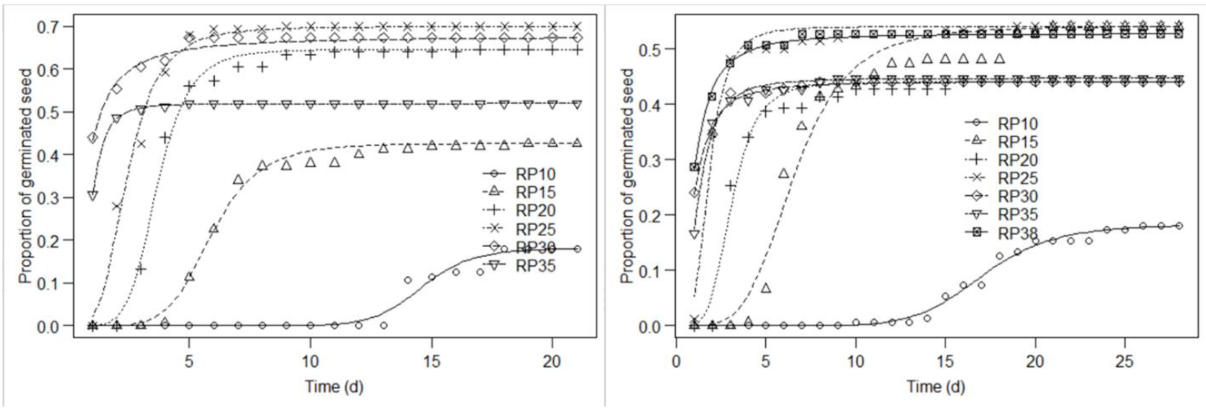


Figure 1. Proportion of germinated red pigweed seeds with respect to time and temperature. The graph on the left is from Run 1, and on the right is from Run 2.

When the time to 1/50% germination was plotted against temperature for the two runs, the resultant equation was y = 0.046x – 0.495. This corresponded to a base temperature for red pigweed of 10.75^{o}C.

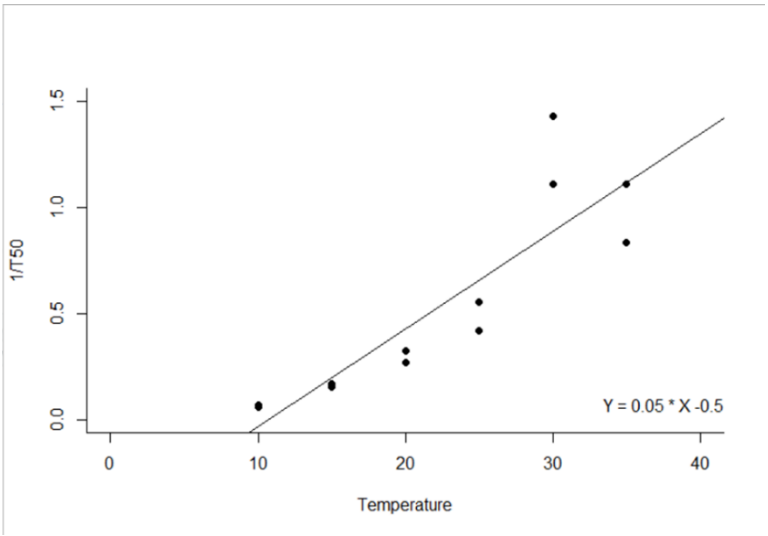


Figure 2. Inverse of time to 50% germination plotted against temperature for red pigweed. The regression equation is y = 0.046x – 0.495 with the x-axis intercept and base temperature at 10.75°C (R^2 = 0.75).

Dwarf Amaranth

The temperature requirements for dwarf amaranth were slightly higher than that of red pigweed. There was no germination below 15°C, with only 10% of seeds germinating at this temperature. The highest germinations occurred at 25°C (70%) in run 1 and 35°C (60%) in run 2 (Figure 3). The germination response time was slightly slower than that of red pigweed, with the maximum reached after approximately12-13 days after incubation.

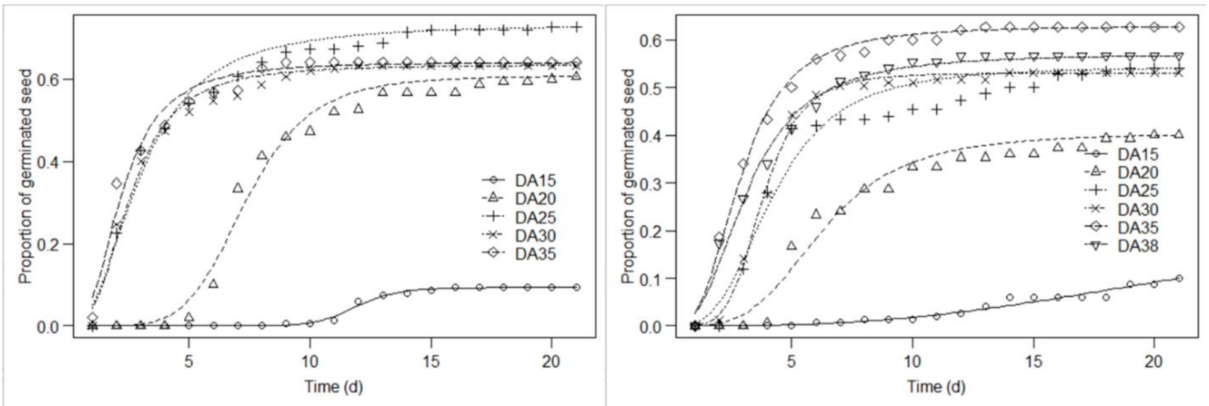


Figure 3. Proportion of germinated dwarf amaranth seeds with respect to time and temperature. The graph on the left is from Run 1, and on the right is from Run 2.

When the time to 1/50% germination was plotted against temperature for the two runs, the resultant equation was y = 0.017x – 0.179. This corresponded to a base temperature for red pigweed of 10.6°C.

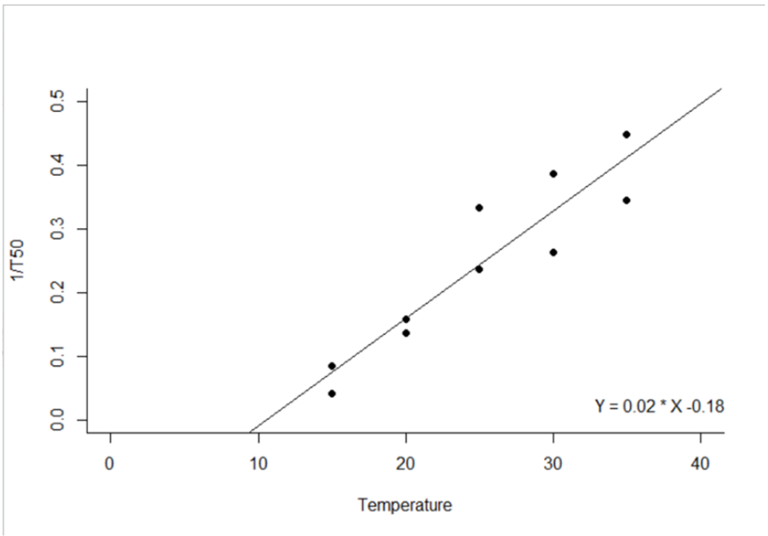


Figure 4. Inverse of time to 50% germination plotted against temperature for dwarf amaranth. The regression equation is y = 0.017x – 0.179 with the x-axis intercept and base temperature at 10.6°C ($R^2 = 0.84$).

It is important to note that sometimes when working with equations, the end result can be different from what is expected from the data. This was the case for the base temperature of dwarf amaranth, as its base temperature was similar to that of red pigweed although there were no germinations for dwarf amaranth below 15°C. Perhaps some germination would have occurred at 11 or 12°C. However, both species were similar in the temperature range required for their germination. Dwarf amaranth has a slightly larger seed than red pigweed, which explains the longer time required for its imbibition and subsequent germination. These results indicate that both species can germinate as soil temperatures rise above 10°C which is likely to occur early spring. They will then be able to germinate through summer into autumn. Their hard seed coats also indicate that they will emerge in scattered cohorts throughout the season. Both these factors combine to explain why they are continuing to be a problem.

Emergence and persistence of red pigweed

Red pigweed is a very small seeded species (0.5 – 0.8 mm), and therefore we would expect it to primarily emerge from the soil surface. This was reflected in the results obtained from this experiment (Figure 5). Most seeds germinated from 0, 1 and 2 cm depths and were significantly greater than emergences from 5 and 10 cm throughout the experiment.

Emergences from 0 and 1 cm depths were significantly greater than 2 cm in the 3 and 12-month pots. Both exhumation times corresponded with cooler seasons, winter/early spring (3 months) and autumn/winter for the 12-month pots. Red pigweed is known to germinate from late spring to summer with seeds remaining dormant over the winter months. Sufficient rainfall (148.5 ml) had been received at the commencement of the experiment to ensure emergence from surface-sown and 1 cm seeds with the onset of warmer conditions. Over the first 9 months of the experiment a total of 1146.5 ml was received followed by another 322 ml in the next three months and 407 ml during the final 6 months of the experiment.

As pots for later exhumation times were left in the shade house emergences tended to increase. This was the case particularly for the 1 cm depth pots, although this effect was not significant as the bulk of emergences occurred within the first 3-6 months. Although red pigweed emergence was favoured by the shallower depths, it is interesting to note that some emergences did occur from 5 and 10 cm. In similar research, germination was greatest for surface sown seed and declined up to a depth of 1 cm with no emergences at 2 cm. While this contrasts with results obtained in this experiment, research undertaken on common purslane (red pigweed) by Benvenuti *et al.* (2001) found that seedlings emerged from up to 6 cm in depth but not beyond. This shows that red pigweed still can emerge from depth, however weed management practices such as cultivation that can bury the seed to depths of 5 cm or more will significantly reduce emergence.

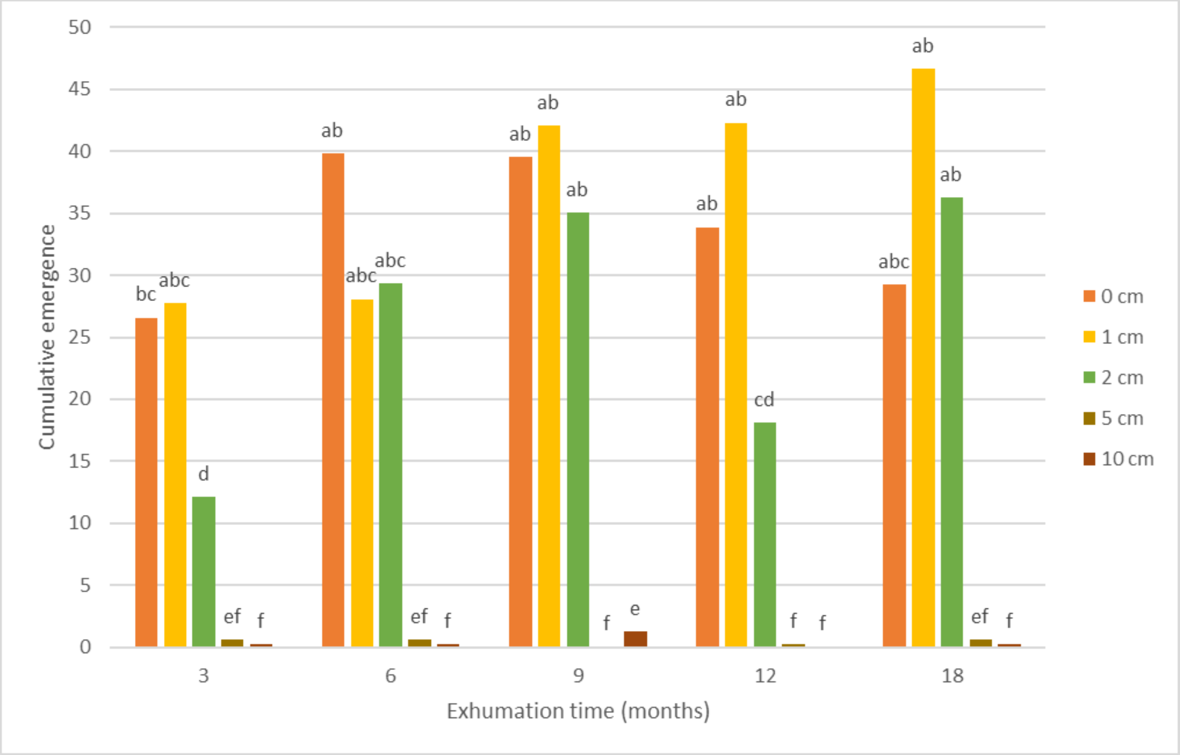


Figure 5. Emergence of red pigweed in relation to burial depth and time. Bars with different letters for each respective depth and exhumation time are significantly different ($p < 0.05$).

The other factor to consider with burial depth is persistence. It is expected that as burial depth increases, so does persistence. This was the case with red pigweed in this study (Figure 6).

For seed buried at the lower depths up to 2 cm, most of the viable seeds remaining in the soil germinated after the initial 3-month burial period. Seed sown on the surface had the lowest persistence, decreasing over time with negligible germinations after 18 months. Seed buried at 1 cm persisted longer than that on the surface, decreasing from a viability of 19% after 3 months to approximately 3% still viable after 18 months. After 3 months, seed buried at 2 cm had a viability of 32% which decreased at a slower rate ranging 5-10% from 6 months to 18 months. Seed buried at 5 and 10 cm persisted significantly longer than surface-sown, or seed buried to a depth of 1 cm. The highest geminations occurred from seed buried at 10 cm and exhumed after 12 months. Seed buried at this depth had similar germinations when exhumed at 9 months as seed exhumed at 18 months. This indicates that seed can persist at 10 cm for extended periods and this study provided no clear indication of when the persistence of red pigweed seed buried at this depth will decline. At all exhumation times, seed buried at 5 cm were statistically the same as those buried at 10 cm. It does appear that there is a decline in persistence of seed buried at 5 cm after 18 months, however again this study was not conducted for long enough to determine when persistence will substantially decline.

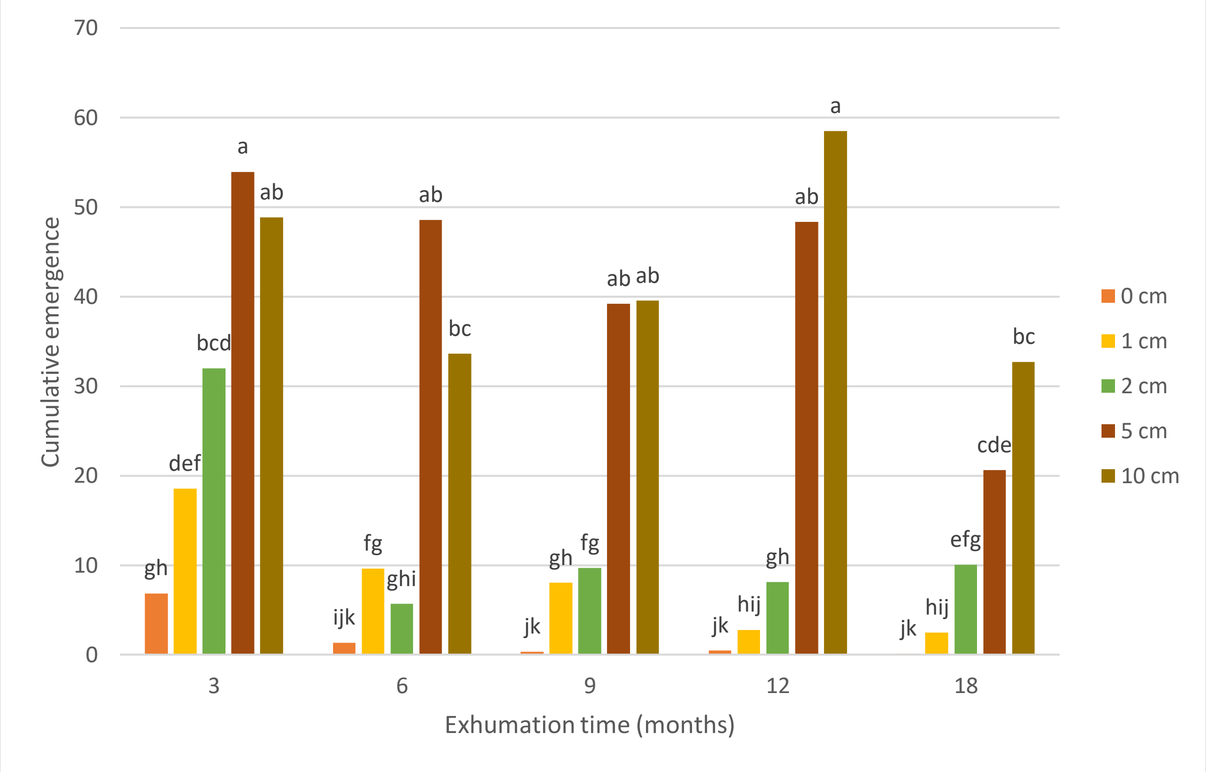


Figure 6. Persistence of red pigweed seeds in relation to burial depth and length of burial (measured at germinations from each exhumation time). Bars with different letters for each respective depth and exhumation time are significantly different ($p < 0.05$).

Seed that was stored in the shade house reached its peak gemination after 3 months, followed by 0 and 6 months. After 18 months there were still significant germinations with just under half of the seed stored germinating (Figure 7).

The times in this study were set to correspond to the exhumation time in the pot study in the shade house. However, these seeds were collected approximately 18 months prior to establishing the study. After collection in the field, seeds were stored at room temperature, prior to establishing the experiment. This ultimately means that these seeds were stored for up to 36 months. This provides some indication of their persistence. If we attempt to combine the results from the stored seed to that of the seed placed in the soil at 10 cm, we can estimate that seed would need to be buried for at least 36 months (3 years) before persistence would begin to decline.

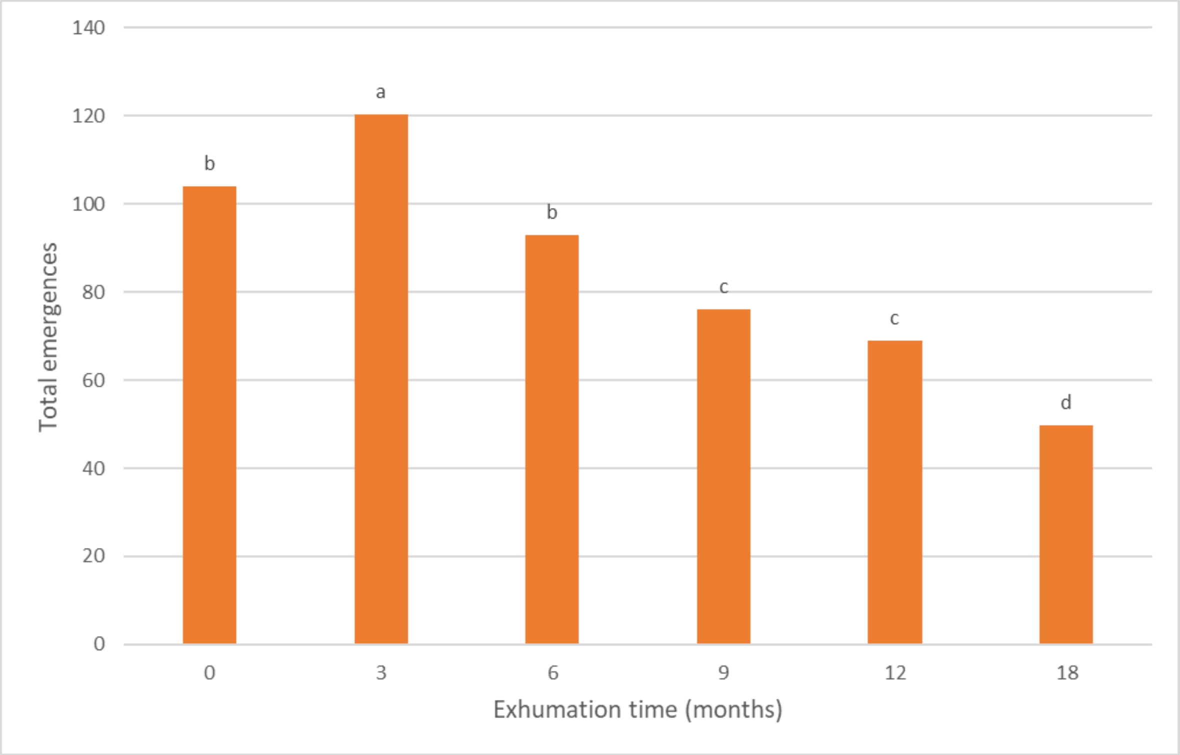


Figure 7. Total emergence of red pigweed seed stored at shade house temperature and germinated in petri-dishes with respect to each exhumation time. Bars with different letters for each respective exhumation time are significantly different ($p < 0.05$).

The management strategy for red pigweed is not a simple one. In order to reduce the population, it appears that leaving the seed on the surface and applying a range of pre- and post-emergent herbicides to reduce emergences and then control subsequent emergences is a viable option. Our results indicate that this would need to be done for at least 18 months to 2 years. Cultivation can also be a viable option, however once seed is buried it would need to remain buried for at least 3 years or more. Otherwise seed buried at depth that is then brought up to the surface will be able to emerge. This contrasts with weeds like feathertop Rhodes grass and fleabane where persistence drops after two years. The burial strategy might be more useful when targeted to fields where red pigweed is the major weed of concern.

Milestone 3.3.3 – Determining if summer growing annual ryegrass is a new biotype of this weed

Background

Annual ryegrass has been the primary weed of southern winter cropping systems, competing strongly with cereal crops, and has developed resistance to most of the herbicide modes of action used to manage this weed. Much of the southern management of this weed focuses around harvest weed-seed capture and destruction, but plants are developing “resistance” to this tactic, emerging later in the season to escape pre-planting and at-planting inputs, growing more quickly, and maturing before cereal harvest, shedding their seed before harvest and thus avoiding harvest weed-seed capture. This “plasticity” of annual ryegrass (ability to grow differently to “evolve” to avoid weed control tactics) is fundamental to why this weed is so problematic in southern farming systems.

Glyphosate resistant annual ryegrass has become a common weed of the southern cotton system and plants are spreading into the more northern areas. Resistant annual ryegrass has been common on the Liverpool Plains for many years and is now becoming problematic on the Darling Downs, although generally, the annual ryegrass encountered in the cotton system is relatively easily managed, although all is resistant to glyphosate.

One grower from the Macquarie we spoke to during the 2016 industry workshops commented that he had annual ryegrass on a property in the Macquarie that was resistant to all his in-cotton grass herbicides other than metolachlor. This was not confirmed but resistance to other herbicides is likely to be a future problem with annual ryegrass as it has been elsewhere in the south.

A concerning new development from the southern cotton areas is that some annual ryegrass is now growing in cotton throughout the summer, moving from being a winter weed problem to become a serious summer weed!

This experiment was established to determine whether this summer growing annual ryegrass is a new summer-growing biotype of annual ryegrass, or whether this is just a reflection of the plastic nature of this weed finding opportunity for plants to survive through the summer.

Annual ryegrass growing in cotton in summer at Darlington Point.

A paper discussing this question was published in 2022, but does little to answer the question: Thompson M & Chauhan B (2022) Changing seasonality of *Lolium rigidum* (Annual ryegrass) in Southeastern Australia. Frontiers in Science, 4, doi.org/10.3389/fargo.2022.897361

Continuity of our research was lost with challenges using growth cabinets that malfunctioned and turnover in staff. Some intended treatments were not completed.

Methods and materials

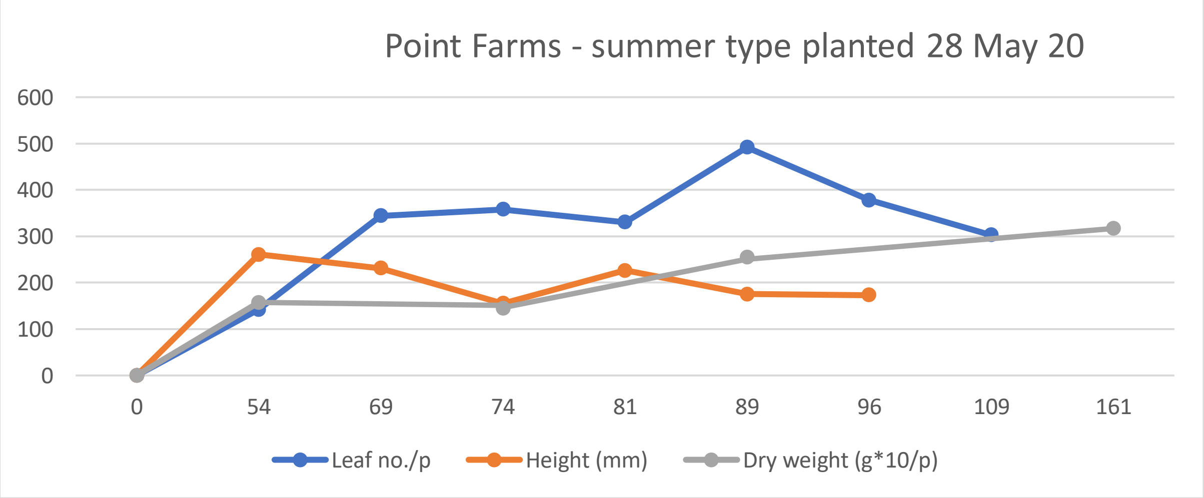
Seed was collected from plants that grew and set seed over summer from several sites at Darlington Point, Whitton, Leeton and Forbes. Unfortunately, only the seed from Darlington Point was viable. The growth of seedlings from this population was compared under glasshouse conditions with the growth of winter growing seedlings from the Namoi Valley; Bullawa Creek, Boggabri and Breeza. Plants were observed and growth was measured during the spring of 2020 and the senescence of these plants was recorded. There were initially 28 plants from each source, with one plant per pot. Destructive harvests were undertaken on 10 pots during the observation period. Following senescence, seed was returned to each pot and pots were monitored to observe the start of the following germination. The established plants grew through the following season.

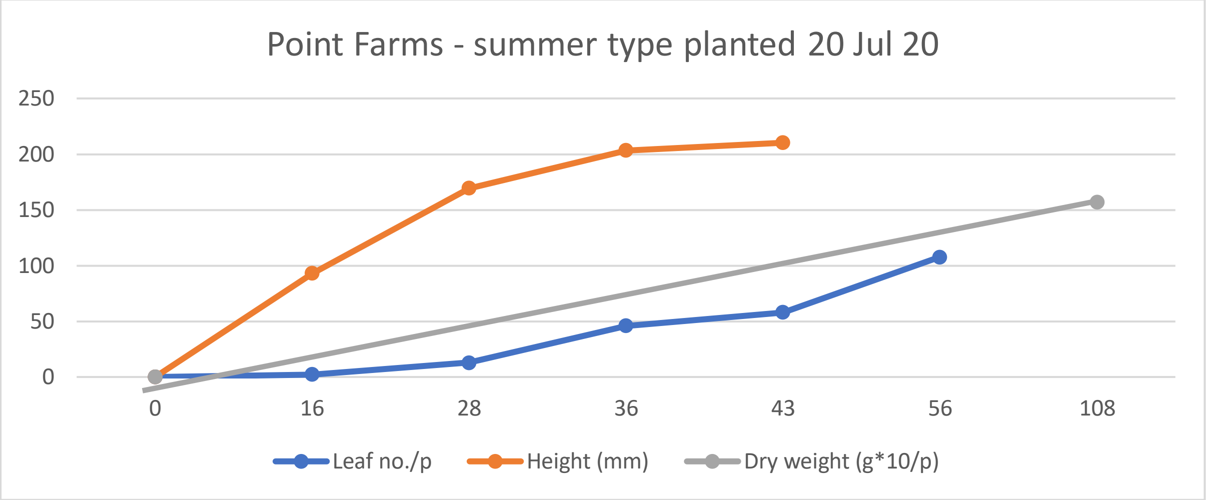
Seed was again collected from the second season for germination testing in controlled temperature cabinets to be tested for germination under constant temperatures of 10, 20, 30 and 40°C, with comparisons of germination rate between the different sources (some seed was lost to mice). However, when tested, none of the four cabinets (two germination cabinets and two growth cabinets) owned by the weeds group were functioning correctly. These cabinets had been purchased under the 2nd Cotton CRC and their electronic controls had never been satisfactory. The controls on one had since been replaced at great expense, but this cabinet was also not working. A local electrical company undertook to replace the controls with a much simpler system. This conversion took nearly 12 months to complete, with only two of the four cabinets working satisfactorily at the end of the process. Seed was stored it 4°C during this period.

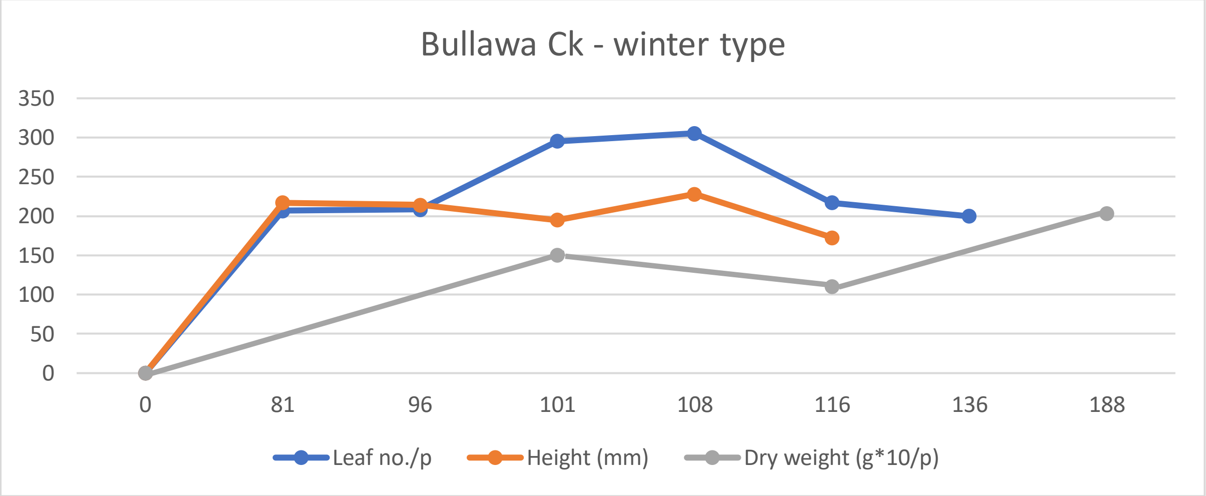
For each temperature, 25 seeds from each pot were placed on moist filter paper in Petrie dishes, with 4 replicates from 4 pots from each source. The seed from 40°C was lost when the cabinet used for this temperature failed. The experiment was resumed when another cabinet became available but the seed was no longer viable. No cabinet was able to reliably achieve the 10°C temperature, leaving results only from 20°C and 30°C.

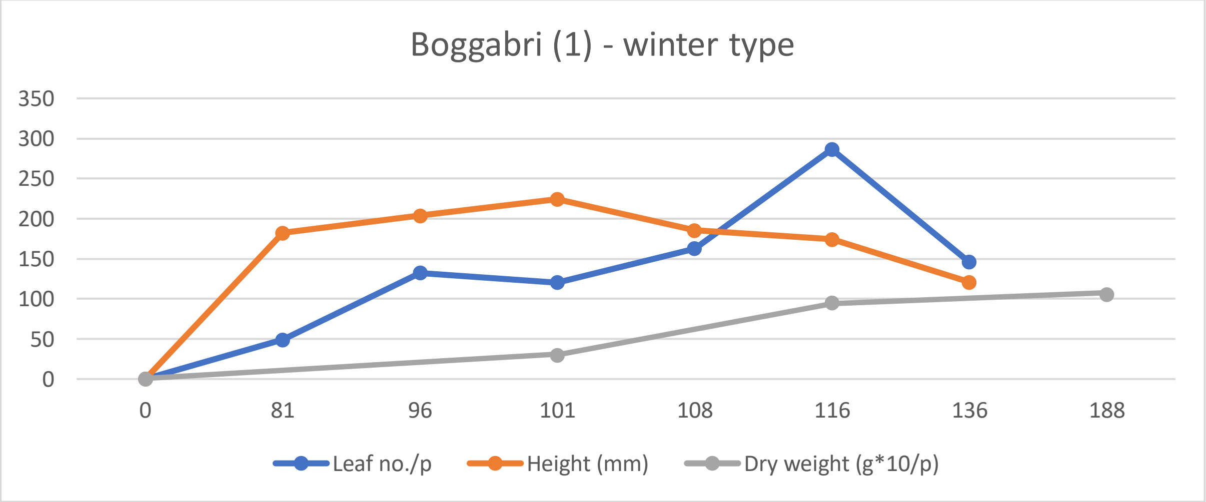
Results and discussion

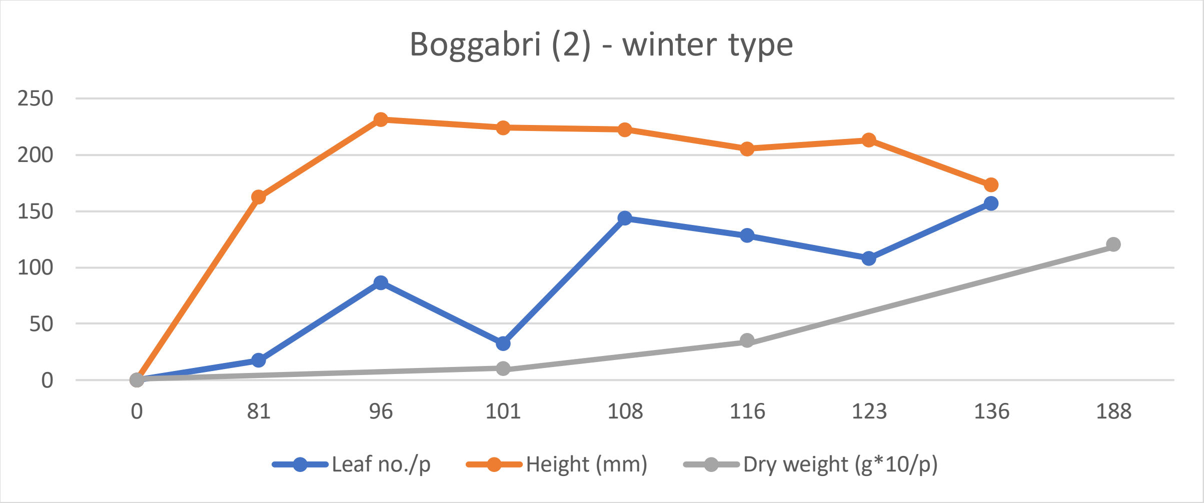
Results for growth and development of plants from each source under glasshouse conditions are shown below.

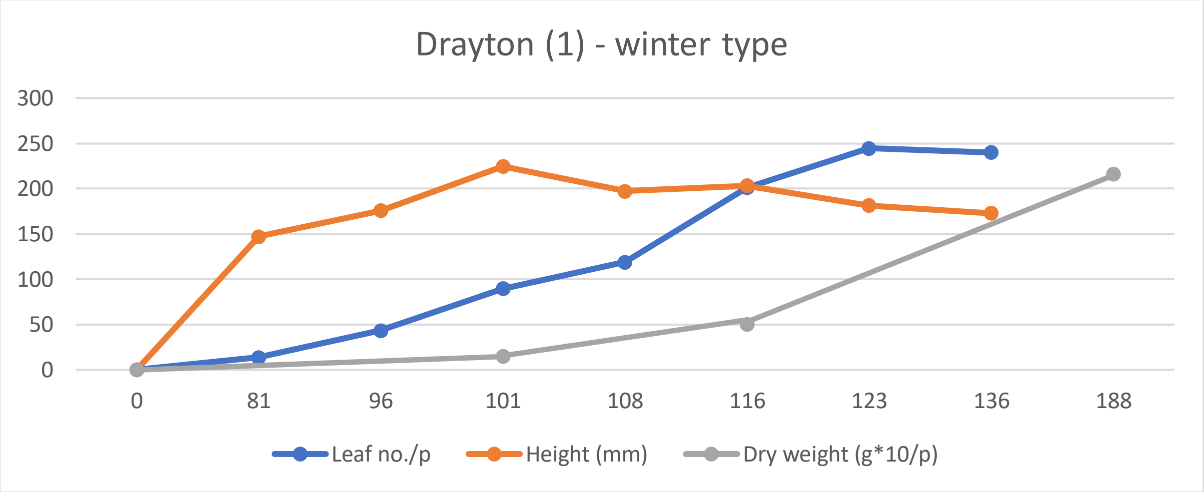


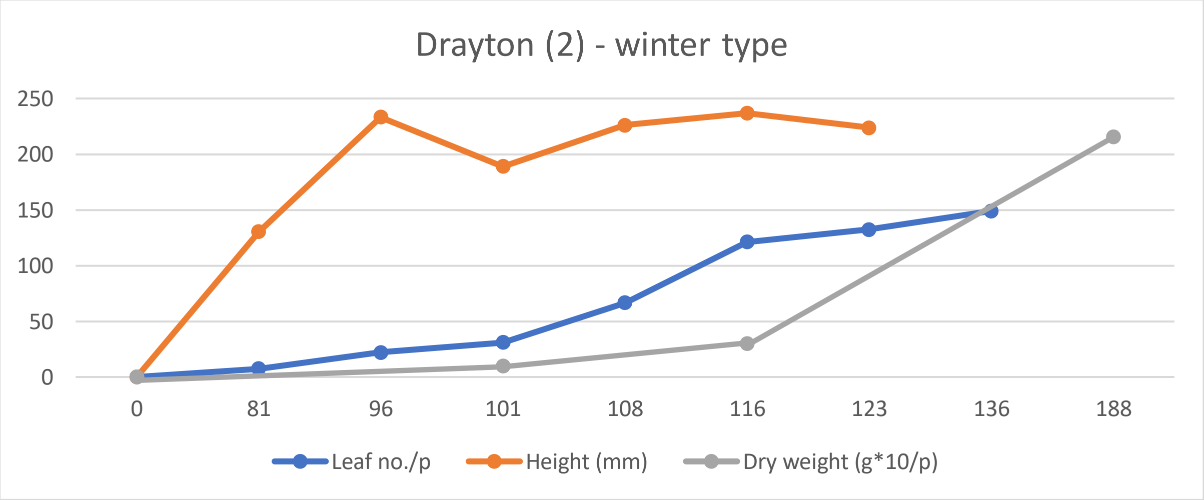

Point Farms - summer type planted 20 Jul 20
250
200
150
100
50
0
0
16
28
36
43
56
108
Leaf no./p
Height (mm)
Dry weight (g*10/p)


Bullawa Ck - winter type
350
300
250
200
150
100
50
0
0
81
96
101
108
116
136
188
Leaf no./p
Height (mm)
Dry weight (g*10/p)


Boggabri (1) - winter type
350
300
250
200
150
100
50
0
0
81
96
101
108
116
136
188
Leaf no./p
Height (mm)
Dry weight (g*10/p)







Plants established from seed from Point farms, taken from summer growing plants, planted 28 May, grew more rapidly and were larger than plants from the other sources, growing to 492 leaves/plant and biomass of 32 g/plant at senescence. However, plants grown from the same seed source, planted 2 months later (20 Jul), were similar to or smaller than plants grown from the other sources, only growing to 108 leaves/plant and 16 g biomass/plant. Plants from all sources and planting dates senesced at the same time of late-Nov, early-Dec. A summary of the data is shown below.

Source	Max. leaves/plant	Max plant height (mm)	Max biomass (g/plant)
Point Farms (1)	492	261	32
Point Farms (2)	108	210	16
Bullawa Ck	306	228	20
Boggabri (1)	287	224	11
Boggabri (2)	157	231	12
Drayton (1)	245	225	22
Drayton (2)	149	237	22

Note. Seed from Point Farms was sourced from ryegrass plants growing over summer.

The comparison between seed sources emphasises the variability of this weed, but indicates no real differences in growth type between the plants sourced from “summer growing” and “winter growing” sources. Plants from Boggabri were notably smaller (lower biomass) than plants from the other sources.

Seedlings from all sources emerged at a similar time in autumn 2021, grew over winter and again senesced in late spring, with no obvious differences between the apparently different growth types.

Results for emergence from the different seed sources at set temperatures of 30°C and 40°C are shown below.

Source	20°C		30°C	
	Germination %	s.e.	Germination %	s.e.
Point Farms (1)	61%	6%	66%	5%
Point Farms (2)	55%	5%	60%	4%
Bullawa Ck	65%	5%	57%	5%
Boggabri (1)	68%	3%	63%	8%
Boggabri (2)	79%	4%	69%	4%
Drayton (1)	62%	9%	62%	7%
Drayton (2)	61%	7%	62%	5%

The germination percentage was lower than was expected (ryegrass is typically around 95% viable) on all seed at both temperatures, probably reflecting the long period between seed collection and the experiments, but was similar between all sources.

The rate of emergence (average number of days to achieve emergence) is shown below.

Source	20°C		30°C	
	Average days	s.e.	Average days	s.e.
Point Farms (1)	4.7	0.7	4.2	0.4
Point Farms (2)	4.5	0.4	3.8	0.3
Bullawa Ck	4.7	0.5	4.0	0.5
Boggabri (1)	3.2	0.2	3.8	0.9
Boggabri (2)	3.3	0.2	3.1	0.4
Drayton (1)	4.9	1.1	3.1	0.3
Drayton (2)	4.7	0.6	3.7	0.3

The rate of emergence results appear to be highly variable, but the difference between the quickest and slowest is only 1 to 1.7 days, with little real difference between the germination rates from the different sources. Of particular interest, the seed from Point Farms, sourced from a summer growing population, had a similar germination percentage and germination rate when compared with seed from the other sources, with all seed germinating as readily from 30ºC as it did from 20ºC.

These experiments did not detect any real differences between “summer growing” and “winter growing” types of annual ryegrass, although only one viable source of summer growing seed was used. However, the experiments did highlight the variable nature of annual ryegrass, a known characteristic of this weed. A reasonable conclusion from this work is that there is not a “summer growing” biotype of this weed, but rather the “selection pressure” of irrigated summer cropping in areas where annual ryegrass is prevalent, has extended the growth range of this weed, with plants increasingly able to grow at any time of the year as opportunity allows. The practice of relying primarily on glyphosate for weed control has resulted in this glyphosate-resistant weed becoming increasingly common in the cotton area.

It is also noted that annual ryegrass, as a winter-growing weed, is steadily moving north, becoming a common weed of winter cropping on the Darling Downs, an area where it was not previously found. It must be expected that annual ryegrass will spread as a summer weed over the next few years. It can be expected to become a common weed of cotton production and will be most problematic if populations resistant to the commonly used herbicide groups become established. Annual ryegrass has a long history of developing resistance to the herbicide groups and management practices used to manage it.

It is recommended that future herbicide resistance surveys include summer growing ryegrass to monitor the development of herbicide resistance in this weed in the cotton system.

Milestone 3.3.4 – Assessment of black roly-poly (*Sclerolaena muricata* var. *muricata*) and soft roly-poly (*Salsola australisa*) as problem weeds for cotton production

Background

The roly-polys are prolific and abundant weeds of the western areas, occurring in high numbers throughout much of the grazing country and around the edges of cotton fields. They are minor weeds of fallows and can occur in cotton.

During the last drought, it was reported that roly-poly was not being controlled by normal fallow sprays and was becoming problematic in fallows, although it was not clear as to which of the species was causing the issue.

This research aimed to determine some basic ecology of these weeds and their tolerance to the commonly used herbicides of the cotton system.

Continuity of this research was lost with challenges using growth cabinets that malfunctioned and turnover in staff. Some intended treatments were not completed.

Materials and methods – soft roly-poly

Seed was collected from plants found on and around the Cotton Research Station at Myall Vale. The rate of germination was tested in a germination cabinet at 15°C and two batches of seeds were tested on the surface of pots in a glasshouse at 20–30°C, with 25 seeds per sample and 4 replications.

Sixty germinated seedlings were transferred to pots in a glasshouse and grown for 100 days, at which time they were sprayed with herbicide as shown below. Four pots were allocated to each treatment, with destructive harvests on additional untreated pots at the time of spraying. Pots were selected to achieve relatively uniform size across treatments. Plant size was recorded at spraying, and 4, 31 and 65 days after spraying. All alive plants were destructively harvested at 65 days, with measurements recorded.

Treatment	Herbicide	Herbicide rate (x/ha)
1	Basta	1 L
2	Basta	2 L
3	Basta	4 L
4	Dicamba 700	143 g
5	Dicamba 700	285 g
6	Dicamba 700	570 g
7	Roundup Ready Herbicide	0.75 kg
8	Roundup Ready Herbicide	1.5 kg
9	Fluometuron 900	3 kg
10	Prometryn 900	2.5 kg
11	Diuron 900	2 kg
12	Untreated	

Results and discussion – soft roly-poly

Most soft roly-poly seed germinated without the need for additional treatment. Germination was tested on seed from two sources. Seed collected from the road side at Myall Vale achieved 60% ± 5% at 15°C, with average germination taking 4.1 ± 0.4 days from planting. Seed from a second collection achieved 62% ± 7% germination at 15°C, with average germination taking 2.2 ± 0.4 days. Seed planted on the surface of pots in a glasshouse at 20 – 30°C achieved 50% ± 5% germination in 5.3 ± 0.1 days.

Germinated seeds were transferred to pots, one plant per pot, and grown in the glasshouse. At 100 days after planting, plants were still quite small at 9.8 ± 3 cm tall, with 12 branches per plant, weighing 0.7 g/plant. Plants were sprayed 100 days after planting, with results shown below.

Treat	Herbicide	Rate	31 DAS	65 DAS	
			% Alive	% Alive	Biomass (g/plant)
1	**Basta**	1 L	100	100	5.2
2	**Basta**	2 L	100	100	3.5
3	**Basta**	4 L	-	-	-
4	**Dicamba**	143 g	25	25	1.0
5	**Dicamba**	285 g	50	50	1.2
6	**Dicamba**	570 g	25	25	0.7
7	**Roundup**	0.75 kg	100	100	7.4
8	**Roundup**	1.5 kg	-	-	-
9	**Fluometuron**	3 kg	-	-	-
10	**Prometryn**	2.5 kg	-	-	-
11	**Diuron**	2 kg	25	-	-
12	**Untreated**		100	100	8.7

Soft roly-poly plants were killed by standard rates of Basta, Roundup Ready Herbicide, Fluometuron 900, Prometryn 900, and Diuron 900. Dicamba 700 at rates up to 570 g/ha didn't kill soft roly-poly, but did suppress this weed, with no growth recorded at the highest rate, 65 days after exposure, and little growth at the lower rates. Interestingly, a lower rate of Roundup Ready Herbicide didn't control or even supress this weed.

These results show that soft roly-poly is a surface germinating weed that can readily establish under zero tillage, but it has a slow growth rate and is easily controlled by many of the common herbicides that can be used with cotton production. Actively growing plants of soft roly-ploy are readily controlled by a full rate of Roundup Ready Herbicide, but plants were unaffected by a half-rate. It can be conjectured that stressed plants, and plants that receive a lesser dose of glyphosate (possibly plants on the edge of a camera-spray application) are likely to survive a glyphosate application, leading to the apparent issue of roly-poly survival observed during the drought. It seems likely that soft roly-poly seedlings will be readily controlled by any of the standard residual herbicides used in cotton.

Materials and methods – black roly-poly

Seed was collected from plants found on and around the Cotton Research Station at Myall Vale. The rate of germination was tested in a germination cabinet at 15°C and in a glasshouse at 20–30°C, at 0, 5, 10 and 15 mm depth, with 25 seeds per sample and 4 replications.

Sixty germinated seedlings were transferred to pots in a glasshouse and grown for 71 days, at which time they were sprayed with herbicide as shown below. Four pots were allocated to each treatment, with destructive harvests on additional untreated pots at the time of spraying. Pots were selected to achieve relatively uniform size across treatments. Plant size was recorded at spraying, and 15 and 28 days after spraying. All alive plants were destructively harvested at 28 days, with measurements recorded.

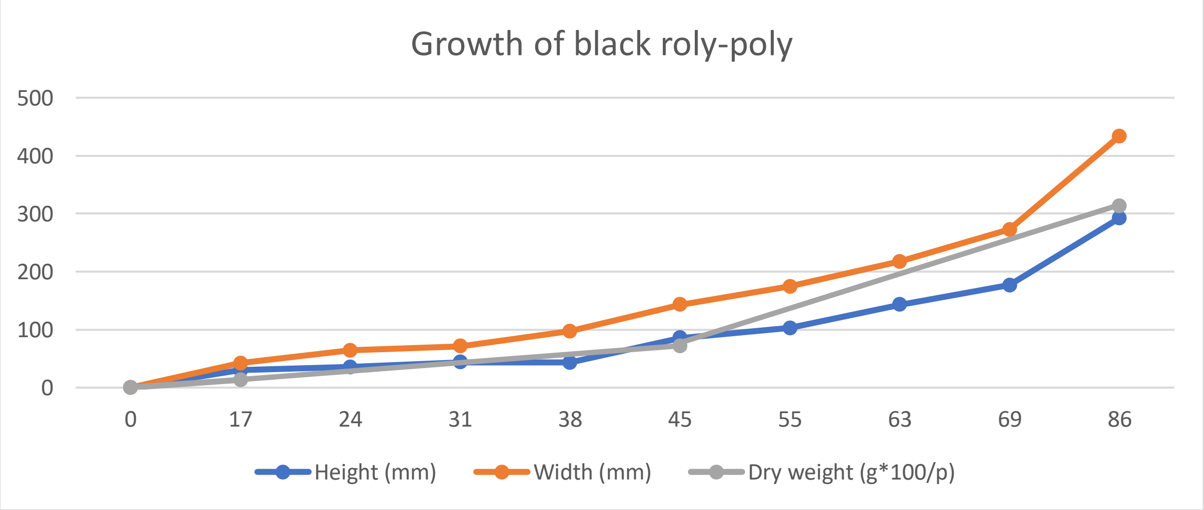
Treatment	Herbicide	Herbicide rate (x/ha)
1	Basta	1 L
2	Basta	2 L
3	Basta	4 L
4	Dicamba 700	229 g
5	Dicamba 700	457 g
6	Roundup Ready Herbicide	0.75 kg
7	Roundup Ready Herbicide	1.5 kg
8	Fluometuron 900	3 kg
9	Prometryn 900	2.5 kg
10	Convoy (fluometuron 440 g/kg + prometryn 440 g/kg)	2.9 kg
11	Diuron 900	2 kg
12	Untreated	

Results and discussion – black roly-poly

Black roly-poly seed germinated without the need for additional treatment, as shown below. Seed germinated in 6 -10 days from the soil surface and shallow depths, although the results suggest that black roly-poly is a surface germinator that won't emerge from much more than 15 mm depth.

Treatment	Germination %	s.e.	Days to emergence	s.e.
15°C	94%	2%	16.0	0.5
Surface	61%	5%	6.3	0.6
5 mm	47%	11%	6.3	0.4
10 mm	46%	12%	10.3	1.3
15 mm	17%	4%	7.9	0.7

Seedlings grew steadily under glasshouse conditions from seeds planted in mid-June, achieving 434 ± 10 mm diameter by late-August, 71 days after planting. This growth rate was much faster than was observed for soft roly-poly.



Herbicides were applied to all plants 71 days after planting, with the results shown below.

Treat	Herbicide	Rate	At spraying	28 DAS		
			"Size" (m^2)	% Alive	"Size" (m^2)	% "Size" reduction
1	Basta	1 L	0.067	100	0.175	0
2	Basta	2 L	0.045	25	0.004	97
3	Basta	4 L	0.046	25	0.006	95
4	Dicamba	229 g	0.054	100	0.062	51
5	Dicamba	457 g	0.049	100	0.094	26
6	Roundup	0.75 kg	0.058	100	0.112	11
7	Roundup	1.5 kg	0.059	75	0.045	64
8	Fluometuron	3 kg	0.061	100	0.100	21
9	Prometryn	2.5 kg	0.058	25	0.005	96
10	Convoy	2.9 kg	0.045	25	0.005	96
11	Diuron	2 kg	0.041	75	0.066	48
12	Untreated		0.053	100	0.127	

Note. "Size" was an indication of plant size, calculated as the product of plant height and width.

Black roly-poly was not killed by any of the standard rates of the herbicides used. Even a full rate of Roundup Ready Herbicide killed only one of four plants and supressed growth by 64% when compared with untreated plants. The best treatments were Basta at the 2 and 4 L rates, Prometyrn and Convoy, each giving 75% control and 95% or better reductions in plant size 28 days after spraying.

These results show that black roly-poly is a shallow germinating weed that can readily establish under zero tillage and is not easily controlled by any of the common herbicides that can be used with cotton production. Stressed plants are likely to be even less affected by these herbicides, but it is likely that the cotton residual herbicides, especially prometryn, will control emerging black roly-poly seedlings in cotton. Sensitivity to 2,4-D and fluroxypyr were not tested in this experiment, but it may be that these herbicides are normally controlling black roly-poly in fallows.

These results suggest that the observed issue of roly-poly being poorly controlled in fallows during the drought is likely to have been a combination of the high tolerance of this weed to many common herbicides, together with moisture stress, reducing the weed's susceptibility to these herbicides.

It is concerning that black roly-poly is tolerant of most of the commonly used herbicides and is a very wide-spread weed, apparently being primarily controlled by cultivation and 2,4-D (conjecture at this time). Thus, there appears to be significant selection pressure for this weed to develop resistance to 2,4-D. Resistance to 2,4-D could make this a challenging weed of the future, potentially like the tumble weed of North-America.

Milestone 3.3.5 – Phenology and germination studies on feathertop Rhodes grass

A comprehensive phenology study of four populations of FTRG interaction with 4 sowing times (4 Sep, 4 Nov, 4 Jan and 4 Mar) has been completed at Wagga Wagga. The results showed that the mid-summer emerged cohort had the longest reproductive period whereas the early-autumn cohort died before switching to a true reproductive stage due to cold stress. Plants between growing condition varied from prostrate to upright. Mid-summer cohorts required slightly longer to achieve seed head formation and less time for seed maturity than those initiated in early and late spring.

All the reproductive features were varied together by emergence time and population types. The number of seed heads, spikelets, seed head biomass and reproductive biomass allocation pattern and seed production was different between populations and generally increased at mid-summer emerged cohort. Seed production was 10% and 70% higher at mid-summer (9,942 seeds/plant) cohort than late spring (8,000 seeds/plant) and early spring (3,240 seeds/plant) cohorts respectively.

Controlling seedlings prior to reproduction particularly in late-spring to mid-summer emerged cohorts will alleviate the negative effect not only in the present year but also in future. Because of the highest seed production of feathertop Rhodes grass that emerged during these times in southern NSW. The fitness of four population has varied, but roadside populations appear better adapted than cropping populations. So, controlling bare ground infestation of feathertop Rhodes grass is also critical to reduce the new infestation from fence-lines to cropping

Feathertop Rhodes grass seeds are generally available on the soil surface but may also be buried at varying depths under field conditions as a result of management operations. A seed burial study under glasshouse condition showed that seeds of this species can germinate from 0 – 2 cm depth. This seedbank can contribute significantly to the assembly of weed communities in cropping paddocks. Such buried seeds may affect post-dispersal seed predation and decay.

Seed germination biology study of feathertop Rhodes grass evaluated under two treatments: year of seeds collection and geographic locations. The result showed that both have significant impact of viable seed production. The first cohort produced more viable seeds than second cohort (seeds collected in 2021 from same location). Germination and viability also significantly different between populations. This indicates that Rhodes grass biotypes' characteristics vary widely between habits and environmental conditions or combination of both.

A new publication for the Best Management Practice for control of feathertop Rhodes grass has been printed and is available through GRDC. The update includes research data from new residua herbicides and the inclusion of grazing as a control tactic in southern NSW.

Milestone 3.3.6 – Phenology and germination studies on cowvine

A phenology study of one population of Cow vine interaction with 2 sowing times (13 Nov and 22 Jan) was conducted under natural condition. The results showed that there was no significant difference between two sowing times in terms of date of seedling emergence, flowering date, seed maturity start date. However, number of branches and berry (seed pods) was significantly higher in late emergence plants (22 Jan).

A scientific publication was accepted on the germination ecology and growth phenology of cowvine in *Weed Science*.

Key Objectives:

- **To determine how growers can better utilise residual herbicides in both dryland and irrigated farming systems by:**
    - Exploring issues with residual herbicides used in cotton, wheat, chickpeas and fallows,
    - Exploring selected residual options in commercial irrigated northern and southern valleys and dryland fields,
    - Exploring potential issues with residual use from camera sprayers (high rates) and band-spraying behind header tracks where weed seeds are concentrated.
- **To determine what non-chemical strategies can be adopted to reduce the reliance on herbicides in cotton and grains systems by:**
    - Evaluating non-chemical weed control options developed in the grains industry. Evaluating the potential introduction into the non-cropping phase of cotton.
- **To determine the emerging and new weeds and resistance threats to the cotton industry by:**
    - Undertaking targeted resistance surveys of weeds in the cotton farming system in collaboration with the GRDC surveys,
    - Screen weed seeds for resistance to glyphosate, glufosinate, paraquat and group A chemistry,
    - Undertake phenology studies on emerging weeds, identify potential weakness to target control.
- **To assist to achieve BMP for weeds in the dryland system by:**
    - Supporting dryland farming experiment at PBI with advice and monitoring support for the Dryland Cotton Research Group,
    - Supporting other dryland farming experiments with advice and monitoring support.
- **To determine what are the weed implications of cover cropping by:**
    - Supporting CCA cover cropping experiments with advice and monitoring support.
- **To input to the industry through the herbicide tech panel sub-committee of TIMS, grower meetings, field days, meetings and conferences by:**
    - Providing ongoing technical support to industry,
    - Updating the HRMS to include data on dicamba and glufosinate

Background to research

The Australian cotton industry is considered a global leader in sustainable agriculture. However, herbicide resistance and problem weeds threaten the productivity and profitability of the cotton industry and the farming system. Over time, the industry is increasingly moving back to relying on residual herbicides to manage herbicide resistant weeds in cotton, in rotation crops and in fallows, with glyphosate now ineffective for controlling some grass and broadleaf weeds, and resistance to the grass herbicides (Group 1) and paraquat also becoming increasingly common.

With the increasing use of residual herbicides, comes the problem of crop safety to the following crop, an even more difficult issue in dryland cropping, where rotations are often determined by planting opportunities, but selection of a residual herbicide applied in the fallow may restrict these options. The issues are further complicated by the increasing range of herbicides available for fallow use, with multiple herbicides potentially applied and multiple applications within a fallow period common. On top of this, camera sprayers are becoming standard in the industry and it is common to apply higher than normal rates through these rigs. There is a big need to explore the potential for these herbicides and herbicide combinations and rates to damage following cotton and other rotation crops.

Previous research has included surveillance of the herbicide resistance status of some of the more problematic weeds in the cotton system. It is important that this work is continued to inform industry of developing issues and thus enable the industry to be proactive in its management of herbicide resistance. In addition, targeted research will again be undertaken on some of the emerging problem weeds to provide background information to assist weed managers in developing control strategies for these weeds.

Summary of research

The primary research focus of this project was on the impact of residual herbicides applied to rotation crops and in fallows on the following cotton crops. Research was carried out over a series of seasons (replicated in time), on replicated, randomised field experiments, some with split-plot designs, in fields grown under typical commercial conditions. Components were tested at Warwick (Southern Qld), Narrabri (Northern NSW) and Leeton (Southern NSW). The experiments were on solid plant, irrigated cotton, picked with modified commercial pickers, and ginned to determine lint yield. Excessively wet conditions delaying herbicide applications and flooding in spring 2022 were challenging for some experiments.

These field experiments addressed the project's objectives, producing results directly relevant to the industry. However, the limitation of this work was that it could not test every potential herbicide, herbicide combination and application scenario. The largest of the experiments (at Narrabri) examined eight in-crop herbicides in two rotation crops (wheat and chickpea) and 9 fallow herbicide combinations, a total of 80 treatments, with four replications. While the findings from the results from this work are extremely valuable to industry, a common scenario in the cotton system would be two in-crop herbicides and two or more fallow herbicides, increasing the potential herbicide combinations four-fold or more (as other herbicides could have been included).

Future research should focus on the impacts of some of the more common multiple-herbicide strategies. The current work, for example, showed that the standard cotton herbicides are not causing issues for the following rotation crops. However, only single herbicides were considered, applied at cotton planting. The potential impact of multiple herbicides, some applied pre-crop and others in-crop is yet to be examined, but is likely to be damaging to rotation crops.

Further work is also needed to correlate herbicide soil and plant concentrations to crop damage as we note that with more residual damage occurring in the industry and increasing concern around damage from residual herbicides, there is currently no information that can relate herbicide concentrations in soils or plants to damage. Where a grower sees damaged plants, it is becoming increasingly common to test for herbicide residues. When a herbicide is detected from a laboratory sample, it is assumed that the detected herbicide has caused the damage. However, this may not be the case, and conversely, when no herbicide is detected, this does not necessarily indicate that a given herbicide is not causing the damage. We simply have no data to relate laboratory test results to plant damage and this needs to be addressed.

Outputs from this work

This research has generated a bulk of experimental results that will be published in information sheets, articles and scientific papers, and delivered to industry through the CottonInfo network.

The research has generated data on: 1) crop growth reductions and lint yield reductions from residual herbicides used in rotation crops, fallows, and through camera, 2) herbicide tolerance and resistance for a range of grass and broadleaf weeds in the cotton system, and 3) phenology and herbicide tolerance studies on six emerging weeds.

Already from this project there have been a series of scientific publications, articles, conference presentations, and many presentations at grower meetings. Most of these have been documented below, although numerous lesser presentations were made. More presentations and articles will follow.

Implications of this work

This project had three main focuses: 1) exploring the impacts of residual herbicides, 2) screening for emerging herbicide resistance threats, and 3) exploring the potential of emerging weeds. Each area has implications for the industry.

Our research has highlighted: 1) that a) residual herbicides used in rotation crops, fallows, and through camera sprayers have the potential to seriously impact following cotton crops, reducing seedling vigour and lint yield, and b) combinations of herbicides can be more damaging than expected, such that label crop-safety information may underestimate the damage from combinations.

Herbicide screening 2) showed that samples of awnless barnyard grass, feathertop Rhodes and windmill grass had some level of resistance to glyphosate, the Group 1 grass herbicides, paraquat and glufosinate. These levels of resistance have big implications for managing weeds. The resistance to glufosinate is surprising and unexpected and will diminish the value of this relatively new mode of action herbicide to the cotton system, especially if resistance occurs amongst broadleaf weeds.

The studies on emerging weeds 3) highlighted the challenges of managing some of these weeds, especially as they develop herbicide resistance. Cotton growers and consultants need to be aware of these issues with these weeds and develop management strategies for fields where they become problematic.

Recommendations around these issues are included in the report.

Publications

Charles GW, Sindel BM, Cowie AL, Knox OGG (2019) The value of using mimic weeds in competition experiments in irrigated cotton. Weed Technol 33: 601-609

Charles GW, Sindel BM, Cowie AL, Knox OGG (2019) Determining the critical period for weed control in high yielding cotton using common sunflower as a mimic weed. Weed Technol 33: 800-807

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Koetz E Windmill grass

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Koetz E Annual ryegrass; update in WEEDpak

Koetz E (2023) Reducing herbicide drift; NSW DPI Fact sheet

Major Publications

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Charles G, Werth J, Koetz E (2019) Weed issues in cotton cropping systems. Northern Gains Weeds update. Gatton, 9-10 Sep 2019

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