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Part 1 - Summary Details

Please use your TAB key to complete Parts 1 & 2.

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Part 3 – Final Report

Objective 1 – Develop specific IWM strategies for identified at risk (species shift and glyphosate-resistant) weeds in transgenic farming landscapes

Background

The term "Integrated Weed Management" can be described as an overarching goal of weed management. The aim of this objective was to develop specific strategies for key weeds that are applicable to the tools that growers have available. The team recognises the importance of WEEDpak as a manual for weed management in cotton systems. It was therefore an important objective of the project to add specific tactics and strategies from research undertaking in the current and previous project into WEEDpak. In addition to this, it is important that research undertaken is communicated to the industry on how to manage glyphosate resistant and tolerant weeds.

Milestones

1.1 and 1.3 Updating IWM strategies for key weeds in WEEDpak

Outcomes

We have completed three chapters in the "Managing Problem Weeds" section of WEEDpak. These consist of one each for Flaxleaf fleabane, Glyphosate-resistant awnless barnyard grass, and Feathertop Rhodes grass. The information in these chapters covers the biology of the weeds and their management in crop and fallow. These should now be available on the WEEDpak website. A copy of each of these chapters is included in Appendix 1.

We have gained some additional information on using glufosinate as a double knock partner instead of paraquat for fleabane and awnless barnyard grass from experiments conducted in this project. We will continue to update WEEDpak with this information as part of new experiments we will undertake in the new project which will further investigate the application of glufosinate under field conditions.

1.2 Collaborate with extension specialist and aligned National Resistance project on economic analysis of benefits of IWM strategies

Outcomes

Progress in this milestone has been limited due to the vacating of the extension specialist position early in the project. In light of this, the project team had also attempted to collaborate with the economic component of the GRDC IWM project to work with an economist to analyse the benefits of IWM strategies. However, there has been limited progress in this area as well.

An economic analysis for the potential costs of preventing glyphosate resistance proactively compared to a reactive strategy has been compiled by David Thornby for CRDC. Analysis that had been conducted previously for the Cotton Conference was matched to simulations of glyphosate resistance development to determine likely costs for other strategies.

The analysis we conducted demonstrated, as a high level principle, that the costs and benefits of glyphosate resistance prevention are difficult to communicate effectively. It is a relatively simple matter to look at current weed control costs with and without glyphosate resistance present, and to demonstrate that having a resistant population increases real control costs somewhere in the order of $50-150 per ha, above the cost of standard weed control practices. Avoiding this extra cost is clearly desirable. We can also demonstrate, using resistance model outputs, that weed burdens can be kept low if a proactive resistance management program is instituted in a timely fashion, i.e. before resistance overruns the farm. This in turn would result in a lower-cost weed control program once resistance occurs, and cost analyses of weed control in each situation are fairly simple to calculate and compare between.

However, our attempts to define economic significance for successful long-term programs for *delaying* resistance (see below and Appendix 2) were not especially successful in convincing an audience of growers and industry representatives (i.e. the TIMS herbicide technical panel) of the economic value of such a program. Nevertheless, economic data is important and we believe it will be important to continue to search for effective ways to communicate the value of taking action early, not just for weed population sizes but for the economic payoff associated with maintaining control of resistant populations from the first season they become problematic. In this study, we presented data on the cost per year of glyphosate susceptibility, the number of years of glyphosate susceptibility, and the average seed bank density for years 20-30 of each simulation, which in most cases demonstrates the population density expected in the long term after resistance has occurred. From this data we hoped to understand and demonstrate which of the 'successful' programs (ie those with long delays in resistance) were the most cost-effective.

Importantly, we assumed that long-term delays in glyphosate resistance are desirable. Glyphosate is more effective, more affordable, and more flexible than any of the other options available. Therefore, we assume that there is substantial value in maintaining the ability to apply glyphosate for longer, since other options are less able to provide the same kind of weed control benefits in difficult situations. This 'glyphosate advantage' has not been directly quantified here as a stand-alone economic factor, however.

Results Summary

There are a few key findings from this study.

1. The 'failed' scenarios (where resistance was delayed by five years or fewer) cost between $20 and $50 per ha per year of glyphosate susceptibility. In terms of delaying glyphosate resistance, there doesn't appear to be a return from the difference between glyphosate alone ($20/ha) and other more detailed but still unsuccessful strategies.
2. To gain an extra 6-7 years of glyphosate susceptibility by adding IWM measures to summer fallows costs from $17 to $50 per year of susceptibility, depending on whether or not some fallow glyphosate applications can be forgone.
3. The most successful strategies relying on frequent survivor control cost around $50/ha/year more than glyphosate alone in dryland systems. It is difficult to quantify the benefits in irrigated systems where resistance did not develop inside 30 years, and we need to look more closely at situations where glyphosate resistance is never predicted to occur.
4. Useful delays in resistance, and excellent long-term seed bank control even after resistance evolves, can be obtained for around $40/ha/year extra with in-crop and in-fallow IWM measures including residuals and inter-row cultivations. While this is not substantially cheaper than paying $50 per ha extra once resistance occurs, is is a great deal cheaper than the higher-end estimates of the cost of resistance we've received from Australian and American growers, in the order of $150-200 per ha.

1.4 Provide technical support to extension providers and industry on IWM and other related weed matters

Outcomes

The team has been active in this milestone in a number of ways:

- Annual updates to the herbicide resistance section of the Cotton Pest Management Guide
- Contribution to the development of the Herbicide Resistance Management Strategy (HRMS)
- Presentations to researchers at the Australian Cotton Research Conference on glyphosate resistance and weed ecology.
- Presentations to weed researchers at the Australasian Weeds Conferences
- A presentation to industry at the "Cotton Collective" in August on strategies for preventing/managing glyphosate resistance.
- Active membership of the TIMS herbicide technical panel

- Presentations to CCA and TIMS on glyphosate resistance and the HRMS
- Presentations to growers at a number of grower meetings on glyphosate resistance in cotton systems
- Annual presentations to the UNE Cotton Course students on herbicide resistance and herbicide tolerant crops.
- Contributions to a TIMS discussion paper on the perceived impacts of the proposed glyphosate, glufosinate and dicamba (DGT) stack technology to the cotton industry.

For more information on communications in the project see page 58 in the Technical Report.

Objective 2 – Improve the online Risk Assessment Tool

Background

The existing version of the Online Glyphosate Resistance Toolkit (the 'RAT') was used several hundred times by industry and other users to assess both current and possible weed management strategies for their glyphosate resistance risk. It has provided guidance on risk levels openly to the whole industry, and is used by Monsanto in their training for Roundup Ready Flex technology. As such, it has been a successful tool. However, there was room for improvement in a number of areas, so we elected to make those improvements part of UQ2103.

Milestones

2.1 Update and expand Risk Assessment Tool to improve decision making and risk management for glyphosate resistance

Methods

The team generated the following list of desired major improvements for the second version of the RAT, either to improve the quality of the RAT's predictions or to improve the experience for the user.

- Data improvements:
    - Separate calculation of risk scores for grass and broadleaf weeds based on the use of selective herbicides
    - Better identification of how the tool is being used, i.e. testing real risks versus testing possible changes to a grower's weed management strategy.
    - Addition of factors suitable for analysing other regions and cropping systems around Australia
- User improvements:
    - Better methods for comparing between scenarios
    - Improved printing and record-keeping facilities

We determined, based on discussions with the designer of the first version of the RAT (Matthew Curr) and his team at DEEDI Creative Solutions, that upgrades to the existing Flash version would be feasible, and CS agreed to do the programming. Between the two teams, we generated detailed storyboards for the new version including methods for presenting the data for grass and broadleaf weeds separately, and for presenting differences between scenarios tested by the user. We fully reworked all the text in the toolkit, including in the associated 'test your resistance knowledge' quiz, and made a large number of user-experience changes at the suggestion of the designers and editor in the CS team.

As a result of Queensland's machinery-of-government changes in 2011-12, the CS team was amalgamated with similar groups from other departments and became DEEDI Digital Solutions. Upon the splitting of DEEDI into DAFF and other specialist departments, this team was reduced substantially in size and became DAFF Digital Solutions. In July 2012, the remaining team released the prototype version of RAT 2.0 to us, with the understanding that they would not be able to progress the tool from prototype to finished product.

The prototype contained the following improvements over RAT 1.0:

- Separation of grass and broadleaf weed risks including a new set of equations developed by David for the new version
- Addition of an automatically-generated (but not unproblematic) pdf results page for printing and comparing between scenarios.
- Much more detailed feedback on correct answers for the Quiz.
- User-friendliness changes throughout.

Due to the inability of the DS team to continue development, David Thornby undertook to make the necessary remaining changes to the prototype to ensure it could be published. Repairs to various parts of the prototype were carried out including errors in scoring systems, further typographical errors, text changes, and the addition of links to the resource pages in the toolkit. Following the production of a suitable finalised version in late 2012, we commenced discussions with DAFF and CRDC about hosting

RAT 2.0 and determined that the best place to hold the toolkit in the long term would be the myBMP environment. Several discussions with myBMP representatives and other interested parties were held in 2012-13, but to date the toolkit remains unpublished. We anticipate continued discussions with CRDC will lead to publication on myBMP once staff time is available to support the publication.

Outcomes

RAT 2.0 retains the user-friendly interface of the previous version, with several key improvements that allow it to provide better quality information to users. In particular, users can now see the separate risk mitigation associated with grass and broadleaf selective herbicides more easily, can compare between scenarios including current and prospective weed management regimes, and can store results for later use with simple print-outs.

The final objective of the review of the RAT, to incorporate non-cotton, non-northern region crops, weeds, and weed control methods was discussed with the participants of the GRDC's national herbicide resistance project, of which David Thornby was also a team member. While initial discussions with representatives from southern and western farming regions were positive, that team's efforts towards a risk assessment tool eventually went into the publication of the WeedSmart risk assessment app. David did produce a version of the RAT for that project, on the Python programming platform, called pyRAT. That tool does not have a user interface and requires the user to edit lists in plain text documents – it was designed for David to assess weed management case histories, rather than as a self-assessment tool. However, pyRAT is able to assess histories of any length, and can be changed much more rapidly than the Glyphosate Resistance Toolkit. It is possible that future RATs would be less like RAT 2.0 and more like pyRAT, for the sake of flexibility.

2.2 Analyse response data from new Risk Assessment Tool to determine changes in industry risk levels and practices

As RAT 2.0 was not published prior to the end of the project, there was no data available from it to assess for changes in the industry's risk levels or weed control practices. We expect to complete these analyses as soon as data becomes available once RAT 2.0 is published on the myBMP website.

For more information on updating the risk assessment tool, see pages 6-13 of the Technical Report

Objective 3 – Understand the ecology of problem species and why they are surviving current practices in crop and fallow

Background

The ability of weeds to survive in crop and fallow is often related to their ecology. Triggers for emergence such as rainfall and temperature result a number of species being able to emerge throughout the season in multiple cohorts. This often makes them hard to control as emergence events can be outside easier timeframes for control such as mid-late season. This objective endeavours to investigate what the ecological triggers are for emergence of key problematic weeds in cotton systems.

3.1 Conduct a desktop study to identify gaps in knowledge on ecology of key weeds

Outcomes

A desktop study was conducted to determine the gaps in ecology knowledge for key weeds. This information has been entered into a spreadsheet (Appendix 1 in Technical Report) that was used to highlight where the current gaps are. In August 2011, the project team, including Graham Charles, met to determine and prioritise the research to fill the gaps in current knowledge. It was decided to conduct a detailed pot experiment that investigated the effect and interaction of temperature and rainfall on the emergence of key species.

The experiment was then broken up into three phases. Phase I - a detailed experiment investigating the effect of single rainfall events on emergence of fleabane, awnless barnyard grass, sowthistle and feathertop Rhodes grass. Phase II - a similar experiment investigating the effect of accumulated rainfall on emergence of the same species. Phase III – and experiment investigating the effects of single rainfall events on 16 key weed species of cotton farming systems.

3.2 Undertake experiments on the ecology of problem weeds of cotton systems

Methods

All experiments were conducted in a growth room so that temperature and day length could be controlled. Two temperature regimes were used, 25/15^{O}C day/night (25/15) and 30/20^{O}C day/night (30/20) for both experiments with a photoperiod of 12h day/night. These temperature ranges were chosen to mimic the start of the cotton growing season (late spring) and the middle of the season (summer). Temperatures in the field in mid-summer do often get above 35^{O}C, however these temperatures were avoided in the growth room due to the likelihood that the soil surface would dry out too quickly and the ability of the growth room to sustain this temperature without overheating.

Seeds of the all species were collected at least one year prior to conducting the experiment in an attempt to allow for dormancy mechanisms to break down. Seeds were then counted into lots of 100 (50 in Phase III) seeds to be placed in their respective pots.

Seeds of each species were placed on the surface of their respective pots. Larger seeded species in Phase III were mixed into the top 2 cm of soil. Rainfall treatments were applied using a spray cabinet fitted with a nozzle suited for delivering rainfall at approximately 0.5-1 mm each pass evenly across the pot. A rain gauge was also placed in the cabinet to measure the desired amounts of rainfall. In each experiment there were seven rainfall treatments as follows:

Phase I: 0 mm, 2 mm, 5 mm, 10 mm, 20 mm 30 mm and 50 mm.

Phase II: 0 mm, 5 mm x 2 consecutive days, 5 mm x 4 days, 5 mm x 6 days, 10 mm x 1 day, 10 mm x 2 days and 10 mm x 3 days.

Phase III: 0 mm, 5 mm, 10 mm, 20 mm and 30 mm.

Once rainfall treatments were completed (and for each day in Phase II) pots were placed back into the growth room. Emergence counts were conducted each day, and seedlings were removed daily after being counted. Emergence counts continued until there were at least three days without any new emergences.

Results

Phase I

The rainfall amount applied was significant in this experiment ($p < 0.001$). In general, all species responded significantly less to 10 mm than to 20, 30 and 50 mm which were statistically similar (Figure 2). The effect of temperature was noticeable but not significant ($p = 0.067$). Therefore emergence data for each species and rainfall were pooled. In general, all species tended to have higher emergences at 30/20 than 25/15 with the exception of Sowthistle at the 50 mm rainfall amount.

Awnless barnyard grass emergences started at 3 days after rainfall treatment (DAT) at 30/20 and 4 DAT at 25/15. The highest emergences occurred at the 30/20 regime at rainfall levels of 20 and 30 mm with 31 and 34 percent emergences respectively. For this species, emergences were higher when rainfall amounts were above 20 mm.

Emergence times for fleabane were similar to Awnless barnyard grass starting at 3 DAT at 30/20 and 4 DAT at 25/15. Despite generally favouring milder temperatures for emergence, in this experiment fleabane responded poorly to the lower temperature regime of 25/15 with the highest emergence at that temperature being 9 percent with 20 mm rainfall. The highest emergences occurred at 30/20 with rainfall levels of 20 and 30 mm with 10 and 12 percent respectively.

Feathertop Rhodes grass germinated earlier than the other species with emergences starting at 2 DAT at 30/20 and 3 DAT at 25/15. It also consistently had the highest emergence of all the species, with the 53 percent emerging at 30/20 under 20 mm rainfall followed closely by 46 percent emergence at 30 mm.

Emergences of Sowthistle started at 3 DAT at both temperature regimes. At rainfall levels of 10-30 mm it responded better to the lower temperature regime with the highest emergence occurring at 25/15 under 50 mm rainfall with 25 percent emerging.

Phase II

All species responded better to small amounts of rainfall over consecutive days, than the single rainfall events applied in Phase I. Rainfall applications were again significant ($p < 0.001$) with treatments of 0, 5mm x 2 days and 10mm x 1 day being removed from analysis due negligible numbers emerging. The effect of temperature was not significant ($p = 0.429$), so emergence data for each species and rainfall are pooled.

Emergences for Awnless barnyard grass started at 3 DAT at 30/20 and 4 DAT at 25/15. The highest emergence of 66 percent occurred at 25/15 with 5 mm rainfall for six consecutive days. This was followed closely by 63 percent at 30/20 for three consecutive days. Rainfall totals were comparable between 5 mm over 2 or 6 days and 10 mm over 1 or 3 days respectively. However, at the 20 mm rainfall level, emergences were higher for 5 mm x 4 days than 20 mm x 2 days at both temperature regimes.

Fleabane responded consistently better in this phase than the previous one. Initial emergences for fleabane, in the same manner as Phase I started at 3 DAT at 30/20 and 4 DAT at 25/15. Highest emergences of 34 percent were achieved at 10 mm x 3 days for both temperature regimes. Rainfall totals were comparable between 5 mm over 2,4 or 6 days and 10 mm over 1, 2 or 3 days respectively.

Feathertop Rhodes grass emergences were similar to Phase I. The highest emergence of 76 percent occurred at 25/15 with 5 mm rainfall for six consecutive days. This was followed closely by 75 percent at 30/20 for three consecutive days. Rainfall totals were comparable between 5 mm over 2,4 or 6 days and 10 mm over 1, 2 or 3 days respectively. This species consistently had the highest and fastest emergences of the species tested across both experiments.

Emergences of Sowthistle started one day later than Phase I, beginning at 4 DAT at both temperature regimes. Emergence tended to be higher in the cooler temperature regime at all rainfall levels. This effect was only observed in the 50 mm rainfall treatment in Experiment 1. The highest emergence was 39 percent with 5 mm rainfall for six consecutive days, followed by 30 percent with 10 mm rainfall for three days. Like Awnless barnyard grass at the 20 mm rainfall level, emergences were higher for 5 mm x 4 days than 20 mm x 2 days at both temperature regimes.

Phase III

As expected, the smaller seeded species, such as the grasses and Asteraceae, generally responded better to the single rainfall events. The majority of species responded better to rainfall amounts greater than 10mm. Fleabane and Sowthistle responded better to the lower temperature regime of 25/15. Windmill grass responded more favourably to the lower temperature regime with the exception of the highest rainfall amount which allowed the soil surface to stay moist for longer.

The hard-seeded species, such as Peachvine, Bellvine, Sesbania, Rhyncosia and Bladder ketmia generally had low emergences throughout the experiment. This was most likely due to high dormancy levels. No dormancy breaking measures were undertaken, apart from collecting the seed one year earlier and storing at room temperature.

Emergences of Datura tended to be independent of rainfall. This result was unexpected however may be accounted for due to the planting method. For the hard seeded species, seeds were mixed into the top 2 cm of soil rather than them being placed on the surface. Therefore the starting soil moisture level of 70% of field capacity may have been enough for the Datura seeds to imbibe and subsequently germinate. This effect is likely to have affected the other larger hard seeded species; however their germination rates were lower as previously stated.

Outcomes

This study has shown that rainfall rather than temperature is the key driver for emergence of these species during the crop growing season. It has also provided the first step in determining when emergences are likely to occur in the field. Over the three phases of the experiment, numbers of plants emerged were recorded daily. Feathertop Rhodes grass, Windmill grass and Red pigweed germinated as soon as two days after the rainfall treatments were applied.

This research has shown the ability of small seeded species to recruit quickly after rainfall, in particular the feathertop Rhodes grass, Windmill grass, Awnless barnyard grass, Red pigweed, Fleabane and Sowthistle. This quick germination contributes to their success in no-till post-emergent based farming systems. Future research will endeavour to combine this information with timing to key points in plant development such as stem elongation/tillering and flowering.

A detailed report into the experiment in located in pages 14-23 of the Technical Report.

Objective 4 - Develop improved control tactics for glyphosate tolerant and resistant species in fallow and cotton

Background

The key strategy for weed and resistance management is to drive down the weed seed bank. The lower the weed seed bank, the lower the number of weeds emerging reduces pressure on herbicides and thus decreases the chance of resistance development. The key strategy of the CMP for Roundup Ready Flex cotton is to prevent survivors of glyphosate application from setting seed. Survivors may have survived glyphosate application because they are resistant, and allowing them to set seed will perpetuate the issue. We undertook two key experiments relating to this issue. 1. What are the options to control glyphosate survivors, and does previous glyphosate exposure hamper control tactics, and 2. Can the viability of seeds that have past optimal spraying time be reduced so that number of viable seed entering the seed bank be reduced.

4.1 Conduct experiments on new tactics for control of glyphosate sprayed survivors in fallow and cotton

Methods

This experiment was conducted on Awnless barnyard grass and Fleabane. Both these species have confirmed glyphosate resistant populations in cotton growing regions, and are species that are presenting growers with problems on their management in crop and fallow.

Awnless barnyard grass (QBG4.1) used in the experiment was 1st generation seed from a confirmed glyphosate resistant population on the Darling Downs. This population has been characterised and has a 3-4 fold resistance to glyphosate. The fleabane seed was also 1st generation seed that was collected from a field where the population had survived glyphosate applications. Although this population has not been characterised, it is likely to be glyphosate resistant.

Awnless barnyard grass

Experiments commenced in November of 2012 and 2013. Pots were filled with potting mix and seed was applied to the surface. After emergence plants were thinned to four per pot. Treatments applied to plants are listed in Table 1. When plants had reached two tillers, half of the pots were pre-treated with a sub-lethal dose of glyphosate (350 ml/ha of Roundup Powermax) in order to simulate sub-optimal control in the field, but not to kill the plants. Plants were then left for three weeks and then sprayed with the follow-up herbicides (Herbicide 1). At this stage, plants had reached mid-late tillering. Double knock applications of paraquat or Basta (Herbicide 2) were applied seven days after the initial herbicides. Plants were sprayed in a spray cabinet using TT110015 nozzles at 200 kpa. Glyphosate applications were applied with 75 l/ha of water, and all other herbicides were applied with 118 l/ha.

Fleabane

Experiments commenced in August/September of 2012 and 2013 and setup in the same manner as for awnless barnyard grass. Initial glyphosate pre-treatments were conducted when plant had reached 6-8 leaf. Follow-up herbicides were also applied three weeks later. At this stage the majority of plants had reached stem elongation. Herbicides were applied in the same manor that was used for barnyard grass. Treatments applied to plants are listed in Table 2.

Results

Awnless barnyard grass

Pre-treatment with glyphosate did not adversely affect control of awnless barnyard grass, with the exception of Verdict alone in both years and Sequence in 2012 (Table 1). However these slight decreases in efficacy were variable and could not be considered significant. Prometryn alone was least successful in both years with virtually no control on non-pre-treated plants in 2013. All double knock tactics, including paraquat or Basta (glufosinate) were very successful with no survivors occurring in either year, whether they were pre-treated with glyphosate or not.

Table 1. Effectiveness of control options of awnless barnyard grass plants pre-treated with a sub-lethal dose (350 ml/ha Roundup Powermax) of glyphosate compared to plants not pre-treated with glyphosate. Results (means ± s.e.) are percent of untreated controls.

Herbicide 1	**Herbicide 2**	**2012**		**2013**	
		Nil	**Pre - glyphosate**	**Nil**	**Pre - glyphosate**
Nil		100.0 ± 0.0	73.1 ± 15.9	100.0 ± 0.0	131.0 ± 50.1
Alliance 3 L/ha		0.0	0.0	0.0	0.0
Paraquat 2 L/ha		0.0	0.0	0.0	0.0
Paraquat 2 L/ha	Paraquat 2 L/ha	0.0	0.0	0.0	0.0
Prometryn 2.5 L/ha		14.9 ± 2.9	23.8 ± 6.3	96.1 ± 54.4	57.4 ± 25.4
Prometryn 2.5 L/ha	Basta 3.5 L/ha	-	-	0.0	0.0
Prometryn 2.5 L/ha	Paraquat 2 L/ha	0.0	0.0	0.0	0.0
Sequence 375 mL/ha		0.8 ± 0.6	0.5 ± 0.3	3.0 ± 3.0	4.7 ± 2.7
Sequence 375 mL/ha	Paraquat 2 L/ha	0.0	0.0	0.0	0.0
Verdict 150 mL/ha		3.1 ± 0.9	3.9 ± 1.6	8.2 ± 8.2	18.1 ± 18.1
Verdict 150 mL/ha	Basta 3.5 L/ha	0.0	0.0	0.0	0.0
Verdict 150 mL/ha	Paraquat 2 L/ha	0.0	0.0	0.0	0.0

Fleabane

The effect of glyphosate pre-treatment was significant when results from both experiments were combined. However, this was due to pre-treatment having a large effect in 2012 (Table 2). This can be seen by comparing the treatment that only received pre-treatment with glyphosate (Nil) in 2012 having a 90% reduction in biomass, as well as pre-treatment being significant for most of the other follow-up treatments. The effect of pre-treatment was reduced in 2013 with no reduction in the Nil treatment.

Pre-treatment significantly improved control in both years for Sprayseed followed by either Basta or Srayseed and Amicide alone. Double knock treatments of Amicide or Starane Advanced followed by Basta or Sprayseed had very good levels of fleabane control in both years.

Table 2. Effectiveness of control options of fleabane plants pre-treated with a sub-lethal dose (350 ml/ha Roundup Powermax) of glyphosate compared to plants not pre-treated with glyphosate. Results are percent of untreated control means back transformed from √(x+0.5). Means with same subscript are not significantly different at the P = 0.050 level.

Herbicide 1	**Herbicide 2**	**2012**		**2013**	
		Nil	**Pre - glyphosate**	**Nil**	**Pre - glyphosate**
Nil		100.0 i	10.2 bcd	100.0 i	102.1 i
Basta 3.75 L/ha		10.1 bcd	0.0 a	38.9 fgk	29.1 jkl
Basta 3.75 L/ha	Basta 3.75 L/ha	4.0 ac	0.0 a	33.9 gjl	30.2 jkl
Basta 3.75 L/ha	Sprayseed 2 L/ha	4.9 bch	0.0 a	36.4 fgk	30.3 jkl
Sprayseed 2 L/ha		13.0 bd	0.0 a	47.2 efl	54.2 ef
Sprayseed 2 L/ha	Basta 3.75 L/ha	7.1 bc	0.0 a	66.9 em	27.3 jk
Sprayseed 2 L/ha	Sprayseed 2 L/ha	11.1 bcd	0.0 a	13.7 bd	3.3 ac
Starane Advanced 750 ml/ha		19.2 dj	0.0 a	49.4 efg	43.9 fgk
Starane Advanced 750 ml/ha	Basta 3.75 L/ha	0.0*	0.0*	4.6*	1.1*
Starane Advanced 750 ml/ha	Sprayseed 2 L/ha	0.0*	0.0*	5.1*	3.4*
Amicide700 1.35 L/ha		51.9 efg	0.1 a	90.5 im	49.8 efg
Amicide700 1.35 L/ha	Basta 3.75 L/ha	0.0*	0.0*	3.5*	1.1*
Amicide700 1.35 L/ha	Sprayseed 2 L/ha	0.3 ah	0.0 a	6.5 bc	7.2 bc

* Not included in analysis

Outcomes

These experiments have shown that plants that have survived application with glyphosate are still able to be controlled. However, like in the experiments, the plants will be older making them harder to control. Results have shown that best methods to deal with these survivors is to use the double knock, as applications of single herbicides at maximum rates were generally not enough to control these plants, with the exception of paraquat and Alliance (amitrole + paraquat) on awnless barnyard grass.

Basta (glufosinate) has proven to be a successful double knock partner in these glasshouse experiments. Future trials will aim to explore this in the field, as there are potential benefits in glufosinate tolerant cotton and glyphosate/glufosinate stacks in coming years. This also reduces reliance on paraquat as the only choice of double knock partner which has benefits for both herbicide resistance and human safety.

A detailed report into the experiment in located in pages 24-28 of the technical report.

4.2 Investigate feasibility of options to sterilize seeds of key weeds and then undertake experiments

Methods

Two pot experiments were established for each of the three species during the 2012/2013 and 2013/2014 growing seasons at the Leslie Research Facility in Toowoomba, Queensland. The fleabane experiments were established in a glasshouse in July of each year while the grass experiments were established in a shade house in December (2012/2013) and November (2013/2014).

Six herbicide treatments were applied and as the plants had been grown in optimum conditions the application rates were at ¾ full label rates in an attempt not to kill the plants (Table 1). Flaxleaf fleabane plants were sprayed at two growth stages (budding and flowering) while the grasses were sprayed at two growth stages (late tillering/booting and flowering). Herbicides were applied to the plants at their respective growth stages in a spray cabinet using a DG95015EVS even flat fan nozzle at 2 bar delivering 147 l/ha.

Table 1. The herbicides and rates used in applying treatments to fleabane, barnyard grass and feathertop Rhodes grass.

Herbicide	Rate
Nil	
2,4-D	750 ml/ha
Glufosinate	2.8 l/ha
Paraquat	1.2 l/ha
Glyphosate	1.2 l/ha
2,4-D+picloram	700 ml/ha
Haloxyfop (grasses only)	100ml/ha

Plants from each species had distinct regrowth phases after herbicide application. . For Fleabane, the phases were referred to as existing heads, regrowth one (R1) (inflorescences produced on lateral branches off the main stem) and regrowth two (R2) (inflorescences produced on secondary lateral stems branching off R1). In the grasses the growth phases were referred to as existing heads and new heads. Up to five heads were collected from each growth phase per plant for each of the treatments. Heads from the different phases were not combined but collected separately.

Seed production was calculated for each growth phase for the three species. For flaxleaf fleabane, the seeds from one replicate of each growth phase were counted and 100 of the seeds were weighed. The remaining seed collections were weighed and the number of seeds calculated by multiplying the total weight by the weight of the 100 seeds for the relevant treatment. Seed production was then estimated by multiplying the average of these values by the number of buds produced in each growth phase. For the grasses seed production was estimated by multiplying the average number of seeds (actual counts) by the total number of heads per plant

Seed viability for each treatment was determined by conducting germination tests on seeds from each growth phase. Flaxleaf fleabane seeds do not possess innate dormancy so were tested on completion of seed collection. As the seeds of awnless barnyard grass and feathertop Rhodes grass have short periods of dormancy following harvest, germination tests were not conducted until 12 months after seed collection. Results in this report for Awnless barnyard grass and feathertop are only shown from the first experiment as we are conducting tests to determine if dormancy in the seeds from the second experiment has broken down.

Results

Fleabane

The viability of plants sprayed at flowering was totally reduced in to treatments except glyphosate (51%) and 2,4-D+pilcoram (8%) (Figure 1). Seed viability in the first regrowth (R1) was not reduced except for the 2,4-D (41%), glyphosate (13%) and 2,4-D+pilcoram (1%) treatments. In the second regrowth (R2) only 2,4-D+picloram reduced seed viability to 20%. There were no significant differences between both years for plants sprayed at flowering, so data was pooled for both years.

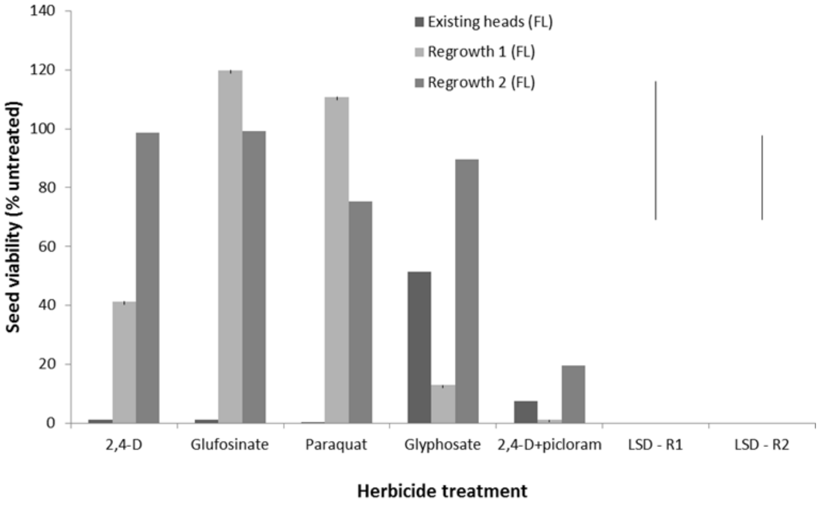

Figure 1. Average viability of flaxleaf fleabane seeds (% untreated control) for each growth phase (existing, R1, R2) from plants sprayed at flowering (FL) in two trials (LSDs for the R1 and R2 are shown in the last two columns)

There were significant differences between seed viability and treatments when fleabane was sprayed at budding in years one and two (Figure 2). In both trials only 2,4-D+picloram consistently reduced seed viability. While 2,4-D and glyphosate reduced viability in R1 in year one (28% and 0% respectively), this was not duplicated in year two with both treatments having seed viability above 80%. Seed viability in R2 decreased in all treatments from year one (93% to 100%) to year two (58% to 75%) with the exception of 2,4-D+picloram.

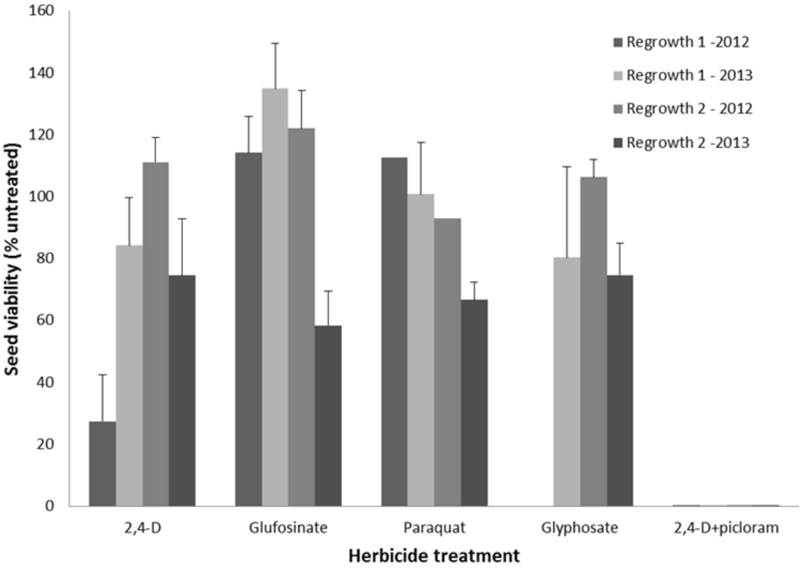

Figure 2. Average viability of flaxleaf fleabane seeds (% untreated control) from plants sprayed at budding. Data presented includes the viability of seed in two distinct regrowth phases.

Feathertop Rhodes and awnless barnyard grass

Spraying feathertop Rhodes grass at late tillering/booting reduced seed viability to a low of approximately 71% in the paraquat and haloxyfop treatments (Figure 3). When sprayed at flowering, the seed viability of seed from existing heads was 0% for glufosinate increasing to 0.7% in the new heads. The viability of seed on existing heads also decreased for 2,4-D (16%) and paraquat (35%). Seed viability for the seed on new heads in these two treatments increased (72% and 93% respectively) compared to a decrease in viability for the remaining treatments.

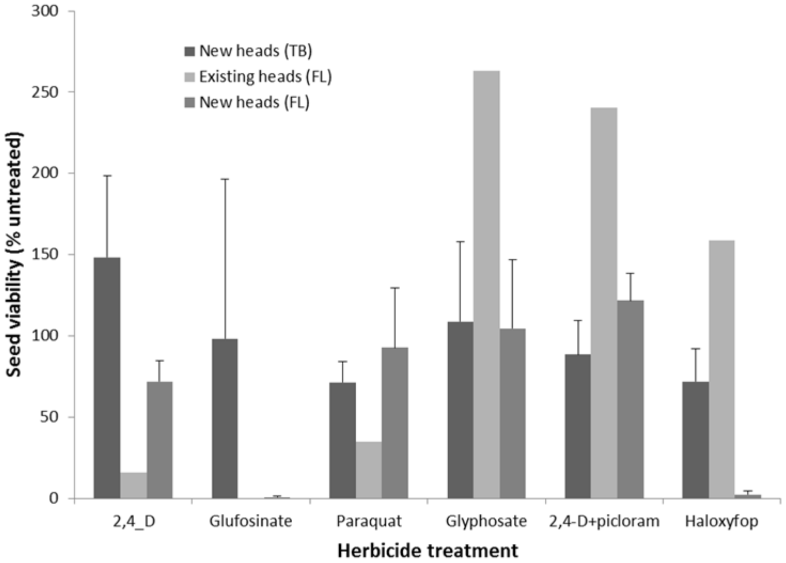

Figure 3. Average viability of feathertop Rhodes grass seeds (% untreated control) from plants sprayed at late tillering/booting (TB) and flowering (FL).

Spraying at late tillering/booting did not reduce viability in awnless barnyard grass seeds to under 60% except for glufosinate (50%). When sprayed at flowering, the viability of seeds in existing heads was reduced to 0% for glufosinate, paraquat and glyphosate, and 0.8% for haloxyfop. For new heads that emerged after spraying seed viability ranged from 25% (glufosinate) to 85% (paraquat). With the exception of 2,4-D+picloram the viability of seeds in the new heads increased compared to the viability of seeds in the old heads.

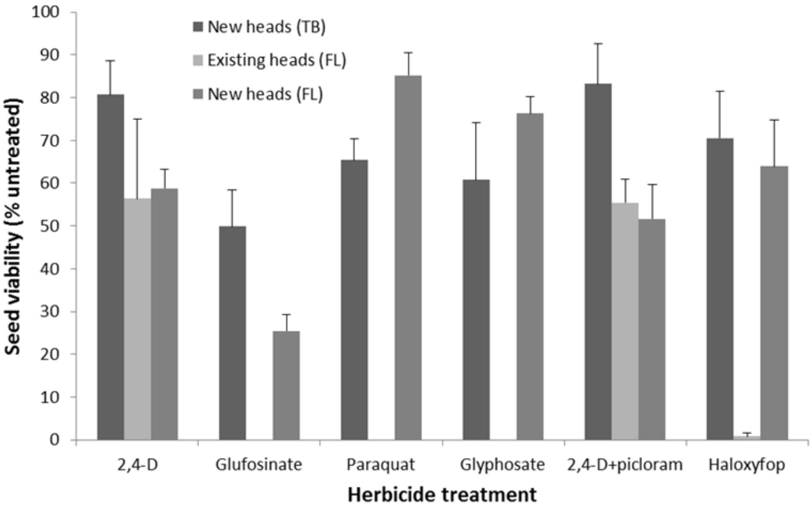

Figure 4. Average viability of awnless barnyard grass seeds (% untreated control) from plants sprayed at late tillering/booting (TB) and flowering (FL).

Applying herbicides at flowering was more successful than at late tillering/booting. Seed viability was reduced to zero in existing heads of awnless barnyard grass for glufosinate, paraquat and glyphosate treatments and zero in feathertop Rhodes grass for glufosinate treatments. These chemicals were less effective, only slightly reducing viability for awnless barnyard grass heads that emerged and flowered after herbicide application. For new heads on feathertop Rhodes grass, viability was reduced for glufosinate and haloxyfop.

The auxinic herbicides (2,4-D and 2,4-D+picloram) had little effect on seed viability at both growth stages on awnless barnyard grass and feathertop Rhodes grass, this was contrary to previous studies on Japanese brome. However 2,4-D+picloram decreased seed viability in flaxleaf fleabane as well as retarding and reducing the production of new heads.

Outcomes

Preliminary experiments have shown that seed viability of flaxleaf fleabane, feathertop Rhodes grass and awnless barnyard grass can be reduced with a range of herbicides. Glufosinate showed the greatest potential in this experiment for the grasses and 2,4-D+picloram provided the best reduction for flaxleaf fleabane seed viability.

Further testing in the field will determine if reducing seed viability using herbicides is a viable tactic for growers. However, species such as flaxleaf fleabane and feathertop Rhodes grass have the capacity to regrow and produce viable seeds. In such situations, plants will need to be monitored and controlled before regrowth occurs.

A detailed report into the experiment in located in pages 29-38 of the Technical Report.

4.3 Investigate the feasibility of adapting weed detector technology for weed control between rows in dryland cotton

Outcomes

We completed a desktop study investigating a shielded weed detector unit that has been developed by Crop Optics, that can be used in a range of row crops including cotton. The shielded weed detector could be used in a number of ways including:

- Controlling survivors of glyphosate application with. products such as paraquat, glufosinate, 2,4-D, fluroxypyr, picloram, amitrole
- Minimising seed production on plants that have passed the optimal growth stages for spraying (i.e. salvage situations)

The study highlighted that the efficacy of the technology itself has been proven in broad-acre situations and does not change when incorporated with a shielded sprayer, and thus does not need to be tested. We have tested some possible use situations, independently of the technology, such as controlling glyphosate survivors and reducing seed viability, in Milestones 4.1 and 4.2 of this project. The use of detector spray systems could become a critical part of the economic equation of delaying and managing resistant populations, so we also expect to conduct an economic analysis of its use in the future, to compare with broad-acre use as investigated in part of Milestone 1.2.

Objective 5 – Determine the feasibility of eradicating glyphosate resistant populations

Background

Glyphosate resistant awnless barnyard grass (barnyard grass) is now widespread in grains systems, and is becoming increasingly common in non-irrigated cotton systems. Barnyard grass is a small seeded, predominately self-pollinating species with a relatively short seed bank life (up to 5-6 years), and is not dispersed by wind. In the field, resistance generally appears as small patches that spread if not correctly managed. The population dynamics of barnyard grass make it a potential candidate for eradication if suspect patches are detected and managed early.

5.1 Desktop study investigating options for eradicating patches of summer grasses and suitable modelling approaches

Outcomes

We conducted a basic review of literature in three areas: experimentation investigating patch dynamics; modelling approaches used to examine patch dynamics; and research into the feasibility and requirements for eradicating weed patches. We also reviewed a number of current models used for patch dynamics in Australian agro/ecosystems and chose a suitable approach that will link to (but not rely on) an approach used at UWA.

The review of literature provided useful information regarding how real and modelled experiments could be conducted, the types of parameters that would need to be included in a model of patch eradication, and estimated values of some of those parameters. The dynamics of weed patch expansion are driven by seed and pollen creation and dispersal, and the spatial patterns of seedling mortality. Thus, eradication is a function of the competing processes of:

- the patch expanding and becoming more dense by natural seed creation and dispersal;
- transport of seeds by 'other processes' – on machinery, in soil, and by water;
- attempts to kill the plants that emerge, and reduce emergence, within the patch area; and
- vigilant selection and destruction of seedlings that emerge outside the existing patch margin.

In the case of patches of herbicide resistance, the resistant patch usually makes up part of a larger population. The resistance gene can move from the resistant patch into the surrounding susceptible part of the population by pollen movement, creating satellite patches of resistance. This is common in outcrossing species where control of susceptibles is good, but not complete, and resistant plants are uncontrolled. In selfing species, it is expected that this process would be slower to occur. Nevertheless, where there are large resistant populations and smaller numbers of susceptibles nearby, it is still an important part of the patch dynamics. Panetta and Lawes (2005) suggested that the key criteria for eradication (or 'extirpation' as they term local extinction at a small scale) are delimitation (or knowing the extent and location of the patch or patches, and how they move and change size) and containment (the effort taken to prevent the increase in size and number of existing patches). They also note that the 'search effort' undertaken is very important, as changes in the size and number of patches can only be useful information if it is known by the land manager.

Any strategy for attempting to eradicate resistant patches, then, relies on applying tactics to prevent seed production, limit seed movement, and anticipate gene movement through pollen. Given that trying to prevent seed production with extreme vigilance is time-consuming and costly, working on eradication of patches while they are relatively small makes the likelihood of success greater and the cost and difficulty smaller. Eradication is known to become less likely and much harder as the size of the population and the area it covers increase (Panetta and Brooks), and this is likely to be the case in the relatively small-scale patches we are interested in here. Eradication attempts must be both physically and economically feasible. Research in the past has tended to concern itself with optimising one or the other factor (eg Epanchin-Niell and Hastings 2010, cf. Christensen *et al.* 2009) and assuming that the non-assessed factor is implicitly feasible and desirable.

Some authors suggested using automated systems for detecting and eradicating small patches (Christensen *et al.* 2009). These are limited in scope where there is no ability to detect the difference between susceptible and resistant biotypes, but could be an important tool in first detection of patches distributed across large areas.

In order to develop a model that would produce useful data leading to practical recommendations, it was clear from the literature that we would need to model spatial dynamics explicitly, including gene flow in pollen and seeds, and some kind of spatially explicit method for applying management tactics. There have been a number of spatially-explicit weed models developed over the last few decades. Some of them are descriptive, useful mainly for categorising actual cases of spatial heterogeneity in fields. (eg Blanco-Moreno et al. 2008). Despite having often very sophisticated methods for analysing the effects of spatially heterogeneous weed populations on crop yield, they are not designed to analyse dynamics in a mechanistic way. Other models represent large-scale invasion fronts mechanistically but schematically and non-numerically (eg de Souza et al. 2010), and are not suited to paddock-scale dynamics with fine detail applied to control methods, either due to their schematic nature or because their scale is too great (eg Renton et al. 2011). While various models offered useful mechanisms for spread and biological processes, none of them were sufficiently explicit in their treatment of weed control methods for our purposes.

We elected to build a new model to cover the spatial dynamics of weeds in similar ways to some existing models, and to provide the level of agronomic explicitness required to deliver information leading to practical recommendations.

A list of selected papers from the literature review are given in pages 41-44 of the Technical Report.

5.2 Conduct experiments investigating summer grass seed bank depletion

5.2.1 Investigating the outcrossing rate of awnless barnyard grass

The ability of a plant to cross-pollinate and transfer genes outside a resistant patch and create ‘new’ satellite patches is critical in determining if patches can be eradicated. This experiment used glyphosate resistance as a marker to determine and estimate of the outcrossing rate of awnless barnyard grass.

Methods

Two barnyard grass populations were used in this experiment: PLG3 which is strongly resistant, and QS which is susceptible. Plants of each population were planted together in a growth room. Once plants started anthesis, mating was forced by brushing plants against adjacent plant to enable pollen movement between populations. Upon maturity, seeds were collected from each plant, making note of which population the seed parent had been taken. At the same time additional isolated tubs were planted with pure stands of each population, from which seeds were collected.
Four populations were used in a dose response experiment from seed collected in the growth room: PLG3 – pure resistant, QS – pure susceptible, and QP1 and QP2 – two cross-pollinated populations with a QS susceptible parent. The dose response consisted of seven herbicide doses: 0, 200, 400, 600, 800, 1000 and 1200 g ae glyphosate/ha. Survivor counts were then conducted 21 days after glyphosate application.

Results

Percent survivors were calculated, graphed and estimates of LD_{50} for populations were determined by the point where the line on the graph crossed the 50% survivors mark. From these calculations the percent change in susceptibility to glyphosate after forced crossing ranged from 1.9% - 9.6%. It is therefore reasonable to expect that the cross-pollination rate of awnless barnyard grass is similar to this.

Outcomes

This experiment has confirmed that barnyard grass is predominately self-pollinating. In the field, practical outcrossing rates are likely to be lower, and the possibility of glyphosate resistance moving in pollen flow would be minimal. Barnyard grass is therefore a potential candidate for eradication strategies, however as some outcrossing does exist eradication attempts in the field must take into account the need to monitor new satellite patches at least within the same field.

A detailed report into the experiment in located in pages 45-40 of the Technical Report.

5.2.2 – Investigating options for eradicating patches of glyphosate-resistant summer grasses

Methods

The trial is located at Hermitage Research Facility near Warwick, Queensland. The site had an existing population of awnless barnyard grass which were allowed to set seed in the first year of the experiment in order to increase the barnyard grass seed bank.

The experiment is based on the "2+2" strategy from previous simulations and consists of nine treatments (Table 1). A glyphosate-resistant population is "assumed", therefore glyphosate applications are aimed at allowing 30-40% survivors. Each season the experiment is broken up into three phases: 1 - Early season (October – mid December). 2 - Mid season (mid December – mid February). 3 - Late season (mid February onwards).

Table 1. Overall treatments on Hermitage patch eradication site.

Treat No.	**Treatment**
1	Glyphosate only (sub-lethal)
2	BMP
3	BMP + Erad (phase 1)
4	BMP + Erad (phase 2)
5	BMP + Erad (phase 3)
6	BMP + Erad (phase 1 and 2)
7	BMP + Erad (phase 1 and 3)
8	BMP + Erad (phase 2 and 3)
9	BMP + Erad (phase 1,2 and 3)

The BMP treatments contained two additional non-glyphosate tactics as per the "2+2" strategy. The eradication treatments consisted of an additional tactic applied in the phase/s as is listed in Table 1. A detailed record of the control tactics applied in each of the treatments and their efficacy is contained on page 46 of the Technical Report.

Soil cores were taken at the start of the experiment, and after each season to determine changes to the seed bank in each treatment. The starting seed bank ranged from 49 000 to 100 000 seeds/m^2. Differences in the starting seed bank before applying treatments were significant. There subsequent analysis each treatment was taken in relation to the respective starting seed bank for that treatment. Plant counts were taken approximately one-two weeks after rainfall to measure emergences, and two-three weeks after post-emergent herbicide applications to measure survival rates.

Results

The total barnyard grass emergence throughout the season was high due to the starting seed bank (Figure 1). However, in proportion to the starting seed bank the proportion of emergence was relatively low, ranging from 1.3% in the glyphosate only treatment to significantly less in the eradication treatments (0.1-0.2%). This is a result of the pre-plant metolachlor reducing emergence at the seat of the season.

The glyphosate only treatment had the highest number of plants remaining at the end of season one (27.9 plants/m^2) compared to the next highest (9.7 plants/m^2) in the BMP + Erad (phase 1) treatment. However, when expressed as a percentage of total emergences in each treatment (Table 2), both of the BMP + Erad (phase 1 and 2) had significantly higher proportions of plants remaining than the other treatments. Reasons for this are unclear, are likely linked to a higher starting seed bank and no additional eradication tactics in phase 3.

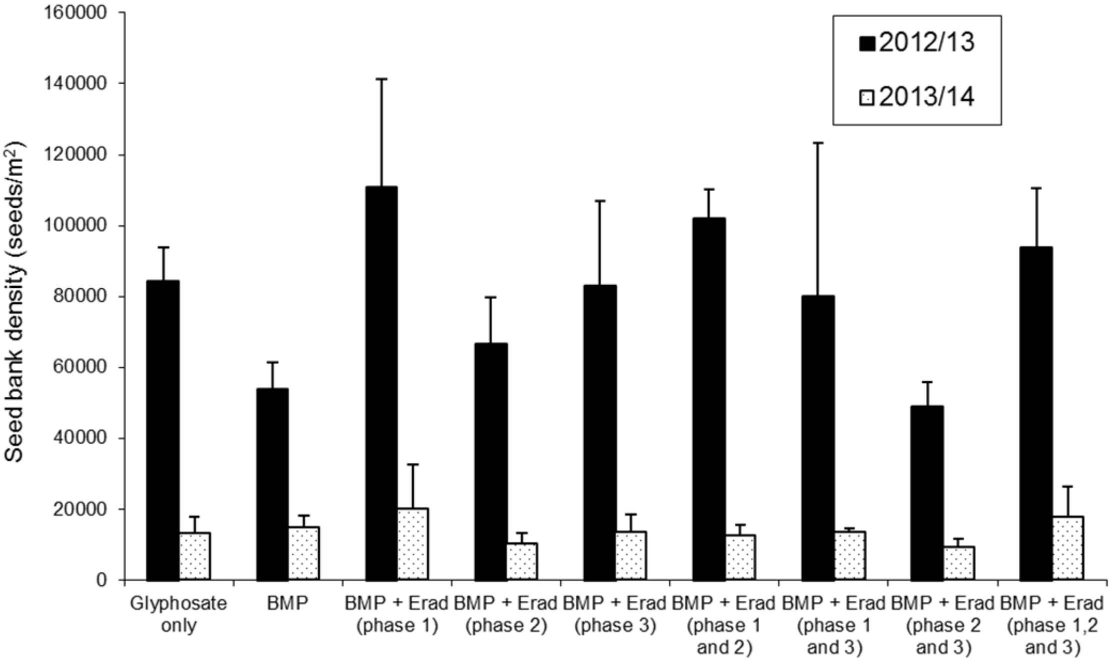

Figure 1. Seed bank density of awnless barnyard grass at start of growing season for each treatment.

Emergence throughout the second season was lower than the first. However, they were slightly higher in proportion to the starting seed bank for that year. Emergence in the glyphosate only treatment was 3% and ranged from 0.35-0.6% for the other treatments. The application of early season metolachlor again had a significant impact on reducing barnyard grass emergence. The second season consisted of a long hot dry spell which negated the need for expected control measures to be applied. As a result there appeared to be no difference between the BMP and the BMP+Eradication treatments. The slight difference in plants remaining at the end of the second season was due to a slight variability in the last double knock application.

Table 2. Awnless barnyard grass emergence and number of plants remaining with respect to each treatment in the first two years of the eradication experiment. Emergence is expressed as the percentage of the starting seed bank with respect to year and treatment. Plants remaining are expressed as the percentage of total emergence with respect to year and treatment. Means with the same subscript are not significantly different.

Treatment	Year 1 - Cotton		Year 2 - Fallow	
	Emergence (% starting seed bank	Plants remaining (% emergence)	Emergence^{A} (% starting seed bank	Plants remaining^{B} (% emergence)
Glyphosate only	1.34 a	2.34 a	2.99 b	9.26
BMP	0.38 bc	2.55 a	0.35 a	0.00
BMP + Erad (phase 1)	0.12 d	6.63 b	0.47 a	0.00
BMP + Erad (phase 2)	0.42 b	2.63 a	0.42 a	1.35
BMP + Erad (phase 3)	0.48 b	0.59 a	0.42 a	0.35
BMP + Erad (phase 1 and 2)	0.09 d	6.29 b	0.38 a	0.00
BMP + Erad (phase 1 and 3)	0.21 cd	2.21 a	0.44 a	0.30
BMP + Erad (phase 2 and 3)	0.40 bc	1.15 a	0.37 a	0.49
BMP + Erad (phase 1,2 and 3)	0.13 d	1.82 a	0.60 a	0.00
LSD (P<0.05)	0.20	2.89		
P-value	<0.001	0.003	0.003	

^{A}Back transformed means Log(x+1)

^{B}Plants remaining was not analysed due to the presence of zero values.

All treatments considerably reduced the barnyard grass seed bank after the first season. At this point there appear to be no differences in the size of the seed bank in relation to treatment. This is most likely due to the large starting point for seed bank numbers, and the impacts of each treatment are expected to be seen after a couple of seasons.

Outcomes

To this point, the BMP and BMP+Eradication treatments have reduced the level of emergence, and the numbers of plants remaining at the end of the season compared to the glyphosate only treatment. This shows the "2+2" (two non-glyphosate tactics in crop and fallow) strategy is effective at managing patches of glyphosate-resistant barnyard grass. At this stage the extra benefits of eradication measures are only marginally apparent, however these are expected to be more significant as the experiment continues.

5.3 Construct model and simulate implications of long-term use of tactics to deplete seed banks and eradicate resistant patches

Methods

In order to examine the spatial dynamics of herbicide resistance in an agricultural situation, we developed SHeRA, the **S**patial **He**rbicide **R**esistance **A**nalyser. SHeRA is a stochastic integer-based model of weed life cycles and gene flow, implemented in Python, a free, generic, extendable programming language with a large community of users. The greatest advantage of using Python is that many of these users have already programmed routines for some aspects that would be needed to construct this model: in particular, advanced maths and methods for displaying the data in graphical form. These routines are contained in the additional packages numpy, scipy, and matplotlib.

In SHeRA, sub-populations of weeds of 1 m^2 each, arranged in a square grid, are subjected to a set of management tactics and, through flowering, seed set, and seed dispersal, communicate with each other through short- and long-distance movement of pollen and seeds. The weed population is assumed to contain a single, partially dominant allele providing resistance to glyphosate, with the plants that carry this gene isolated (initially) in a small patch 4 m^2 in size. Barnyard grass's staggered germination is simplified to three large cohorts. Other aspects of barnyard grass ecology were given parameter estimates based on data from literature and from the long history of research into this species by the DAFF team and various collaborators.

SHeRA runs on a yearly timestep. The events in each step are as follows, processed in order separately for in each cell in the grid:

1. Germinate weed cohort one
2. Apply control measures to cohort one (including self-thinning of the population)
    a. (optional-Process any seed movement due to early-season movement events)
3. Germinate cohort two
4. Apply control measures to cohort one survivors and cohort two
    a. (optional-Process any seed movement due to mid-season movement events)
5. Germinate cohort three
6. Apply control measures to cohort one and two survivors and cohort three
7. Apply control measures to mature survivors of all cohorts
    a. (optional-Process any seed movement due to late-season movement events)
8. Determine potential seed production
9. Produce and move pollen between neighbouring cells and at long distance
10. Determine progeny genotypes
11. Move progeny (seed) between neighbouring cells
12. Process end-of-year mortality of new seeds prior to entering seed bank, and between-seasons mortality of old seeds in seed bank
13. Seed rain enters seed bank – update the seed bank states in each cell in the grid
14. Update the patch and containment zone sizes (where used) and return to start

The model is set, generally, to run for six simulated years, as testing determined that this length of time is sufficient to result in eradication of the resistance gene in each case where it was predicted to occur. At the end of each run of the model, output (optionally including a heat map-style visualisation of the distribution of resistance in the field, population counts and types for each cell, and/or a summary of the annual status of the resistance patch and the population density of the whole field) is sent to files for saving. As the model is stochastic, each run of any simulation is slightly (or markedly in some cases) different from other runs. We ran each scenario either five or ten times, and report here on means of those runs where numerical data is given. Code was included in SHeRA to automate this multi-run process.

As each cohort germinates, a number of plants (proportional to the cell's current seed bank density, rounded down) are entered into a Python list either as a 0 (no resistance alleles), 1 (one resistance allele, heterozygous) or 2 (homozygous resistant). Separate lists are maintained for each cohort. As each control tactic is applied, each individual is extracted from the list and at random may be killed by or survive the tactic depending on the estimated efficacy of the tactic applied. Efficacy is lower for surviving members of earlier cohorts, as they are assumed to have grown large enough to become proportionally more difficult to kill between their own emergence and that of the next cohort.

The cell-structure of the model facilitates zonal management, with pre-identified ‘resistance patch’ cells able to receive different management from other, background cells. The field is broken up into areas that we term the **eradication zone** (ie the cells where the patch is known to exist at the start of the simulation); the **containment zone** (a zone around the eradication zone in which controls are used that attempt to counteract the patch’s propensity to spread); and the **background zone** (the rest of the field, in which only susceptible plants exist at the start of the simulation). The patch treatment zone and the eradication zone can be defined as square areas of any dimensions, or as linear strips the whole length of the field. The former would be an example of management using some kind of mapping technique, and the latter an example of management by varying whole linear runs of a spray rig.

Simulations Plan

SHeRA was designed to test a range of ecological, weed management and agronomic questions, including:

- Is eradication possible, given a reasonable set of ecological and control efficacy estimates?
- Assuming eradication is possible, what is the least intensive set of management options (drawn from those available for use in cotton farming in Australia) that can achieve it?
- How quickly does resistance spread from a patch to surrounding areas by mostly short-distance pollen and seed movement in a mainly self-pollinating species?
- How does the intensity of management of the non-resistant biotype affect the rate of patch expansion?
- What are the optimal sizes of the containment and eradication zones?
- Can glyphosate be used alone in the background zone?
- Can growers effectively respond to a large seed-movement event (as in overland water flows in flooding), and still aim for eradication?

The full set of simulations conducted in this project using SHeRA can be found in pages 50-59 of the Technical Report.

Results

SHeRA provides outputs for total and per-cell values of seed bank density (separated by genotype) and resistance proportion, per step. This output can be used to analyse the rate of expansion of resistance patches and the success of any given strategy at controlling weed numbers across the whole field.

A simple test of SHeRA’s ability to simulate patch dynamics is shown in Figs 1-3, using the visualisation map included in the model. We simulated three scenarios: glyphosate used alone after the emergence of every cohort (Fig 1); the glyphosate strategy plus paraquat applied to every cell in a containment zone 15m^2 in diameter around the original resistance patch (Fig 2); and the glyphosate strategy plus paraquat applied only to cells in the original patch zone (Fig 3). As expected, glyphosate alone allows the patch to spread. The addition of paraquat was only successful at severely limiting spread when applied in a zone outside the original patch. Applications to the patch area alone were soon made unsuccessful by survivors spreading seed and pollen outside the patch zone.

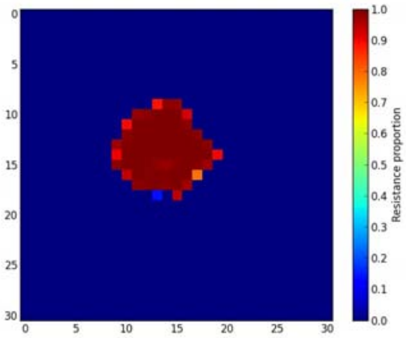

Figure 1. Resistance proportion in each cell of a test field after five years of glyphosate applied after emergence of every cohort. Dark blue cells contain no resistant plants. Dark red cells contain only resistant plants.

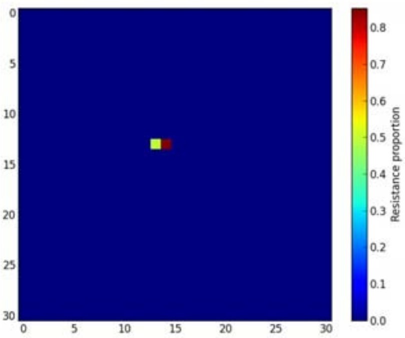

Figure 2. Resistance proportion in each cell of a test field after five years of glyphosate applied to every cohort plus paraquat applied to every cohort in a zone 12m^2 in diameter around the original resistance patch

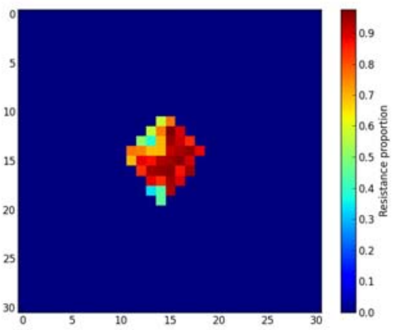

Figure 3. Resistance proportion in each cell of a test field after five years of glyphosate applied to every cohort plus paraquat applied to every cohort in the 4m^2 diameter of the original resistance patch

A summary of the outputs from some of the scenarios tested with SHeRA is shown in the table below.

Table 2. Size and population density of resistant (R) patches and background population density of susceptible (S) plants after six years, under a range of simulations with SHeRA

Simulation	# cells infected[a]	Mean R plants m^{-2} [b]	Mean S plants m^{-2}
A: Glyphosate alone			
A1: No tillage	263	61032	5
A2: Annual tillage	474	34799	234
A3: Biennial tillage	427	34543	199
A4: Annual tillage, reversing direction	525	35551	131
A5: Biennial tillage, reversing	465	34352	224
B: Best Management (BMP) plus eradication early, mid, or late season			
B1: BMP (see Milestone 5.2.2)	50	4010	990
B2: BMP+early	60	5200	930
B3: BMP+mid	57	1546	18724
B4: BMP+late	0	0	0
C: Containment zone size			
C1: 6m cont. zone	0	0	2
C2: 1m cont. zone	23[c]	337	7
C3: No cont. zone	228	22894	26

a-As cells are 1 m^2 each, this figure also describes the size of patches in m^2.
b-This figure describes the mean density of R plants in cells that contain resistance – not the mean over the whole field.
c-In 80% of simulations of scenario C2, the resistance gene was eradicated; the remaining simulations resulted in patch escapes leading to eradication failure.

These results demonstrate several key points. Seed movement by artificial means (i.e. machinery) or by overland water flows, if not managed, makes eradication difficult. Even restricting tillage (when used alone) to every second year results in substantially faster patch expansion in the direction of movement. The BMP tactics tested in the real experiment in milestone 5.2 were predicted to reduce seed bank size and slow patch expansion appreciably over glyphosate alone, but did not result in eradication unless extra efforts towards eradication were made after the last cohort emerged. Containment zone size is predicted to be very important. Where the patch zone alone is treated for eradication, failure results. Where the containment zone is small, results are unpredictable. Only containment zones of 6m beyond the edge of the starting patch provided consistent eradication.

Further results are given in the Technical Report.

Outcomes

When a patch of herbicide-resistant plants is identified, the manager of the land in which the patch occurs could choose to either manage the whole area as if it were herbicide-resistant, or to isolate the patch and preferably some surrounding additional area, and treat them differently from the rest of the area. The patch eradication zone should receive highly intensive management aimed at preventing all seed set on all emerged plants, for as long as necessary to exhaust the supply of resistant seeds. The surrounding containment zone should receive sufficiently robust management to ensure that recruits from short-distance gene flow are likely to be controlled. The background zone receives some version of 'business as usual' management, which in a best-management-practice case would consist of glyphosate plus a range of options used in rotation, which would be of use in preventing the successful establishment of satellite patches of resistance. We have used the outputs of the model described here and in the Technical Report to generate a set of basic recommendations for patch eradication, discussed in Milestone 5.4. We will continue to use SHeRA in future, to generate more specific and detailed recommendations, and to increase our knowledge around spatial patch dynamics in cotton systems generally.

Other future work that will improve SHeRA's ability to predict the success of eradication programs includes the filling of information gaps relating to some of the parameters used in SHeRA. In particular, gene flow is an area where data is limited. SHeRA would benefit especially from knowing more about seed movement in overland water flows, and the distances and frequencies at which rare cross-pollination events occur in the field.

5.4 Develop generic strategies for patch eradication

Outcomes

The simulations we undertook with SHeRA were analysed and led to the following basic recommendations for eradication:

- Start early, with small patches, for the best chance of success
- Never leave late cohorts uncontrolled
- Containment zone should be at least 6m. One spray pass wide is a useful, simple containment zone.
- If the patch is large, the gene will move, expanding and creating satellite patches. Monitor glyphosate results and redefine zones yearly if possible.
- Be aware that machinery causes long-distance seed movement in the direction of travel
- Use two non-glyphosate actions in the background zone per season, plus:
  - At least one non-glyphosate action on every cohort in the containment and patch zones
  - A final follow-up eradication tactic on late germinators and survivors in the patch zone

These basic recommendations will be refined as our work on spatial management of glyphosate resistance continues.

6. **Please describe any:-**
   a) **technical advances achieved (eg commercially significant developments, patents applied for or granted licenses, etc.);**

Not applicable

   b) **other information developed from research (eg discoveries in methodology, equipment design, etc.); and**

Not applicable

   c) **required changes to the Intellectual Property register.**

No changes to Intellectual Property register

Conclusion

7. **Provide an assessment of the likely impact of the results and conclusions of the research project for the cotton industry. What are the take home messages?**

The last few years have seen emerging threats to weed management in cotton system, become common challenges that a number of growers are dealing with on their farms. This project has aimed to investigate further the findings of previous research to find specific tactics to manage glyphosate resistant and tolerant weeds.

Three management packages have been developed for inclusion into WEEDpak for key weeds in cotton systems. These have been for fleabane, glyphosate-resistant awnless barnyard grass and feathertop Rhodes grass. Information in these packages has detailed management in the cotton crop, rotation crops and fallow. A considerable amount of ecological information on these weeds has also been included, so that growers can better understand their management.

The online glyphosate resistance risk assessment tool has been updated. Version 2 enables differentiation in the resistance risk between grass and broadleaf weeds, and a more user friendly way for users to compare their current strategies with changes they might make to decrease the resistance risk on their farms. The new version will be available on the myBMP website for growers and consultants to utilise.

An increased understanding of the triggers for emergence of key species, in particular awnless barnyard grass, feathertop Rhodes grass, fleabane and sowthisle has been gained. Our research has shown that these species can emerge within 2-3 days after rainfall events over 10 mm, whether the rainfall event is either a single event or accumulated over consecutive days. The smaller seeded species such as the summer grasses and asteraceae (fleabane and sowthistle) are able to emerge quickly at most temperatures across the growing season. Therefore growers need to vigilant after rainfall events to monitor weeds and control them in a timely manner.

Previous research has shown that the key to resistance management is to prevent weed seeds entering the seed bank. The project investigated options for controlling survivors of glyphosate application for both awnless barnyard grass and fleabane. Results showed that previous glyphosate exposure should not hamper efforts to control survivors. A number of options were effective for survivor control with double knocks with paraquat and glufosinate being consistently effective on both weeds.

Preliminary experiments have also shown that seed viability of fleabane, awnless barnyard grass and feathertop Rhodes grass can be reduced when sprayed close to flowering. However, with the exception of fleabane sprayed with 2,4-D+picloram which was very effective, in most situations plants were able to regrow and produce viable seed. Results at this point suggest that attempts to reduce viability can be and effective short-term measure until a more robust control tactic is able to be applied.

Patches of glyphosate-resistant awnless barnyard grass are able to be managed. After two years of experimentation, all treatments that have two non-glyphosate tactics in crop and fallow (2+2) have had significantly less emergences than patches managed with glyphosate only. At this stage it is too early to tell the benefits of additional eradication tactics on the weed seed bank. This effect will become more evident as the experiment progresses. Simulations have shown that when a patch of herbicide-resistant plants is identified the grower will be able to isolate the patch and a surrounding additional area and undertake intensive management on the selected area. By preventing seed set on emerged plants, for as long as necessary to exhaust the supply of resistant seeds, the patch should be able to be effectively eradicated.

Extension Opportunities

8. Detail a plan for the activities or other steps that may be taken:

(a) to further develop or to exploit the project technology.

A new research project has been funded that will continue to investigate options for eradicating patches of glyphosate resistant awnless barnyard grass. This research has been ongoing for two years, and further studies are still required to examine if this is a viable option. Field data from this experiment will also be used to validate the SHeRA model.

Studies on glufosinate double knock tactics will be further examined in depth in the field in the new project. Preliminary studies on reducing viability will also be extended in the new project in an investigation into pre-picking weed seed management.

(b) for the future presentation and dissemination of the project outcomes.

- Updates to Weedpak on key species will be made
- Presentation will be made relevant conferences
- Articles will be drafted from project outcomes to be published in Cottongrower magazine
- Three papers are scheduled this year for submission to scientific journals

(c) for future research.

The economics of preventing glyphosate resistance in terms of taking preventative measures or waiting until resistance occurs still remains a question. It is still unclear whether a detailed economic comparison into this “risk vs reward” scenario would be beneficial as each growers situation is often specific. In the new project we are planning to adapt the RIM model to cover awnless barnyard grass. This way, growers/consultants will be able to input their own specific practices/data into the model and see for themselves the benefits of resistance prevention and management.

This project has concentrated heavily on glyphosate resistance management. However we are still unsure of the mechanisms of glyphosate resistance in species present in cotton systems. Research into what these mechanisms are, and potential interactions between plant stresses and non-target-site mechanisms is important to obtain a clearer understanding of the causes of resistance and how it can best be managed.

The ability of genetic material (seed and pollen) of resistant plants to move across fields, farms and catchments needs to be researched. On farm resistance prevention strategies may be hampered by the addition of resistant material from outside. It is important that the pathways, potential distances and possible prevention strategies for movement of genetic material are investigated.

9. A. List the publications arising from the research project and/or a publication plan. (NB: Where possible, please provide a copy of any publication/s)

Publications

Refereed Journals

Thornby, D., Werth, J. and Walker, S. (2013) Managing glyphosate resistance in Australian Cotton farming: modelling shows how to delay evolution and maintain long-term population control. Crop and Pasture Science 64: 778-788.

Werth, J., Boucher, L., Thornby, D., Walker, S. and Charles, G. (2013) Changes in weed species since the introduction of glyphosate-resistant cotton. Crop and Pasture Science 64:789-796.

Werth J, Thornby D, Walker S (2011) Assessing weeds at risk of evolving glyphosate resistance in Australian sub-tropical glyphosate-resistant cotton systems. Crop & Pasture Science 62, 1002-1009.

Conference Papers

Charles. G. and Werth, J. (2014) Managing fleabane in the cotton system. In proceedings of the 17th Australian Cotton Conference, Broadbeach.

Keenan, M., Werth, J., Thornby, D. and Walker, S. (2014) Reducing seed viability of flaxleaf fleabane, feathertop Rhodes grass and awnless barnyard grass. In proceedings of the 19th Australasian Weeds Conference, Hobart.

Keenan, M (2013) Emergence of four weed species in response to rainfall and temperature. Australian Cotton Research Conference, Narrabri 8-11 September.

Keenan, M. and Werth, J. (2012) Emergence of four weed species in response to rainfall and temperature. Pages 367-368, In proceedings of the 18th Australasian Weeds Conference, Melbourne.

Thornby, D., Werth, J. and Walker, S. (2014) Patch management solves early infestations of glyphosate resistant awnless barnyard grass. In proceedings of the 19th Australasian Weeds Conference, Hobart.

Thornby, D (2013) A new model for testing field-level epidemiology of herbicide resistance in cotton. Australian Cotton Research Conference, Narrabri 8-11 September.

Thornby, D (2013) Weeds in space: field-level epidemiology of herbicide resistance. 7th International Conference on Functional—Structural Plant Models, Saariselka, Finland, 9-14 June 2013.

Thornby, D. and Renton, M. (2013) "Modelling as an integration tool for helping to understand, predict and manage herbicide resistance." Global Herbicide Resistance Challenge, Fremantle, February 2013.

Thornby, D., Werth, J. and Walker, S. (2012) Modelling the effectiveness of glyphosate resistance prevention strategies in Australasian sub-tropical farming systems. Pages 233-236, In proceedings of the 18th Australasian Weeds Conference, Melbourne.

Werth, J., Thornby, D., Keenan, M. and Walker, S. (2014) Managing patches of glyphosate resistant *Echinochloa colona* – can they be eradicated. In proceedings of the 19th Australasian Weeds Conference, Hobart.

Werth, J. (2013) Managing herbicide resistance in cotton systems: have we covered everything? Australian Cotton Research Conference, Narrabri 8-11 September.

Werth, J., Thornby, D., Taylor, I. and Charles, G. (2013) "Glyphosate resistance and its implications in glyphosate-resistant cotton systems in Australia." Global Herbicide Resistance Challenge, Fremantle, February 2013.

Seminars, Workshops, Grower Meetings and Other

Thornby, D (2014) Avoid transporting herbicide resistance across the landscape. Weed Smart Media Release, 12th May.

Thornby, D (2014) Early intervention: patch management of herbicide resistant. Weed Smart Media Release, 22nd January.

Thornby, D (2013) Managing patches as patches. Giving a RATS newsletter, GRDC, Spring 2013.

Thornby, D (2013) Radio interview with Chris Brown/GRDC, 5 November: patch management approaches and modelling.

Thornby, D (2013) Managing patches as patches. Giving a RATS newsletter, GRDC, Spring 2013.

Werth, J., Green, T., Widderick, M. and Wu, H. (2013) Managing flaxleaf fleabane in cotton. In WEEDpak – A guide for integrated management of weeds in cotton.

Werth, J., Osten, V., Widderick, M. and Walker, S. (2013) Managing feathertop Rhodes grass in cotton. In WEEDpak – A guide for integrated management of weeds in cotton.

Werth, J., Thornby, D., Cook, T. and Walker S. (2014) Managing glyphosate-resistant awnless barnyard gass. In WEEDpak – A guide for integrated management of weeds in cotton (In press).

Werth, J. (2013) Glyphosate resistance: Status and Management. Rabobank Cotton Seminar, Norwin, 17th September.

Werth, J. (2013) Glyphosate resistance: Status and Management. Namoi Cotton Seminars, Cecil Plains and Brigalow, November.

Werth, J. (2013) Herbicide tolerant technologies: What are they and how do they work. UNE Cotton Course, Narrabri, 2nd September.

Werth, J. (2013) Resistance – the threat. UNE Cotton Course. Narrabri, 2nd September

Werth, J. (2013) Glyphosate over-use a risky business. Weed Smart Media Release, May 16. 2013

Werth J. and Widderick M. (2012) IWM for key problem weeds in Central Queensland. CQ Grower Solutions Workshops, Dauringa, Biloela, Theodore, Gindie, Clermont and Capella, June 2012.

Werth J. (2012) IWM for key problem weeds. Waggamba Landcare AGM, Billa Billa, November.

Werth J. (2012) Current research in cotton systems. CRT Meeting, Toowoomba, April.

B. Have you developed any online resources and what is the website address?

Version 2 of RAT. Currently unpublished, awaiting attention from the myBMP team.

Part 4 – Final Report Executive Summary

The Australian Cotton Industry is now in the midst of dealing with both glyphosate resistant and tolerant weeds in the cotton system. Glyphosate, the world's most important herbicide continues to be relied on as the primary source of weed control. The sustainability of this herbicide is dependent upon the ability to incorporate it into a diverse system and prevent the introduction and spread of glyphosate resistant weeds in the farming system.

Previous research has demonstrated how glyphosate resistant and tolerant weeds can be managed in cotton systems. This information has been packaged into management guides in WEEDpak for three species: flaxleaf fleabane, feathertop Rhodes grass and glyphosate-resistant awnless barnyard grass. This information is designed to help growers understand the ecology of these weeds as well as their management in crop and fallow. As more information is compiled from current research, these management packages will continue to be updated.

An updated version of the online glyphosate resistance risk assessment tool has been developed. This new version enables users to determine their resistance risk for grass and broadleaf weeds independently. Users can also compare different strategies for resistance prevention/management with greater efficiency.

An in-depth understanding of triggers for emergence of a number of key species, in particular awnless barnyard grass, feathertop Rhodes grass, fleabane and sowthistle has been gained. This research has shown that the smaller seeded summer grasses and asteraceae (fleabane and sowthistle) can emerge within 2-3 days of rainfall events of 10 mm or greater. This has contributed to their success in glyphosate based farming systems, and it important that fields are monitored soon after rainfall event so the control measures can be conducted in a timely manner.

Studies have been conducted on how to manage survivors of glyphosate application. This is an important part of the CMP for Roundup Flex cotton, and weed management in general. Results from trials on fleabane and awnless barnyard grass have shown that double knock applications with either paraquat or glufosinate as the second knockdown herbicide are most effective. Particularly as these plants are often larger, and well past optimal spraying time.

Minimising the numbers of weed seeds entering the seed bank is critical for sustainable weed management. Preliminary experiments on reducing seed viability have shown that this is achievable when plants have past optimal spraying time. Results have shown the glufosinate was most effective on awnless barnyard grass and feathertop Rhodes grass, and 2,4-D+picloram was most effective on fleabane. However, fleabane and feathertop Rhodes grass in particular are able to regrow and produce viable seeds. At this stage research indicates that an attempt to reduce seed viability is a short-term option until plants can be subsequently controlled with more robust methods.

Field and glasshouse trials that provide data to a spatial simulation model has been developed to determine the feasibility of eradicating patches of glyphosate-resistant awnless barnyard grass. Results to this point have shown that species such as awnless barnyard grass that are predominately selfing, have a relatively short seed bank life and are not transported by wind can be effectively managed at a patch level. Long-term management strategies that include two non-glyphosate tactics in crop and fallow have been successful in significantly reducing the seed bank and the number of emergences in the short-term. As the trial continues, the added benefits of extra eradication tactics will be determined for their effect on driving down the seed bank.

Appendix 1.1

MANAGING FLAXLEAF FLEABANE IN COTTON

Jeff Werth, Todd Green, Michael Widderick, Steve Walker & Hanwen Wu

(Qld. Department of Employment Economic Development and Innovation, University of New England, & NSW Dept. Primary Industries)

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The fleabane family

Flaxleaf or hairy fleabane (*Conyza bonariensis*) is a member of the Asteraceae, or daisy family of plants. The Asteraceae is the largest of the plant families and includes many weedy species, most notably the thistle family.

The Conyza genus (the part of the Asteraceae family including the fleabanes) contains 60 species, found throughout the temperate zones of the world. There are seven *Conyza* or fleabane species in Australia, the three most important species being flaxleaf fleabane, Canadian fleabane (*C. canadensis*) and tall fleabane (*C. sumatrensis*). Flaxleaf fleabane is native to South America and is the most weedy and the most common of the fleabane species in cropping systems in New South Wales and Queensland. Tall fleabane tends to be the more problematic species elsewhere in the world, but is of minor importance in Australia, where it is most commonly found on roadsides and in pastures.

Flaxleaf fleabane is a member of the daisy family. It has become a major problem in the conservation farming systems of northern NSW, southern and central Queensland. It is easily confused with tall fleabane and Canadian fleabane.

The flaxleaf fleabane plant

Flaxleaf fleabane is an annual or short-lived perennial weed that is now common right across the cotton industry.

Flaxleaf fleabane germinates between temperatures of 10°C and 30°C, with optimal emergence occurring from 20 – 25°C (Figure 1).

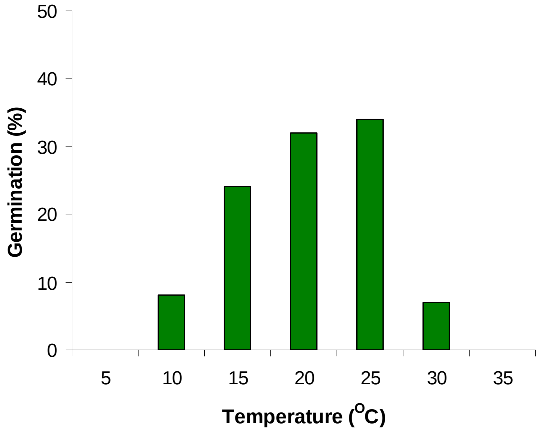

***Figure 1**. Temperature range for flaxleaf fleabane germination.*

In the field, this correlates to mild conditions, generally in autumn, early winter and spring. However, there can be some emergence during mid-winter and summer when conditions are right. The likely times for emergence are illustrated in the lifecycle and management tables (Tables 8 and 9).

Flaxleaf fleabane rosettes in mature cotton. These plants are likely to have emerged during mild/wet conditions in mid-summer.

The growth rate of flaxleaf fleabane is affected by the time of its emergence. Plants that emerge in autumn and early winter grow slowly above ground, however below ground the roots continue to grow. This provides the plant with the ability to grow to flowering quickly when temperatures warm up in spring. Plants that emerge in spring grow relatively more quickly, putting more resources into above-ground growth, but mature later in summer compared to the plants that established in autumn.

Due to the larger root system, the over-wintered plants are harder to control than plants of the same size that have emerged in spring.

A single fleabane plant is capable of producing over 100 000 seeds. Therefore, even at a low germination percentage (say, 5%), there is potential for 5000 seedlings to emerge at 30°C from just a single, uncontrolled plant.

Each seed has a pappus, or light hairs attached which enable the seed to be easily dispersed by wind.

Flaxleaf fleabane plants have multiple flowers and can produce a large number of small seeds. Seeds can be dispersed by wind due to a pappus.

Most fleabane seeds lose their viability within 12-18 months on the soil surface. However, when buried, fleabane seeds can persist for several years (Figure 2).

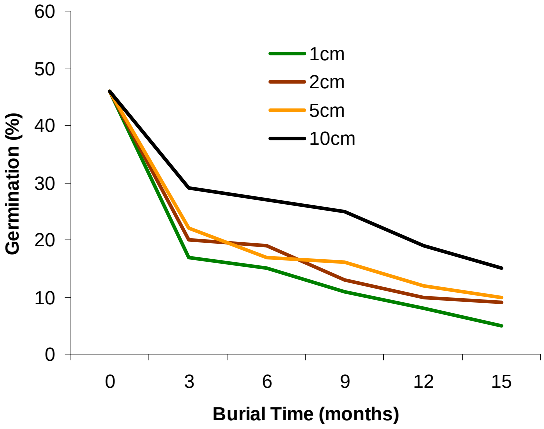

***Figure 2.** The persistence of flaxleaf fleabane increases as the depth of seed burial increases.*

Flaxleaf fleabane requires light to germinate. Experiments have shown the even when temperature and moisture conditions are right, fleabane seeds will not germinate in the absence of light. This is illustrated in Figure 3, where no germination occurred under 100% shade. However, some germination still did occur on 90% shade, indicating that although flaxleaf fleabane requires light, it may not need much light to germinate.

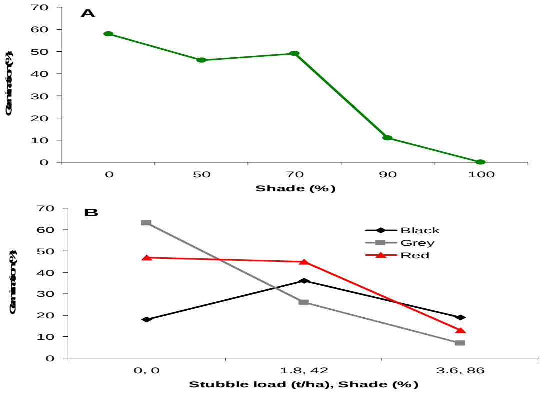

Figure 3. *Effect of partial and complete shading under shade cloth on flaxleaf fleabane germination.*

This is further illustrated in Figure 4, which shows the effect of stubble load and soil type on flaxleaf fleabane germination. Germination was highest on grey soil, followed by red soil with no stubble. In general, as the stubble load increased, flaxleaf fleabane germination decreased. However, even under the highest stubble load of 3.6 t/ha (which equated to approximately 86% shade), approximately 10 - 20% of seeds were still able to germinate, dependant on soil type.

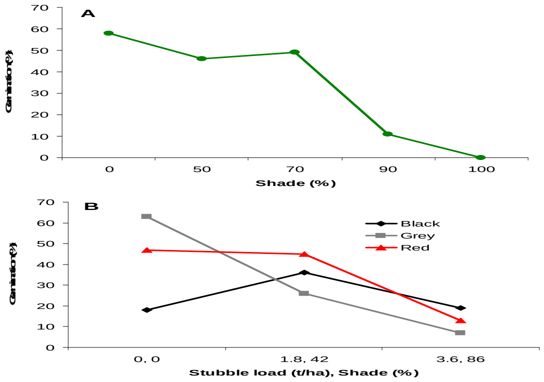

Figure 4. *Effect of shading on flaxleaf fleabane germination, using stubble and three soil types.*

Strategies for managing flaxleaf fleabane

Successful management of flaxleaf fleabane requires an IWM program centred on reducing the seed bank replenishment. That is, the easiest way of controlling flaxleaf fleabane is to not have it in the first place.

A number of components will be central to any fleabane management program. These include:

- monitoring seedling emergence,
- knowing the field history,
- using a variety of IWM tools, and
- preventing survivors from setting seed.

Monitoring seedling emergence

Be aware of when flaxleaf fleabane is likely to emerge. Generally, it is more likely to emerge following rain in late autumn, early winter and early spring. However, flaxleaf fleabane will emerge whenever there are moist and mild conditions, and this could be at any time of year, ever mid-summer. Plants are much easier to control when they are young, so it is important to closely monitor potential fleabane emergence throughout the cropping system, including the fallow period.

Field history

It is important to know previous herbicide history, as fleabane populations that have been exposed to glyphosate over a number of years are likely to be more difficult to control with glyphosate compared to populations that have no previous history of glyphosate. In fact, some flaxleaf fleabane populations have been classed as being resistant to glyphosate. Larger fleabane plants will be almost impossible to kill using glyphosate on these populations.

Using a variety of IWM tools

It is important to use a variety of chemical and non-chemical tactics to manage flaxleaf fleabane. When herbicides are used as the primary management tools, it is important to rotate herbicide groups. Robust herbicide rates must be used in order to get maximum effectiveness to keep weed numbers low. Keeping weed numbers low is important for resistance management, as resistance is less likely to develop in fields with fewer weeds than in heavily infested fields.

Preventing survivors from setting seed

Control of survivors is vitally important; flaxleaf fleabane’s prolific seed production means that even if very few plants are left, they will produce very large numbers of seeds, with the potential for a large, future weed problem. This will considerably reduce the effectiveness of previous control measures and perpetuate the problem.

Controlling flaxleaf fleabane in fallows

Flaxleaf fleabane has emerged as a problem weed largely due to the prevalence of no-till, glyphosate based farming systems. It is obvious in the trial results of Table 1 that glyphosate is much less effective on larger plants. A number of tank-mix partners were trialled for their effectiveness to improve control in fallow. A number of tank-mixes were relatively successful. The most successful in this case was glyphosate mixed with Tordon 75-D, which is now registered for control of flaxleaf fleabane seedlings and young rosette plants.

Table 1. *Effects of post-emergent treatments on flaxleaf fleabane in winter fallow in 2003. Weed kill was assessed nine weeks after application.*

Treatment	Rate (L or g/ha)	% Weed kill
Spray.Seed	2.4	57
Paraquat (rosette < 8 cm)	1.5	53
Glyphosate CT (rosette < 8 cm)	1.5	88
Glyphosate CT (rosette > 10 cm)	1.5	13
Glyphosate CT fb Spray.Seed*	1.5 fb 2.4*	96
Glyphosate CT + Amitrole T	1.5 + 2.5	93
Glyphosate CT + Group B	1.5 + 7	90
Glyphosate CT + Group I	1.5 +	97
Glyphosate CT + Group B + Group I	2.5 + 7 + 1	93
Glyphosate CT + Tordon 75-D	2.5 + 1	99
Glyphosate CT + Group I	2.5 + 0.75	98
Glyphosate CT + Group I	2.5 + 0.7	96
Glyphosate CT + Group I + Group B	2.5 + 0.12 + 7	96
Group I + Amitrole T	2 + 2.5	94
Group I + Group B	2 + 7	95

Note. Fb – indicates the first herbicide application was followed by the 2nd herbicide. Other herbicide combinations in this table were tank-mixed.*

Herbicide performance depends largely on weed size and growing conditions at spraying. In general, responses from herbicide applications can be quite slow, with some visual symptoms not becoming apparent till nearly a month after application.

It is interesting to note that none of the treatments in Table 1 provided 100% control of flaxleaf fleabane, although the Tordon 75D and other group I treatments came close. It was also noted that in practice, the results that growers have been experiencing have been quite variable. Due to its very high seed production, even very small numbers of escapes of flaxleaf fleabane can have considerable consequences.

As a result, it was decided to trial the "double-knock" herbicide tactic on fleabane. "Double-knock" is the sequential application of knock down herbicides from different herbicide mode of action groups. This technique, developed to control glyphosate resistant ryegrass, involves applications up to 2 weeks apart, where it is assumed that the 2nd herbicide application will control potential survivors of the 1st application. Therefore, it is assumed that the 1st application will also be relatively effective on the weeds sprayed, and it is important the both applications contain robust herbicide rates of herbicides which are effective against the target weed.

Table 2. *Percentage kill of flaxleaf fleabane plants using the "double-knock" tactic at Dalby in 2006. The second knock was applied 7 days after the initial knock.*

Initial knock	Second knock	% Weed kill
No herbicide (Control)		0
Roundup CT 2 L/ha	na	55
Roundup CT 2 L/ha	Spray.Seed 1.6 L/ha	95
Roundup CT 2 L/ha	Spray.Seed 2.4 L/ha	97
Roundup CT 2 L/ha + Surpass 1.5 L/ha	Spray.Seed 1.6 L/ha	99
Roundup CT 2 L/ha + Surpass 1.5 L/ha	Spray.Seed 2.4 L/ha	99
Roundup CT 2 L/ha + Surpass 3 L/ha	Spray.Seed 2.4 L/ha	100
Roundup CT 2 L/ha	Amicide 625 1.5 L/ha	94
Rooundup CT 2 L/ha	Amicide 625 3 L/ha	91

The effect of the double-knock is shown in Table 2. Note that this fleabane population was not well controlled by the single application of glyphosate, with 2 L/ha of Roundup CT only controlled 55% of weeds sprayed. The double-knock significantly improved fleabane control, however a combination of glyphosate+ 2,4-D followed by Sprayseed, all at robust rates was required to achieve 99 - 100% control.

Using the double-knock tactic of glyphosate followed by paraquat greatly improved the control of flaxleaf fleabane compared to the result from glyphosate alone.

Further experiments were conducted to determine the best time between applications using the double-knock tactic. The effectiveness of paraquat was also examined compared to Spray.Seed®, which contains both paraquat and diquat. The time between treatments ranged from separate applications on the same day, to 14 days for paraquat and Spray.Seed, and 5 days for 2,4-D (Figure 5).

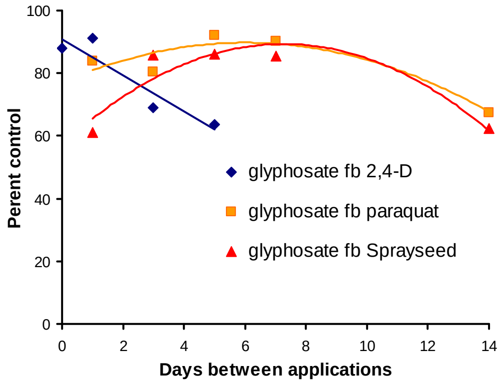

Figure 5. *Effect of timing between glyphosate and follow-up applications of 2,4-D, paraquat and Spray.Seed on flaxleaf fleabane control.*

The control of flaxleaf fleabane with applications of glyphosate followed by either Spray.Seed or paraquat were similar, with the optimum timing between applications being between 5 -10 days. However, as the time increased between applications of glyphosate and 2,4-D, control decreased, with the best results achieved by applying the 2,4-D within one day of the glyphosate.

Residual herbicides for controlling flaxleaf fleabane

Flaxleaf fleabane seedlings often emerge in the field in dense populations, such that the rosettes are often overlapping, with larger plants shading the smaller plants, making it very difficult to achieve good herbicide coverage on all plants. The high density of seedlings places pressure on post-emergent herbicides to provide effective control, particularly where poor coverage occurs due to the shading of smaller plants. Residual herbicides, therefore, have an important role in minimising the number of seedlings that emerge and sunsequently need to be controlled using a post-emergence herbicide.

A number of residual herbicides have been trialled for their effectiveness at minimising flaxleaf fleabane emergences. An experiment combining residual herbicides with the 2nd herbicide application in a double-knock tactic was conducted at Dalby in 2009. The aim of this experiment was to simulate controlling existing fleabane rosettes, while minimising future emergences.

All herbicides had a significant effect on fleabane emergences, with atrazine, Balance, and Sharpen performing the best (Table 3).

Table 3. *Residual control of flaxleaf fleabane when combined with a double-knock treatment. Trial was conducted at Dalby in 2009.**

Herbicide	Emergences per 100m^2 (126 DAT)
Glyphosate CT 1.5 L/ha + Surpass 475 1.0 L/ha fb Spray.Seed 1.6L/ha combined with...	
No residual	1543
Group C 4 L/ha	0
Diuron 1.5 kg/ha	58
Sharpen 200 ml/ha	5
Group B 20 g/ha	13
Group B 100 g/ha	2

Note* Refer to herbicide labels for plant-back periods to cotton.

The residual control significantly improved when Surpass 475 was replaced by Tordon 75D as the mix partner with glyphosate in the first application (Table 4). The addition of picloram in the Tordon 75D considerably reduced fleabane emergence even when no further residual herbicides were applied.

Table 4. *Residual control of flaxleaf fleabane when combined with a double-knock treatment. Trial was conducted at Dalby in 2009.**

Herbicide	Emergences per 100m^2 (126 DAT)
Glyphosate CT 1.5 L/ha + Tordon 75D 0.7 L/ha fb Spray.Seed 1.6L/ha combined with…	
No residual	178
Group C 4 L/ha	0
Diuron 1.5 kg/ha	0
Sharpen 200 ml/ha	0
Group B 20 g/ha	12
Group B 100 g/ha	8

Note* Refer to herbicide labels for plant-back periods to cotton.

All the herbicides trialled in Tables 3 & 4 have significant plant-back periods to cotton, although diuron can be used as a pre-emergent and post-emergent (lay-by). Therefore, another experiment was conducted to determine the effectiveness of the residual herbicides more commonly used in cotton.

The results in Table 5 are from one field experiment. These preliminary results have been backed up by two glasshouse experiments. The group C herbicides were both effective at reducing fleabane emergence. The group F herbicide, actually registered for nutgrass at a rate of 5 kg/ha, also reduced fleabane emergence when used at 1 kg/ha in this trial.

Table 5. *Residual control of flaxleaf fleabane with residual herbicides used in cotton. Trial was conducted in 2010 at Millmerran.*

Herbicide	Plants/m^2	
	36 DAT	51 DAT
Nil	4.2	7.0
Group B 3.3 L/ha	3.5	7.5
Group C 2.9 kg/ha	0.0	0.3
Group C 2 kg/ha	0.0	0.2
Group K 2 L/ha	0.5	1.2
Group F 1 kg/ha	0.5	1.2

Control of flaxleaf fleabane in cotton

The herbicide options for controlling flaxleaf fleabane in cotton are limited. The use of pre-emergent herbicides such as diuron (not specifically registered for fleabane control, but registered for broadleaf control) or Convoy will aid to reduce fleabane emergence in crop. The application of a lay-by, such as diuron or prometryn, will reduce possible emergences that may occur later in the season. However, there are likely to be some escapes and plants which establish will continue to grow throughout the season and by the time of picking, will be large, mature and setting seed. Any control measures applied at this time will prevent further seed set, but are generally too late and are ineffective in managing the weed population.

Knowing that glyphosate is not likely to be effective in controlling flaxleaf fleabane in Roundup Ready Flex cotton crops, a useful strategy may be to apply a band of residual herbicide to the plant-line to reduce emergences in the plant-line of these crops. This could then be followed by a partial double-knock, consisting of a robust rate of Roundup Ready herbicide over-the-top of the crop, with a shielded paraquat or Spray.Seed application in the inter-row area, or inter-row cultivation between the rows 5-10 days after the glyphosate.

The use of non-chemical methods, such as inter-row cultivation and hand hoeing, can be very valuable to control plants between rows and escapes from previous control measures.

Managing flaxleaf fleabane in the farming system

Flaxleaf fleabane populations need to be monitored and managed in the whole farming system, all year round, in order for effective control to be maintained. How fleabane is managed in one crop or fallow, is likely to have a large impact on the following crop or fallow.

Flaxleaf fleabane plants can produce large quantities of seed, potentially creating a heavy penalty when escapes mature. However, seed persistence is relatively short and a few years of consistent and effective management will significantly reduce numbers.

Control in winter cereals can be quite variable, as is shown in Table 6. However, winter cereals can also be effective in competing with fleabane for light and nutrients. Wheat and barley that has been grown with high plant populations and relatively narrow rows (25 cm) have been shown to be very competitive with sowthistle. The same principles apply to flaxleaf fleabane. Crop competition can be an effective tool that reduces reliance on herbicides, as any fleabane plants that do establish in a competitive cereal crop will be small and produce relatively little seed.

Table 6. *Control of emerged flaxleaf fleabane in wheat. Trial was conducted at Warwick in 2010.**

Herbicide	% Weed kill	
	4 week old fleabane	8 week old fleabane
No herbicide	0	0
Group B 5 g/ha	40	12
Group I 1.2 L/ha	69	57
Group I 750 mL/ha	83	62
Group I 600 mL/ha	64	11
Group I 1 L/ha	77	69
Tordon 75D 300 mL/ha	54	77
Group B 5 g/ha + Group I 750 mL/ha	48	40
Group I 750 mL/ha + Group I 750 mL/ha	79	19
Group I 600 mL/ha + Group I 750 mL/ha	63	49
Group I 1 L/ha + Group B 5 g/ha	58	76
Tordon 75D 300 mL/ha + Group I 375 mL/ha	69	70

*Refer to herbicide labels for plant-backs periods to cotton.

Summer crops, such as sorghum, are generally less competitive than winter crops (due to the wide row spacing normally used), but allow the use of atrazine, which is effective for reducing flaxleaf fleabane emergence (Tables 3 and7). Atrazine applications made early in a fallow before planting sorghum can provide season-long control.

However, cotton can not follow close-on to an atrazine application. Atrazine plant-back periods to cotton range from 6 months for applications up to 1.26 kg active/ha, to 18 months for applications between 1.26 – 2.97 kg active/ha (the plant-back periods will be longer in dry conditions). In the experiments presented in Table 7, 4 L atrazine/ha (2 kg active/ha) was the more effective rate and this rate has a plant-back period to cotton of 18 months. It is therefore, very important to consider cropping rotations and the whole farming system when planning control of flaxleaf fleabane with herbicides such as atrazine, that have prolonged plant-back periods to cotton.

Table 7. *Control of flaxleaf fleabane in 3 sorghum experiments*.*

Herbicide treatment (product/ha)			% Weed kill		
Fallow	Pre-plant	Pre-emergent	2004	2005(1)	2005(2)
Atrazine 4L/ha			89	84	99
Atrazine 2L/ha			60	64	85
	Glyphosate CT 2L/ha + Group I 3L/ha	Atrazine 4L/ha	99	95	100
	Glyphosate CT 2L/ha ⇨ Sprayseed 1.5L/ha	Atrazine 4L/ha	99	88	99
	Glyphosate CT 2L/ha + Group I 3L/ha	Atrazine 2L/ha	98	100	97
	Glyphosate CT 2L/ha + Group I 1.0L/ha	Atrazine 2L/ha	99	95	100

*Refer to herbicide labels for plant-back periods to cotton.

An understanding of the lifecycle of flaxleaf fleabane and how it fits into the farming system is illustrated in Tables 8 and 9. As control is more effective when plants are young, it is important to be aware of when flaxleaf fleabane is likely to emerge. Tactics can then be adapted to either reduce the numbers emerging, or control emerged plants. Stopping plants from maturing and setting seed is vital to preventing additions to the seed bank.

Table 7. *Fleabane lifecycle and integrated weed management options in back-to-back Roundup Ready Flex® cotton cropping systems*

	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr
Fleabane Emergence	Likely		Less likely				Likely			Less likely		Likely			Less likely				Likely	
Fleabane Flowering / seeding	🟨	🟨	🟨	🟨	🟨	🟨						🟨	🟨	🟨	🟨	🟨	🟨	🟨		
Crop	Roundup Ready Flex® cotton								Fallow				Roundup Ready Flex® cotton							
Double-knock for a clean start and to control survivors									🟦			🟦								
Pre-emergent herbicides											🟦	🟦								
At-planting residual	🟦												🟦							
In-crop directed residual		🟦	🟦	🟦										🟦	🟦	🟦				
Robust Roundup Ready® fb shielded paraquat / Spray.Seed		🟦	🟦	🟦										🟦	🟦	🟦				
Inter-row cultivation			🟧	🟧											🟧	🟧				
Hand chipping			🟧	🟧	🟧	🟧	🟧								🟧	🟧	🟧	🟧	🟧	
Spot spraying – non-selective herbicides			🟦	🟦	🟦															
Scouting (key times)	🟧		🟧	🟧		🟧	🟧	🟧		🟧	🟧		🟧		🟧	🟧		🟧	🟧	🟧
Farm hygeine (key times for equipment)	🟧 Planting equipment Cultivation equipment	🟧	🟧	🟧				🟧 Transport equipment		🟧 Planting equipment	🟧		🟧 Planting equipment Cultivation equipment	🟧	🟧	🟧				

Table 8. *Fleabane lifecycle and integrated weed management options in Roundup Ready Flex® cotton/rotation crop farming systems*

	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug
Fleabane Emergence	Likely		Less likely				Likely			Less likely		Likely			Less likely				Likely			Less likely		
Fleabane Flowering / seeding	🟨	🟨	🟨	🟨	🟨	🟨						🟨	🟨	🟨	🟨	🟨	🟨	🟨						🟨
Crop	Roundup Ready Flex® cotton								Winter cereal						Fallow prior to cotton									
Double-knock for a clean start and to control survivors									🟦						🟦						🟦			🟦
Pre-emergent herbicides																							🟦	🟦
At-planting residual	🟦																							
Post-emergent herbicides										🟦														
In-crop directed residual		🟦	🟦	🟦																				
Robust Roundup Ready® fb shielded paraquat / Spray.Seed		🟦	🟦	🟦																				
Inter-row cultivation			🟧	🟧																				
Hand chipping			🟧	🟧	🟧	🟧	🟧																	
Spot spraying – non-selective herbicides			🟦	🟦	🟦																			
Scouting (key times)	🟧		🟧	🟧		🟧	🟧	🟧		🟧	🟧		🟧								🟧	🟧	🟧	🟧
Farm hygiene (key times for equipment)	Planting equipment Cultivation equipment	🟧	🟧	🟧			Transport equipment	🟧		Planting equipment	🟧							Cultivation equipment	🟧	🟧	🟧	🟧	🟧	🟧

Glyphosate resistance

In a recent assessment of species that have a high risk of developing resistance to glyphosate, flaxleaf fleabane was found to be one of the highest risk species. Its capacity to produce large quantities of seed, often resulting in very dense populations, makes it an ideal candidate for glyphosate resistance, particularly if glyphosate is the predominate herbicide used to manage those dense populations.

Flaxleaf fleabane has always been perceived as being relatively tolerant of glyphosate and its prevalence has been attributed to reliance on glyphosate in no-till farming systems. Recent research, however, has shown that this is not the full story and that the level of control with glyphosate is linked with the weed control history.

A large number of samples of flaxleaf fleabane populations from Queensland and New South Wales were gathered in 2003 to test their sensitivity to glyphosate. These populations came from cultivated fields, roadsides and town water reservoirs, all with varied histories of exposure to herbicides. There was a clear difference in the sensitivity of flaxleaf fleabane population that had previous exposure to herbicides, compared to those that didn't (Figure 6). Some of these populations have since been confirmed as being resistant.

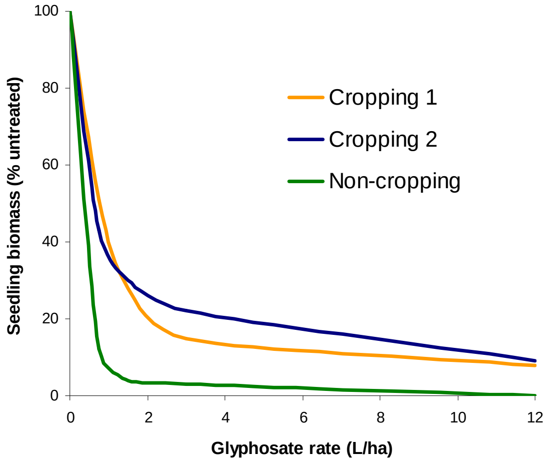

Figure 6. *Decreased response to glyphosate of flaxleaf fleabane populations from cropping backgrounds.*

A further experiment compared the effectiveness of the double-knock tactic on two populations with different herbicide histories. The population from the cropping background was found to be less sensitive to a mix of glyphosate + 2,4-D in addition to being less sensitive to glyphosate (Figure 7). However, using the double-knock tactic still proved to be effective on both populations. When the first application contained glyphosate and 2,4-D, total control was achieved. This further highlights the importance of employing the double-knock tactic in managing flaxleaf fleabane.

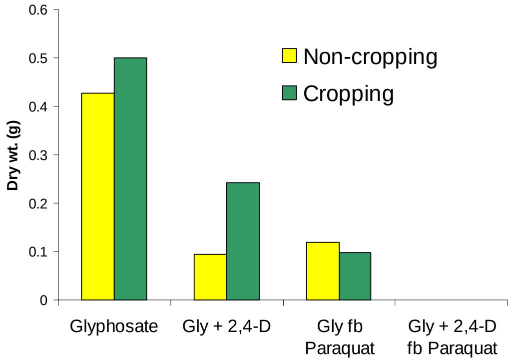

Figure 7. *Response of flaxleaf fleabane populations from non-cropping and cropping areas to glyphosate, 2,4-D and "double-knock".*

Farm hygiene

Controlling flaxleaf fleabane on non-crop areas, such as beside fields, roadsides, irrigation channels and fence lines, is very important as fleabane is easily spread by wind and water. The double-knock tactic can be used effectively in these areas, although it is still important to taget small weeds as larger plants are difficult to control and even the double-knock struggles to control these plants.

A number of residual herbicides have also been trialled for controlling fleabane in non-crop areas, however, diuron was the most consistent of these.

Roadsides, irrigation channels and fence lines can be potential sources of fleabane infestation and must be included in a property-wide management program.

Summary

The success of fleabane in attributed to its ability to emerge in different seasons, relative tolerance to glyphosate and its prolific seeding. A long term, whole farm, integrated approach is needed for its effective control. Key management tactics include:

- close monitoring of seedling emergence flushes,
- controlling weeds when young to maximise herbicide performance,
- controlling survivors to prevent seed production and reduce the soil seed bank
- using a combination of pre- and post-emergent herbicides, cultivation and hand hoeing
- double-knock can be used for effective control and prevention of seed set,
- crop competition is another effective tool in winter cereals,
- an intense control program implemented for 2-3 years will have a major impact on reducing the seed bank, and
- controlling non-crop areas, such as roads, irrigation channels and fence lines, to prevent re-infestation into the crop.

An IWM plan needs to be implemented for the whole farm and crop rotation for effective management and prevention of resistance to herbicides.

Appendix 1.2

Managing glyphosate-resistant awnless barnyard grass

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Awnless barnyard grass (*Echinochloa colona*) is a common grass in cotton and grain growing regions. In recent surveys, awnless barnyard grass was found in over 40% of fields. It is an annual weed that emerges in multiple cohorts from late spring through until autumn. The largest cohort generally emerges with rain in late spring/early summer.

This small seeded species has a high fecundity, emerges in high numbers and is often exposed to glyphosate a number of times throughout spring and summer. These characteristics make it an ideal candidate for glyphosate resistance evolution.

Glyphosate resistance

At the time of writing there were almost 60 populations of glyphosate resistant awnless barnyard grass in northern NSW and southern Qld, including a population in northern Western Australia (Figure 1). Most of these are present in grains systems, however one was confirmed in the fallow phase of a non-irrigated Roundup Ready Flex cotton rotation.

The resistance level in these populations ranges from approximately 3-7 times the normal glyphosate use rate to achieve acceptable control.

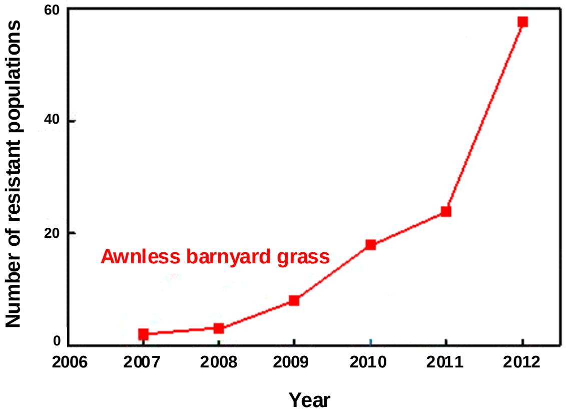

Figure 1. *Increase in the number of glyphosate resistance in awnless barnyard grass between 2007-12. Courtesy – Australian Glyphosate Resistance Working Group (www.glyphosateresistance.org.au)*

There are a number of factors that have resulted in the development of these glyphosate resistant populations. These are:

- Species characteristics of high seed production and emerging in dense populations
- Reliance on glyphosate for the majority of grass control
- Limited options for fallow control other than glyphosate
- Limited post-emergent options for control in crop

Surviving "resistant" awnless barnyard grass plant surrounded by dead "susceptible" plants.

The level of resistance that has been found in the cotton rotation is between three and four times the standard label rate. A dose response test of this showed a resistance level of three times the normal label rate (Figure 2).

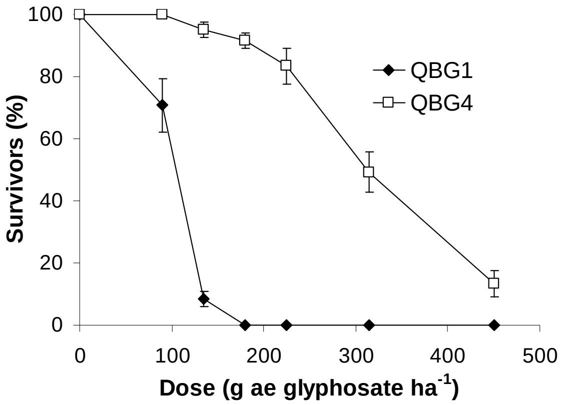

***Figure 2**. Dose response of "resistant" QBG4 compared to the known susceptible QBG1 barnyard grass population.*

The response of this population to glyphosate (Roundup Ready® herbicide) was also tested in the field (Figure 3). At the maximum in-crop rate of 1.5 kg/ha of Roundup Ready® herbicide there was still approximately 10% survival at a young age (4 leaf).

Awnless barnyard grass plants 14 days after glyphosate application. "QGB4" at back with yellow tags, 'QBG1" in front with red tags.

This indicates that while some level of control can be achieved at high rates on young plants, it is essential that glyphosate is not relied upon only for effective control, and alternatives are used.

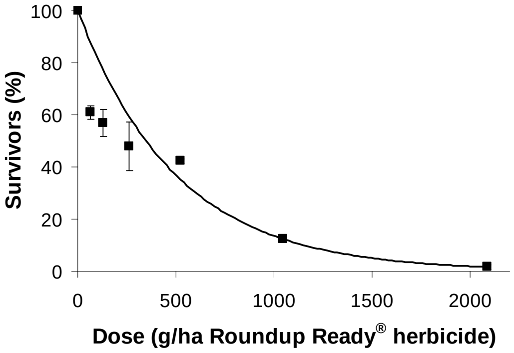

***Figure 3.** Field dose response of "resistant" QBG4 population sprayed at the 4-leaf growth stage,*

Tactics for glyphosate resistant populations

The key to managing glyphosate resistant populations and weeds in general is to reduce the seed bank. This can be done by both minimising the numbers that emerge, and preventing those that emerge from setting seed. This requires a combination of both pre- and post-emergent herbicides including the double knock tactic, tillage and crop competition.

Pre-emergent herbicides

A number of field and pots trials were conducted to determine if current residual herbicides used in cotton were still effective on glyphosate-resistant awnless barnyard grass. Results indicate that these herbicides are still effective at reducing the numbers of awnless barnyard grass emergences. In Table 1, results of one of field trials are shown. The most effective herbicides in this trial were pendimethalin, norflurazon and diuron. Metolachlor and Convoy were effective initially, however their persistence declined at 65 days after treatment. Norflurazon (Zoliar® DF) is registered at 2.3 to 2.8 kg/ha for barnyard grass so control should be improved at the label rate.

Table 1. *Number of emerged "resistant" awnless barnyard grass plants in the field after residual herbicide application at 30 and 65 days after treatment (DAT).*

Herbicide	Plants/m^2	
	30 DAT	65 DAT
Nil	80.7	88.9
Trifluralin 2.3 L/ha	72.7	79.6
Metolachlor* 2 L/ha	14.9	23.9
Pendimethalin 3.3 L/ha	6.5	6.8
Norflurazon 1 kg/ha	3.6	7.7
Norflurazon 1.5 kg/ha	5.6	6.8
Convoy† 2.9 kg/ha	18.5	38.5
Diuron 2 kg/ha	3.5	13.6

*Metolachlor formulation was Bouncer® (720 g/L metolachlor)
†Convoy (440 g/kg fluometuron + 440 g/kg prometryn)

The field experiment was repeated in pots in "ideal" conditions to gain a better understanding of the persistence of these herbicides on awnless barnyard grass (Figure 4). In this experiment, soil was sprayed with the respective herbicide and seeds were mixed into the top 2 cm of soil to ensure sufficient incorporation of the herbicides. At intervals of approximately 30 days, additional seeds were mixed into the top 2 cm of soil to determine herbicide persistence.

In general, the herbicides performed similar to that of the field trial with the exception of trifluralin. This much improved trifluralin result was due to much better incorporation of the herbicide. The difference between the trifluralin results in the two experiments highlights both the importance of appropriate incorporation of residual herbicides, and the variability in efficacy that can occur. Residual herbicides play and important role in reducing the numbers of weeds that are exposed to post-emergent applications. However, for effective overall control, residual herbicides should not be relied upon alone.

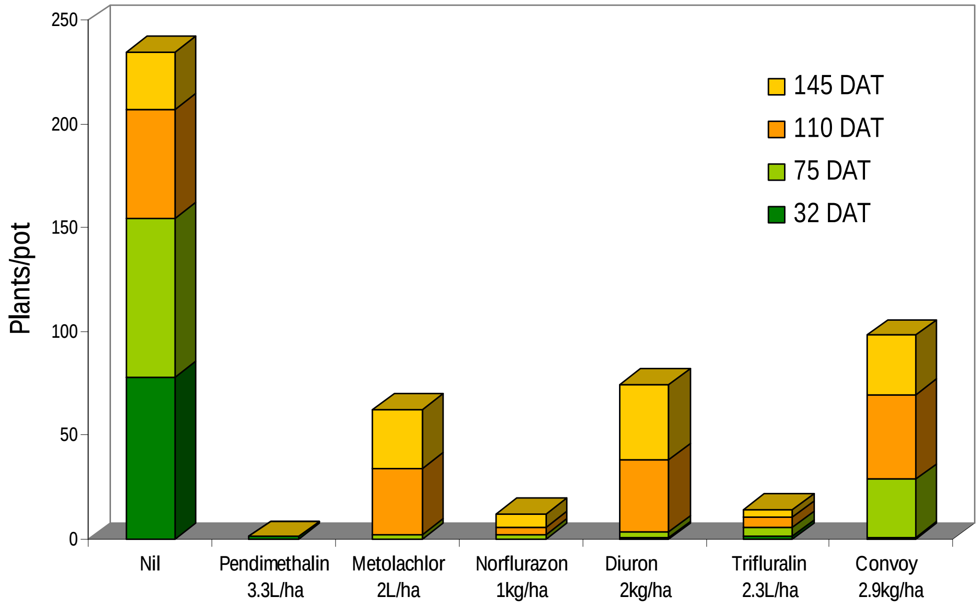

Figure 4. *Numbers of emerged "resistant" awnless barnyard grass plants in pots after residual herbicide application. 100 awnless barnyard grass seeds were mixed into the top 2cm of soil at 0, 31, 73 and 111 days after treatment (DAT) respectively for a total of 400 seeds per pot.*

Post emergent herbicides

A list of registered pre- and post-emergent herbicides that are registered for awnless barnyard grass control in cotton and rotation crops is contained in Table 2. Trials on a glyphosate-resistant population near Bellata showed that post-emergent herbicides are still effective in controlling glyphosate-resistant populations (Table 3).

Table 3. *Control of glyphosate-resistant awnless barnyard grass near Bellata. Plants were sprayed at 2 leaf to 3-4 tillers.*

Herbicide	% Weed kill
Verdict 150mL/ha	96.9
Fusliade 1L/ha	95.8
Factor 180 g/ha	90.3
Sertin 1 L/ha	88
Select 375 mL/ha	86.5
Raptor* 50 g/ha	76.3
Spinnaker† 140 g/ha	77.4

*Raptor has at least a 10 month plant back to cotton (see label).
†Spinnaker has at least a 22 month plant back to cotton (see label).

A recent trial (Table 4) has shown commonly used herbicides in cotton to be also effective on glyphosate-resistant awnless barnyard grass. Herbicides were trialled both alone and as part of a double knock with paraquat or glufosinate (Basta®).

As stated earlier, the key to managing glyphosate resistant populations is to prevent seed production. This is why the double knock is important in controlling survivors of the first herbicide application.

Table 4. *Percent dry matter reduction on tillered glyphosate-resistant awnless barnyard grass plants. Double knock treatments were applied 7 days after the initial knock.*

Initial knock	Second knock	% Dry matter reduction
Nil		0
Verdict 150 mL/ha + Uptake 500 mL/100 L		96
Verdict 150 mL/ha + Uptake 500 mL/100 L	Paraquat 2 L/ha	100
Verdict 150 mL/ha + Uptake 500 mL/100 L	Basta 3.5 L/ha	100
Sequence 375 mL/ha + Bonza 1 L/100 L		99
Sequence 375 mL/ha + Bonza 1 L/100 L	Paraquat 2 L/ha	100
Prometryn 2.5 L/ha + Activator 100 mL/100 L		86
Prometryn 2.5 L/ha + Activator 100 mL/100 L	Paraquat 2 L/ha	100
Paraquat 2 L/ha		100
Paraquat 2 L/ha	Paraquat 2 L/ha	100
Alliance 3 L/ha	Paraquat 2 L/ha	100

Management in other crops and fallow

Management of weeds and glyphosate-resistant populations is best achieved in the whole rotation. The use of other crops and the fallow provide opportunities for different chemistry that can’t be used in the cotton crop.

A systems trial conducted by NSW DPI on a glyphosate-resistant awnless population at Bellata showed the effectiveness of utilising the double knock, residuals and post-emergent herbicides in sorghum and in mungbeans the following year (Table 5). Where glyphosate was used alone prior to sorghum planting, the population remained uncontrolled. The addition of Dual Gold and Atrazine plus inter-row shielded sprays or cultivation were able to reduce emergences in the sorghum. When Primextra Gold is used at rates of 3.2 L/ha or less there is a 6 month plant back to cotton, so this is a definite option that should not prevent a cotton crop being planted the following year.

All treatments in the mungbeans crop were effective at reducing the awnless barnyard grass population, however plant backs to cotton are at least 22 months (refer to label). The use of Group A herbicides in pulse crops and cotton can be effective for awnless barnyard grass control. However, Group A’s have a high resistance risk and should not be relied on as the sole alternative to glyphosate.

Table 5. *Effect of various strategies on a glyphosate-resistant population in a systems experiment with sorghum followed by mungbeans.*

Year 1 - Sorghum crop	Plants/m^2	Year 2 - Mungbean crop	Plants/m^2
DK* + Dual Gold 2 L/ha + inter-row paraquat 3L/ha	0.28	DK + Spinnaker 400 mL/ha + Treflan 1.7 L/ha + Verdict 100 ml/ha	0.07
DK + Dual Gold 2 L/ha + inter-row cultivation	0.19	DK + Spinnaker 400 mL/ha + Treflan 1.7 L/ha + Verdict 100 ml/ha	0.03
DK + Primextra Gold 3.2 L/ha	1.68	DK + Spinnaker 400 mL/ha + Stomp 3 L/ha + Verdict 100 ml/ha	0.04
DK + Primextra Gold 3.2 L/ha + inter-row paraquat 3 L/ha	0.71	DK + Spinnaker 400 mL/ha + Stomp 3 L/ha + Verdict 100 ml/ha	0.2
DK + atrazine 3 L/ha fb atrazine 3 L/ha	2.02	DK + Spinnaker 400 mL/ha + Treflan 1.7 L/ha + Chip + Verdict 100 ml/ha	0
Control (glyphosate 1.5 L/ha pre-plant)	7.81	DK + Spinnaker 400 mL/ha + Verdict 100 ml/ha	0.01

*DK refers to double knock treatment of glyphosate 450 at 1.5 L/ha fb paraquat at 2.4 L/ha

The use of Group A herbicides in summer pulses is highly effective. But it is considered a high risk tactic for developing Group A resistance [Photo: T. Cook].

Research by NSW DPI also investigated the effect of residual herbicides in fallow on reducing awnless barnyard grass emergence (Table 6). Combinations of metolachlor and Atrazine separately and combined (Primextra Gold) proved effective as they did in sorghum. Flame (imazapic) was also effective, however has considerable plant backs to cotton (10 months with over 550mm rainfall for dryland, 24 months for irrigated; refer to label).

Table 6. *Residual herbicide control of glyphosate-resistant awnless barnyard grass in fallow at Bellata in November 2007.*

Herbicide	% Weed kill 1st flush (31 DAT)	 Later flushes (91 DAT)
Primextra Gold 2L/ha	95.7	98
Primextra Gold 4L/ha	99.8	99
Atrazine (500 g/L) 2 L/ha	95.1	93
Atrazine (500 g/L) 4 L/ha	99.6	98
Flame 200 mL/ha	82.1	99
Dual Gold 2 L/ha	81.5	99
Spinnaker 700WG 140 g/ha	87.9	97
Stomp Xtra 3.3 L/ha	66.4	62

Non-herbicide options

The pressure on herbicides to provide the majority of weed control can be reduced by utilising non-herbicide options where possible. This can be done in a number of ways including altering planting times, encouraging crop competition, cultivation and chipping and spot spraying. These can also be used in conjunction with herbicides to enable them to be more effective.

The flexibility of planting time and plant populations is somewhat limited in cotton. However, crop competition can be utilised in irrigated cotton, and to some extent in dryland cotton with narrower configurations by the use of weed free periods.

The trial in Figure 5 examined the competitive ability of cotton on reducing seed production in barnyard grass (*Echinochloa crus-galli*). Three barnyard grass planting times were included, at the same time cotton was planted, 4 weeks later and 8 weeks later. Barnyard grass that was planted when the cotton was 4 weeks old produced less than half the seed of those planted at the same time. However those planted when the cotton was 8 weeks old received very little light and had to compete for nutrients with well established cotton plants. As a result they produced virtually no seed. Starting clean and giving the crop a head start on weeds can have a considerable impact on weed management, reducing the reliance on herbicides.

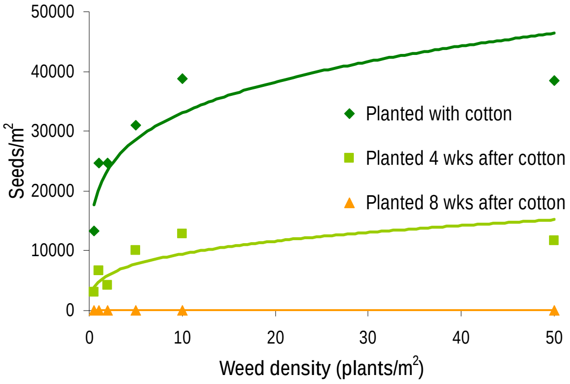

Figure 5. *Seed production of barnyard grass (E. crus-galli) with respect to time of cotton planting.*

Long term resistance prevention and management

When glyphosate is used alone in crop and fallows, resistance is expected to develop in 11-15 years for dryland and irrigated RF cotton respectively. In, fact as stated earlier we are already seeing evidence of glyphosate resistance populations now.

Simulations have shown that glyphosate resistance can be significantly delayed an even prevented by adopting some key practices:

1. Using IWM practices in fallows, rather than glyphosate alone. These include residual herbicides, and using the double knock tactic on large awnless barnyard grass cohorts (Figure 6 A and B).
2. Controlling survivors of glyphosate applications to prevent seed set and possible return of resistant material to the seed bank (Figure 6A).
3. Combining in-crop alternatives such as pre-emergent herbicides with interrow cultivation or other post-emergent herbicides (Figure 6B)

Irrigated crops have a considerable advantage over dryland crops due to a number of factors. Firstly, crop competition is generally higher in irrigated crops. When crops get a head start on weeds they can significantly reduce the seed production of weed species by competing for nutrients and light as was illustrated in Figure 5.

More importantly, in irrigated systems as they are simulated in the model, there are no summer fallows, so the in-crop weed control strategy (which typically contains both glyphosate and non-glyphosate tactics) is used every summer. This means that on average, more barnyard grass cohorts are affected by non-glyphosate actions in irrigated systems than in lower-input, more glyphosate-reliant dryland systems.

Dryland systems can be similar to irrigated systems in terms of preventing or delaying resistance, but it requires planning and commitment to diverse weed control in summer fallows.

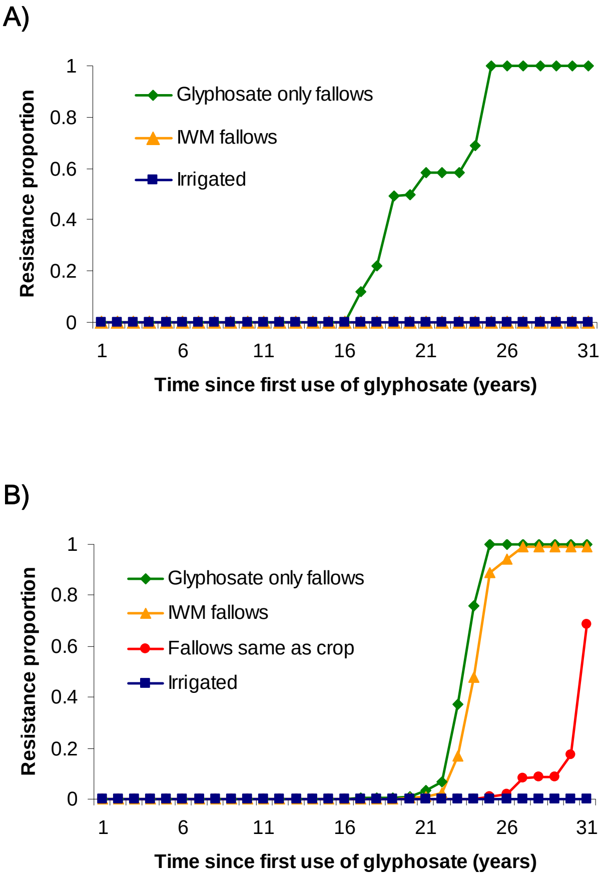

Figure 6. *Timeframe for resistance development in continuous glyphosate-resistant cotton (every 2nd year for dryland, every year for irrigated) with, A) glyphosate survivors controlled after every application at 99.9% efficacy, and B) a pre-plant residual plus a layby plus one inter-row tillage in crop. "IWM fallows" consist of a residual herbicide with a double knock (glyphosate followed by paraquat) on the largest awnless barnyard grass cohort.*

What if resistance is already present?

Unlike ryegrass, awnless barnyard grass plants only cross with other surrounding awnless barnyard grass plants in very small proportions, so the glyphosate resistance genes will remain in the population for the life of the seed bank. In ideal conditions where all resistant plants are controlled and no there is no seed bank replenishment, current research indicates that the seeds will remain viable in the soil for at least six or more years. In practice, it is likely there will always be some seed bank replenishment and therefore resistance will continue to remain (Figure 7).

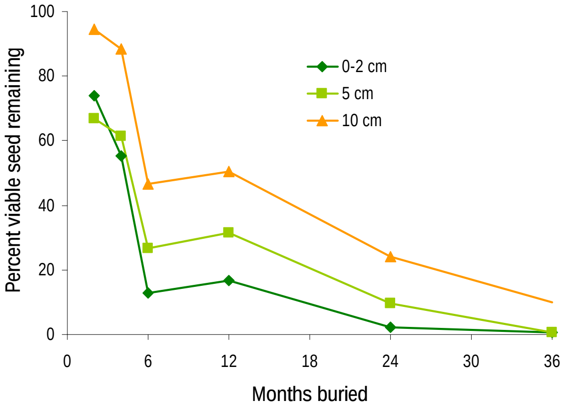

Figure 7. *Persistence of awnless barnyard grass in the soil. As depth increases seed persistence also increases. After 3 years only 0.5% left on the surface remained viable.*

However, simulations show that glyphosate resistant populations can be managed, with the same strategies used to prevent or delay resistance, and this will drive down the seed bank to manageable levels.

The effect of resistance management strategies on the seed bank are illustrated in Table 7. The starting scenario of the simulations consisted of 50% of the awnless barnyard grass population being glyphosate resistant. At this level, resistance would be identifiable in the field, and remedial measures would then be taken. Over a 30 year period when glyphosate was continued to be used alone, the seed bank exploded out to over 2600 and 3500 seeds/m^2 in dryland and irrigated fields respectively. As the intensity of in-crop glyphosate alternatives were used, combined with residual and double knock use in the fallow the seed bank declines to less and 1 plant every 2m^2 in dryland, and almost nothing in irrigated scenarios.

These scenarios show that although the remaining seeds/plants are glyphosate resistant, using glyphosate alternatives regularly results in small populations that are much more easily managed.

Table 5. *Simulated effect of management strategies on the glyphosate resistant awnless barnyard grass seed bank density over 30 years. All dryland scenarios consist of a fallow every 2nd year that includes an early season fallow residual herbicide with a double knock (glyphosate followed by paraquat) on the largest awnless barnyard grass cohort.*

	Seed bank density (seeds/m^2)		
	Glyphosate* only	Gly* + pre-plant residual + interrow cultivation	Gly* + pre-plant and layby residual + 2 interrow cultivations
Irrigated *(RF cotton every year)*			
Year 1	52	52	52
5	225	0.5	0.2
10	2453	1.02	0.01
Average (years 20-31)	2602	0.007	0
Dryland *(RF cotton every 2nd year)*			
Year 1	52	52	52
5	2057	2.9	0.4
10	3944	79	6.8
Average (years 20-31)	3528	445	0.3

*All scenarios consisted of 3 glyphosate applications in-crop ± additional control tactics

Summary

Glyphosate-resistant awnless barnyard grass populations are now present in cotton growing regions. Typically the level of resistance in these populations ranges from 3-7 times the normal glyphosate use rate.

Factors that contribute to glyphosate resistance development are:

- Species with high seed production emerging in dense populations
- Reliance on glyphosate for the majority of grass control
- Limited use of alternatives for grass control in crop and fallow

Tactics such as pre- and post-emergent herbicides, double knock, cultivation and crop competition are effective in managing glyphosate resistant populations.

Glyphosate resistance will last as long as resistance seeds are present in the seed bank.

Long term resistant prevention and management strategies should include:

- Using IWM practices in fallow rather than glyphosate alone
- Controlling survivors of glyphosate application to prevent seed set
- Combining in-crop alternatives such as pre- and post-emergent herbicides and interrow cultivation

Table 2. *Registered herbicide options (other than glyphosate) for controlling awnless barnyard grass in crop and fallow.*

Tactic	MOA	Active	Product	Fallow	Cotton	Sorghum	Sunflowers	Soybeans	Maize	Mungbeans
Pre-plant / Fallow knockdown herbicides	L	Paraquat		✓						
	L	Paraquat+Diquat	Spray.Seed	✓						
	L+Q	Paraquat+Amitrole	Alliance	✓						
Pre-emergent herbicides	B	Imazapic	Flame	✓						
	B	Imazethapyr	Spinnaker					✓		✓
	C	Atrazine				✓			✓	
	C	Diuron			✓					
	C	Prometryn			✓					
	C	Fluometuron			✓					
	C	Fluometuron+prometryn	Convoy		✓					
	D	Trifluralin			✓		✓	✓		✓
	D	Pendimethalin	Stomp		✓		✓	✓	✓	✓
	D	Chlorthal-dimethyl	Dacthal		✓					
	F	Norflurazon	Zoliar		✓					
	J	EPTC	Eptam				✓		✓	
	K	Metolachlor			✓	✓	✓	✓	✓	✓
	K	Propachlor	Ramrod			✓			✓	
	C+K	Atrazine+Metolachlor	Primextra Gold			✓			✓	
Mid-season residual herbicides	C	Fluometuron			✓					
	C	Prometryn			✓					
	C	Fluometuron+prometryn	Convoy		✓					
Post-emergent selective herbicides	A	Haloxyfop	Verdict		✓		✓	✓		✓
	A	Clethodim	Sequence		✓			✓		✓
	A	Butroxydim	Factor		✓		✓	✓		✓
	A	Sethoxydim	Sertin		✓		✓	✓		
	A	Fluazifop	Fusilade		✓		✓			
	A	Propaquizafop	Correct		✓		✓			
	A	Quizalofop	Leopard				✓	✓		✓
	B	Imazamox	Raptor					✓		✓
	B	Imazethapyr	Spinnaker					✓		
	C	Atrazine				✓			✓	

Appendix 1.3

MANAGING FEATHERTOP RHODES GRASS IN COTTON

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Queensland Alliance for Agriculture and Food Innovation)**

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Feathertop Rhodes grass (*Chloris virgata*) is becoming increasingly prevalent in cropping systems in the northern region. This species is already a major problem in central Queensland. This is largely due to an apparent tolerance to glyphosate, combined with minimum and no-till, glyphosate based cropping systems.

In the past feathertop Rhodes grass was considered a very minor weed. As a result, this weed appears only on the labels of clethodim (Sequence®) and butroxydim (Factor®), both which are registered for use in cotton. Recently, a minor use permit for Verdict® pre-plant to mungbeans as part of a double knock with paraquat was released. This permit is current until 31st August 2016.

Feathertop Rhodes grass is a member of the genus *Chloris*. Other *Chloris* species that are found in cotton growing regions are *Chloris truncata* (Windmill grass) and perhaps the most well known *Chloris gayana* (Rhodes grass), a common pasture species. Windmill grass is also becoming a major weed problem in grains systems in southern NSW.

The plant

Feathertop Rhodes grass is an annual grass capable of producing over six thousand seeds per plant. It generally emerges in the warmer months of spring, summer and autumn, however in central Queensland it is able to emerge nearly year round. Trials conducted in CQ at the end of summer showed emergences throughout summer, autumn and winter (Figure 1). Being an annual, the key to managing this weed lies in the seed and seed bank.

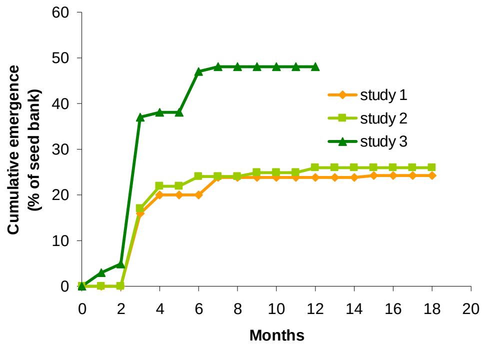

Figure 1. *Cumulative in-field emergence of feathertop Rhodes grass from seed buried in the top 2cm of soil in three separate studies. All studies started at the end of summer.*

Research has shown that seed appears to be relatively short lived regardless of burial depth in the soil. Studies in central Queensland showed that no recovered seed could be germinated after 12 months burial in the soil (Figure 2). This suggests that intensive control to stop seed set for a couple of years will have a major impact on reducing the seed bank. This is now being investigated under southern Queensland growing conditions.

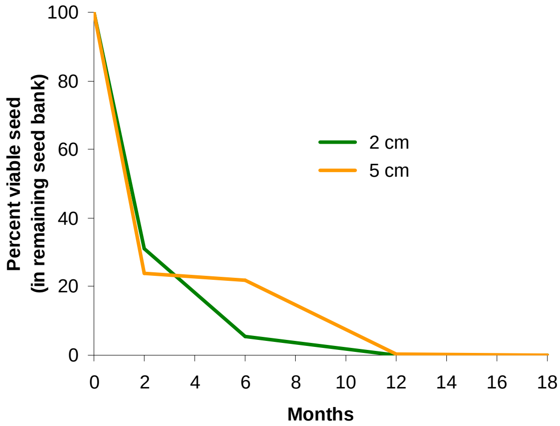

Figure 2. *Feathertop seed bank viability over time in central Queensland*

Feathertop seed responds quickly to small amounts of rainfall. An experiment conducted in controlled conditions examining the effect of rainfall amount on emergence showed that seeds germinated following 10mm of accumulated rain (Figure 3). Another experiment had feathertop emergences following as little as 5mm of rain. Some emergences occurred within two days of rainfall, which was considerably faster than other species in the experiment. The numbers emerging increased significantly with increasing rainfall with over 60-75% emergence following 30mm rain.

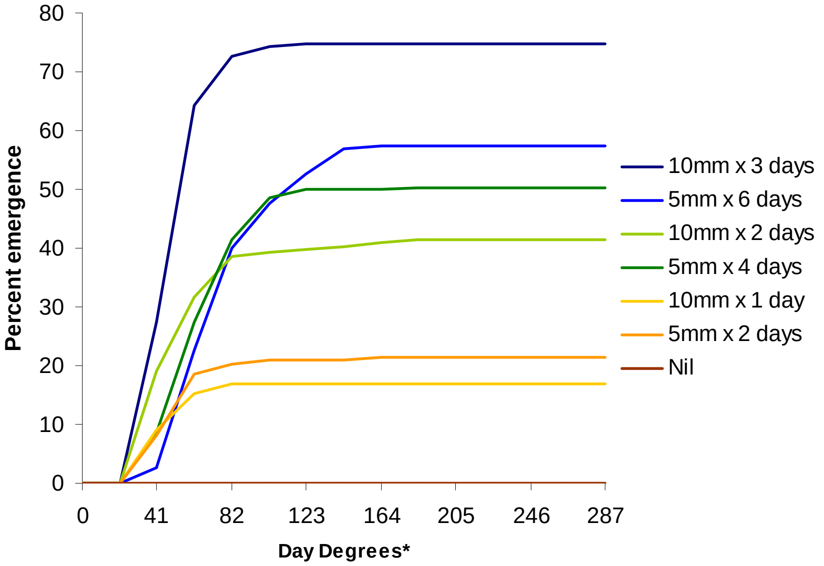

Figure 3. *Cumulative emergence of feathertop Rhodes grass in response to rainfall treatments. *Base temperatures for day degrees calculations were based on Chloris gayana (13°C).*

Strategies for managing feathertop Rhodes grass

Successful management of feathertop Rhodes grass requires a program centred on reducing replenishment of the seed bank.

A number of components will be central to any feathertop management program. These include:

- monitoring for seedling emergence,
- using a diversity of residual and post-emergent herbicides and cultivation, and
- preventing survivors from setting seed.

Peak flushes of feathertop Rhodes grass emerging in close proximity to the mother plant.

Monitoring seedling emergence

As with all species, feathertop is much easier to control when it is in the seedling stage. It is likely to emerge throughout the warmer months even with smaller rainfall events. Therefore control tactics are best aimed at reducing emergences and targeting seedlings.

Reducing emergences

Pre-emergent herbicides

Pre-emergent residual herbicides play an important role in reducing the numbers of seedlings emerging. This reduces the number exposed to post-emergent herbicides and therefore reduces the risk of resistance evolution.

Currently the only registered residual herbicide for use in cropping situation is isoxaflutole (Balance®) in fallow situations at 100 g/ha. However, when using residual herbicides for other species such as awnless barnyard grass recent trials indicate that effective levels of control can be achieved.

Data collected from a number of trials in central and southern Queensland is shown in Table 1. Feathertop can emerge late in winter crops, making it difficult to control in the following fallow after harvest. Research is investigating options for controlling these spring flushes using residual herbicides. A recent trial conducted by the Northern Grower Alliance (NGA) included a number of residual herbicides registered for use in wheat (Table 2). They conducted trials across four sites with a range of responses due to climatic variations. In a number of situations, effective control of feathertop was able to be achieved. A number of these herbicides can be used in cotton crops and rotations.

Table 1. *Residual control of feathertop Rhodes grass approximately one month after application (Source: DAFFQ 2010, NGA 2011, GSCQ 2009-10).*

Herbicide	Rates (ha)	Control (%)	
		Average	Range (n)
Flame	0.15-0.2L	80	5 – 100 (10)
Dual Gold	2L	89	75 – 98 (6)
Atrazine	1.25-2kg	65	20 – 100 (8)
Atrazine+ Dual Gold	3.2L	95	80 – 100 (10)

Fallow paddock heavily infested with feathertop Rhodes grass. Chemical control at this growth stage can be ineffective. (Photo: R. Collins, DAFF)

Table 2. *Residual control of feathertop Rhodes grass in wheat, approximately 3 months after application as incorporated by sowing or post-sowing pre-emergent (Source: NGA 2012)*

Herbicide (MOA)	Rate (mL or g/ha)	Control (%) at wheat harvest			
		Site 1	Site 2	Site 3	Site 4
Incorporated by sowing					
Sakura (K)	118	100	99	46	57
Sakura + Glean (K+B)	118+20	100	100	86	53
Logran (B)	35	89	13	0	34
Boxer Gold (J+K)	2500	95	96	0	48
Avadex Xtra (J)	1600	100	62	0	0
Treflan (D)	2000	97	98	97	58
Stomp 440 (D)	2500	100	74	99	5
Post-plant pre-emergent					
Glean (B)	20	100	0	20	38
Balance (H)	100	100	100	8	63
Balance + Simazine 900 (H+C)	100+883	100	100	0	83
Simazine 900 (C)	2200	0	0	0	0
Terbyne (C)	1400	79	0	18	14
Balance + Terbyne (H+C)	100+1000	100	100	42	0

Tillage

Feathertop Rhodes grass seed is small and therefore unable to emerge successfully when buried. This makes tillage an important option for reducing seedling emergence. A recent trial by DAFFQ demonstrated the effect of tillage on feathertop emergence (Figure 4).

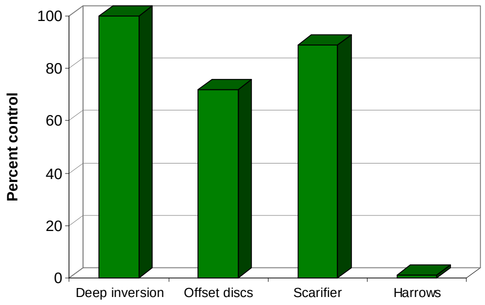

Figure 4. *Impact of different tillage types, some with residual herbicides included, on the control of feathertop Rhodes grass 9 months after application (and after > 200 mm total rain received during the period).*

Tillage operations that bury the seed prevented almost all emergences. Seed burial below 5 cm will place the seed too deep for germination. Lighter tillage operations such as harrows and Kelly chains will do little to minimise emergences, however they can be used to stimulate emergences to facilitate peak flushes, to which control tactics such as the double knock can be applied. This practice can be very effective at driving down the seed bank.

Post-emergent options

As mentioned earlier there are some group A herbicides that are registered for use in cotton. These are clethodim (Sequence®) and butroxydim (Factor®). Haloxyfop (Verdict®) is registered for use in cotton, but not specifically on feathertop Rhodes grass. Haloxyfop has recently been registered for pre-plant use in mungbeans in conjunction with a double knock with paraquat. Also there is a permit for using these products in fallow with a weed detector.

Tables 3 and 4 show results of post-emergent herbicides on feathertop control. As can be seen from Table 3, it is not controlled well by glyphosate alone.

Table 3. *Control of feathertop Rhodes grass when treated at seedling, mid-tillering and mature stages (Source: GSCQ 2011-12)*

Herbicide (MOA)	Control (%)						
	Seedling			*Mid-tillering*		*Mature*	
Rate (ha)	Site A	Site B	Site C	Site D	Site E	Site F	Site G
Roundup Powermax 1L (M)	48	28	30	69	9	0	6
Roundup Powermax 2L (M)	74	60	59	94	5	0	4
Roundup Powermax 4L (M)	86	88	96	99	13	5	6
Verdict 150mL (A)	91	92	98	44	36	48	23
Verdict 300mL (A)	100	99	100	44	60	49	45
Verdict 400mL (A)	100	99	100	70	68	96	78
DAT	*38*	*21*	*38*	*22*	*35*	*49*	*35*

Table 4. *Control of seedling and mature feathertop Rhodes grass with different Group A products at three field sites (Source: NGA 2010)*

Herbicide (MOA)	Seedling control (%)		Mature plant control (%)
Rate (ha)	Site A	Site B	Site C
Verdict 150mL + Uptake (A)	100	81	
Verdict 300mL+ Uptake (A)	100	99	
Verdict 500mL+ Uptake (A)			34
Glyphosate CT 2L + Liase / LI700 (M)	60	0	45
Glyphosate CT 4L + Liase / LI700 (M)	71	60	80

It is also important to note the decline in control as feathertop age and size increase. For example, in Table 3, Verdict was able to provide consistent control of feathertop on seedlings, as plants reached mid-tillering and maturity, both the efficacy and consistency of control across sites declined dramatically. Control of mid-tillering plants was affected by rate and conditions at spraying. It is also important to note the heavy reliance on group A herbicides: this group of herbicides has a high risk for resistance.

Double knock strategies

Using the double knock tactic is one way to minimise the risk of resistance development, and provide improved control of seedlings and older plants. Table 5 shows a trial conducted by NGA on the effect of applying paraquat in a double knock at different intervals to seedling feathertop. In these trials timing of the second knock largely didn't affect the level of control achieved. However, it is important to note the reduced control when glyphosate was applied as the first knock. The tolerance of feathertop to glyphosate was illustrated when a double knock was not applied; this indicates that when paraquat was applied it was providing most of the control. If this practice was to continue over several generations/seasons, the risk of paraquat resistance would become high.

When plants pass seedling stage, the double knock is the best herbicidal option for control. A glasshouse experiment on plants that were mid-late tillering (Table 6) showed that applications of Verdict followed by Sprayseed® provided good control of older feathertop plants The effect of timing slightly differed between the two experiments however the results suggest that a window of 1-4 days between applications is effective. Once again, glyphosate proved to be a poor partner for providing effective control.

***Table 5.** Control of feathertop Rhodes grass with double-knock tactics (DK) when the second knock of Paraquat at 2L/ha is applied at different intervals at two field sites (Source: NGA 2012)*

First knock	Seedling control (%)				
	Site A				
Rate (ha)	-DK	+DK 3 days	+DK 7 days	+DK 16 days	+DK 19 days
Verdict 150mL	95	100	99	96	99
Glyphosate CT 4L	70	74	68	69	79
	Site B				
Rate (ha)	-DK	+DK 4 days	+DK 7 days	+DK 14 days	+DK 21 days
Verdict 150mL	93	100	100	100	100
Glyphosate CT 4L	31	26	76	100	52

***Table 6.** Efficacy of the double knock later-tillering plants in pots, when the second knock of Sprayseed at 1.2L/ha followed glyphosate or Verdict (at sub-lethal rates) at seven intervals (Source: QDAFF 2011-2013)*

First knock Rate (ha)	Weed biomass (g/pot) Interval between knocks (days)							
	-DK	1	2	4	7	10	14	21
	Pot experiment 1							
Glyphosate CT 400mL	6.8	8.9	6.3	2.7	0.3	4.9	4.5	7.7
Verdict 40mL	1.7	0	0	0	0	0	0	0.72
	Pot experiment 2							
Glyphosate CT 400mL	16.7	21.1	13.4	13.1	6.1	7.7	4.4	9.1
Verdict 40mL	4.3	0	0	0	1.4	2.2	1.7	2.8

Combining DK + residual

Adding a residual herbicide to paraquat when applying a double knock can be an effective way to get control of existing plants, and minimise further emergences. This is shown in Figure 5 where residual herbicides were added to paraquat. In this trial a combination of Dual Gold® had the greatest reduction in feathertop emergences. None of the residual herbicides appeared to be antagonistic when mixed with paraquat.

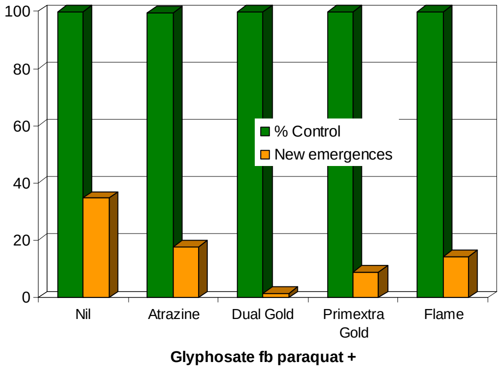

***Figure 5.** Effect on initial control and reduction in emergences in the next flush (plants/m²) from adding a residual herbicide to paraquat (Source: QDAFF)*

Double-knock (Group M herbicide followed 11 days later by Group L mixed with a Group B residual herbicide) in fallow on feathertop Rhodes grass (right) compared with untreated (left).

Summary

Feathertop Rhodes grass is poorly controlled by glyphosate and as a result is increasing in prevalence in cotton growing regions.

It is a small-seeded annual species, so the key to management lies in managing the seed bank and preventing new seed from entering the soil.

This can best be achieved by:

- Utilising tillage and pre-emergent herbicides to reduce numbers of seedlings emerging
- Monitoring emergences and controlling seedlings when they are small
- Using robust herbicides and rates and the double knock tactic to control plants and prevent seed set

Feathertop Rhodes grass seeds have a relatively short life compared to other species, so intensive management for up to two years can have a major impact on driving down the seed bank.