HERBICIDE RESISTANCE AND THE CROP MANAGEMENT PLAN

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Background

For many years herbicide resistance has been the big issue in the winter cropping zones of South Australia and Western Australia but a relatively minor issue in the cotton area of NSW and Queensland. However, those days are gone, and glyphosate resistance is now a major issue for the whole of the northern farming system, threatening the viability of the more marginal areas.

This paper discusses the issue of glyphosate resistance and explains the value of the approach used in the Crop Management Plans of Roundup Ready and Liberty Link cotton for managing the development of resistance.

Introduction

One of the first questions I was asked 25 years ago when I started in the cotton industry was: "Do we have herbicide resistant weeds in the cotton industry yet?"

The answer at the time was a resounding "no", and we shouldn't get resistant weeds as long as we keep using a multi-input approach to weed management in cotton (an integrated weed management approach).

Unfortunately, 25 years later, this is no-longer the case, with glyphosate resistance rapidly becoming one of the biggest issues for the northern cropping system. Cotton is now being grown in a glyphosate centric system, where glyphosate has replaced nearly all the other weed management tools. There are glyphosate resistant weeds in the cereal component of the cotton farming system on most properties, and glyphosate resistant weeds are becoming increasingly common in the cotton component. While these resistance problems may not have been caused by the way weeds were managed in cotton, in the end it doesn't matter. The problem doesn't go away just because it was caused somewhere else in the system.

There are now 220 different weed species resistant to a herbicide somewhere in the world. Thirty six weed species have resistance in Australia, and while many of these are resistant to the high risk Group A and B[1] herbicides, there is resistance to nearly every herbicide group, including the groups that include our residual cotton herbicides and glyphosate. In WA and the US, resistance has even developed to 2,4-D (Group I), a herbicide very widely used since the 50's, which had never had a resistance problem anywhere in the world up until a couple of years ago. It just shows that if you push the system hard enough, resistance will eventually occur.

[1] Herbicides are grouped according to their mode of action. Group A & B herbicides are at high risk of developing resistance, Groups C to Z are at moderate risk. Resistance to any group is possible, regardless of the ranking.

In the cotton growing areas there are numerous instances of ryegrass and wild oats populations with resistance to Group A and B herbicides. We now also have glyphosate (Group M) resistant populations of:

- Annual ryegrass,
- Awnless barnyard grass,
- Liverseed grass,
- Windmill grass, and
- Flaxleaf fleabane.

We have also seen species shift to a number of glyphosate tolerant weeds that are becoming increasingly problematic in the cotton system. These weeds are not glyphosate resistant, but were never effectively controlled by glyphosate, making them equally problematic as resistant weeds. Top of the list of these weeds is:

- Feathertop Rhodes grass

So what causes the problems?

In a single word (or two): selection pressure. The more effective a product is, the more strongly it selects for resistant individuals. If a highly effective product is used often enough on enough individuals, eventually a resistant individual is likely to be encountered and selected (assuming that resistant individuals exist). This is the start of resistance.

A big unknown is the proportion of resistant individuals in the natural population. It is possible that no individuals resistant to a given herbicide exist in a weed population, but there is no way of knowing this. Unfortunately, experience is showing that individual weeds carrying a resistance gene occur in many weed populations, with resistance to a wide range of herbicides now common.

Selection pressure occurs every time a population is exposed to a herbicide. However, it is not simply a matter of how many times a herbicide is applied in a season, but of how many generations of a weed are selected and whether these generations are also being controlled by another input or inputs. The selection pressure is greatly reduced where a range of other inputs is also used on the same weed population (as commonly occurred in the traditional cotton system), as a resistant individual has to simultaneously develop resistance to more than one weed management tool in order to survive.

So, the selection pressure on glyphosate was not overly strong in the traditional weed management system where survivors from a glyphosate spray are normally controlled by cultivation, hand hoeing or a residual herbicide. However, the selection pressure in the glyphosate centric system that has evolved in the north is very strong, selecting for glyphosate resistant and glyphosate tolerant weeds.

Herbicide resistance in the cotton system

The traditional cotton system was a robust system for managing most weeds because it employed a range of weed management tools, including multiple applications of residual herbicides with different modes of action, cultivation, hand hoeing, cropping rotations etc. Few, if any, of the weed management inputs (herbicides, cultivation etc.) were 100% effective (most were less than 95% effective, giving low selection pressure), but the combined system was effective for most weeds. Any weeds which survived the multiple residual herbicide applications (and there were always a few survivors), were controlled by the cultivator, or if they escape this, by the hand hoeing crew, or the next cultivator and the next hand hoeing crew, or the next herbicide etc. Herbicide resistant weeds were unlikely to emerge in this system, as the system responded to any survivors by throwing yet another (different) management tool at them.

Unfortunately, this system had its drawbacks, including expense (in dollars, time, manpower, and soil moisture), undesirable off-target impacts of herbicides and unavoidable damage to the cotton crop. Twenty five years ago, many hand hoeing bills were in excess of $100/ha, with bills of up to $300/ha not uncommon (1990 dollars – so multiply the numbers by 2 or 3 to get today's dollars). These bills are not affordable in the current economic climate, even if the large chipping crews were still available, which they generally are not. These issues forced the weed management system to evolve over the years to one which is glyphosate centric, substituting glyphosate for residual and other contact herbicides, cultivation and hand hoeing.

The down-side with the widespread adoption of Roundup Ready Flex technology in the cotton system is that the system which has evolved relies very heavily on glyphosate in both the cotton and fallow phases, and in some instances, especially with dryland cotton, may be relying exclusively on glyphosate for the control of some weeds. This places very strong selection pressure on glyphosate and is a recipe for glyphosate resistance. Species shift is also an inevitable outcome of this glyphosate intensive system, which has selected for glyphosate-tolerant species. Many of the glyphosate tolerant species, such as rhyncho and emu foot, which were minor pests of the traditional cotton system, have increased in number in the glyphosate intensive system, slowly becoming significant weed problems. Ultimately, the density of these weeds will increase to the point that other weed management tools will have to be reintroduced to manage them.

So, how to maintain a glyphosate based system?

Selection in a glyphosate based system

A number of factors influence the genetic response to selection pressure, including the frequency of resistant genes, the plants reproductive characteristics, seed-bank longevity and the fitness of resistant individuals.

Resistance is not simply a factor of how many times a herbicide is applied in a season, but of how many generations of a weed are selected, the characteristics of the plant and whether other effective weed management tools are being used on the same generation/s.

There was relatively weak selection pressure on glyphosate in a traditional weed management system, where survivors from a glyphosate spray were controlled by cultivation, hand hoeing or another herbicide. However, the selection pressure on individual weed species may be stronger than it appeared to be at first glance. For example, nutgrass is a weed which is not well managed by the traditional weed management system, but can be effectively managed when glyphosate is added to the system. However, when it is only being controlled by the glyphosate component of the system, nutgrass is under intensive selection pressure from glyphosate in the traditional cotton system. Nutgrass would be under the same level of selection pressure in a Roundup Ready Flex crop, where it is again only being controlled by glyphosate. The additional residual herbicides, inter-row cultivation and hand hoeing in the traditional system are not controlling nutgrass, so they do not reduce the selection pressure on this weed. Fortunately, nutgrass is a very low risk weed which is unlikely to develop resistance to glyphosate. This is primarily because nutgrass predominantly reproduces vegetatively, producing 'clones' of itself, so that most, if not all, plants in a field are effectively from the same generation and genetically identical. Even plants in different years are likely to be from a single generation and genetically identical. Continual selection pressure with glyphosate is still only selecting from a single generation and so should not lead to resistance.

Some weeds are exposed to much stronger selection pressure in a Roundup Ready Flex system. A weed such as awnless barnyard grass, for example, was controlled to some extent by each of the residual herbicide inputs used in the traditional system. However, awnless barnyard grass could have 2 or 3 generations within a single season and each generation might be exposed to selection from glyphosate in a Roundup Ready Flex system. Consequently, this weed is at a high risk of developing resistance to glyphosate in this system and numerous examples of resistance have now been found.

Other weeds are at lower risk of developing resistance. The selection pressure on a weed such as Italian cockleburr (one of the Noogoora burr complex), is low in both traditional and Roundup Ready Flex systems. The selection pressure on Italian cocklebur in Roundup Ready Flex cotton, where three or four Roundup Ready Herbicide applications are made during the season, is no higher than the selection pressure where only one application is made. This is because all applications are made to the same generation of the weed (the burrs don't flower until late summer and autumn). Effectively, one late-season application to all burrs would impose the same selection pressure as four applications during the season, although the single application is not a practical option, as the weeds would be very large by this time, would have reduced crop yield and would be difficult to control. Traditional and Roundup Ready Flex systems, where surviving burrs are controlled by hand hoeing or spot-spraying, impose no effective selection pressure on this weed.

Starting the season with low weed numbers is an important component of the CMP with herbicide tolerant cotton varieties. High weed numbers necessitate multiple herbicides inputs and high selection pressure.

The importance of the crop management plan

Of the factors in the development of herbicide resistance, the one a farmer has the most control over is selection pressure. In order to reduce the selection pressure on a weed, it is essential that weeds which survive a herbicide are subsequently controlled by another (different) management tool before they set seed. If this is done, then there is effectively no selection pressure from the first herbicide.

This is the core principle of the crop management plans developed for Roundup Ready and Liberty Link cottons. These plans require that at least once a season, each field is assessed for weeds that have survived a herbicide application (the weed audit), and any survivors are controlled by a different tool (herbicide, cultivation or hand hoeing) before they set seed. Ideally, this would be done after each herbicide application and no surviving weeds would be allowed to set seed. While the requirements of the weed audit may seem onerous, it is a simple way to ensure that each crop is checked for surviving weeds at least once a season, and provides a valuable set of data to TIMS and the APVMA. Collective information over valleys and years provides a broad overview of the performance of these products and gives these bodies a basis for confidence in the application of these transgenic systems, as well as guidance on any issues which may arise.

In reality, good operators check the performance of each weed management input (and other inputs) throughout the season and rectify issues as they arise. The crop management plan provides a simple, auditable framework to facilitate this process.

A second factor the farmer has control over is the number of weeds in a field. This is important because as weed numbers increase in a field, the chance of a resistant individual being present also increases and the chance of the resistant individual surviving a herbicide application increases. This is why the crop management plans recommend entering a cropping phase with low weed numbers. It is statistically unlikely that any resistant individuals will be present in fields with low numbers of weeds.

Low weed numbers can be achieved in one of two ways. Firstly, low weed numbers can be the result of good weed management practices over a number of years. Weed surveys over the last 25 years have found that generally cotton fields have become cleaner, with fewer weeds over time. Fields with low weed numbers are ideally suited to the transgenic systems where residual herbicides are replaced by contact herbicides.

A second way of achieving low weed numbers is by retaining some residual herbicides in the system. Residual herbicides might be applied pre-planting or at-planting, or can be applied from around 6 – 8 nodes (15 cm of crop height) post-emergence. The type of residual herbicide and time of application can be tailored to meet the expected weed population. Inclusion of a residual grass herbicide, for example, is strongly recommended in fields which have a history of high grass numbers. Use of these residual herbicides is a simple and effective way of greatly reducing the numbers of weeds that have to be controlled by the post-emergence contact herbicides, reducing the selection pressure on these herbicides. In practice, if residual herbicides are not included at planting in fields with high weed numbers, post-emergence inputs, which will probably include residual herbicides, will be required to control survivors from the contact herbicides. Where high weed numbers are expected, it is simpler and more effective to apply the residual herbicides at planting.

Maintaining the whole glyphosate system

The biggest threat to the sustainability of the Roundup Ready system is the use of glyphosate in the rest of the farming system and failure to control survivors of glyphosate applications in fallows.

Where cotton is grown in a wheat rotation in an irrigated system, it is common for a field to be in fallow for nearly 12 months in every 24 month period. In this system, weeds in the fallow are commonly controlled with glyphosate, and the field may receive 5 or 6 applications (or even more) over the fallow period, especially where wheat stubble is retained. This places strong selection pressure on glyphosate, but can be addressed using the same approach of controlling any survivors of a glyphosate application using an alternative option before they set seed. This control input could be an alternative herbicide, such as Spray.Seed®, Alliance® or Amitrole T, cultivation or hand hoeing.

An approach increasingly commonly used is to follow a glyphosate application with a Spray.Seed application as a double-knock, with 5 to 7 days between the herbicide applications. This combination is effective for controlling small, annual weeds and the strategy is very effective for preventing resistance developing, provided that resistance to either of these herbicides has not already occurred. The double-knock strategy can be equally applied using a range of alternative management tools, such as cultivation, or other herbicides following closely after the glyphosate application.

One practice commonly used in the cotton system is to tank-mix an alternative herbicide such as 2,4-D with glyphosate applications made to fallows during winter. This may appear to be an effective way of reducing selection pressure on glyphosate, but has major limitations. Firstly, most weeds are seasonal and are more prolific in either the winter or summer. This is more so in the southern areas. Consequently, the spectrum of weeds exposed to the glyphosate/2,4-D combination will not necessarily be the same as the spectrum controlled by just glyphosate in the summer. Some weeds, which predominantly grow in summer, will not be exposed to 2,4-D and so are still under very strong selection pressure. Secondly, the reduction in selection pressure is only applied to broad-leaf weeds. Grass weeds are not controlled by 2,4-D, and so the addition of 2,4-D does not reduce the selection pressure on grasses. Thirdly, the mixture is normally used to achieve some synergism between the two products, increasing the spectrum of weeds controlled but with a reduction in the rate of glyphosate used. To be effective to reduce selection pressure, it is necessary that both products are used at rates that will kill the target weeds, so that if there is resistance to one product, the weed is still killed by the other product. Adding 2,4-D to a reduced rate of glyphosate will improve the spectrum of weeds controlled, but will not reduce the selection pressure on glyphosate.

Selection pressure can be even stronger in the dryland system, where cotton might only be grown every third year, with long fallow periods and little if any thorough cultivation. Glyphosate resistance is most likely to occur in these systems unless an alternative weed control input is used to control weeds which survive the glyphosate applications. The cases of awnless barnyard grass which have developed resistance to glyphosate in the cotton growing area have occurred in zero-tillage dryland farming systems where fallow weeds are being controlled by glyphosate year after year. Unless farmers are proactive in controlling weed survivors, it seems certain that glyphosate resistance will become a major problem in the dryland cotton farming system.

Glyphosate & the resistance spiral

With the increasing number and spread of glyphosate resistant weeds, the conservation farming system is rapidly falling apart. The system is no longer sustainable in the long-term or even the medium-term and failure to change our approach to weed management now will result in Australia joining a growing list of countries where glyphosate technology has already been effectively lost for many of their most troublesome weeds.

However, it doesn't just stop there. The loss of glyphosate for managing the worst weeds in many of these countries has been followed by the successive loss of the most useful alternative chemistries, with these herbicides also falling to resistance in rapid succession.

Much of the US cotton industry has gone from being a "magic" industry a decade ago, where all weeds were cheaply controlled by a couple of in-crop applications of glyphosate, back to a "slave' industry, where weeds are king, demanding heavy inputs of expensive herbicides, inter-row cultivation and large amounts of hand-hoeing to manage them. In some instance, requiring levels of inputs that would make the Australian cotton industry economically unviable, with multiple herbicides, cultivation and hand-hoeing bills of over $1000/ha in Australian terms, just to produce a harvestable crop.

That the industry has selected for glyphosate tolerant and resistant weeds over the last decade it not surprising. However, the trap of the glyphosate centred system, is the assumption that problems can be solved by re-introducing single components of the conventional system to manage these resistant weeds. The approach of reintroducing components of the traditional weed management system to reduce the selection pressure on glyphosate is sound, but the approach is flawed if resistance to glyphosate has already occurred.

A pre-planting application of diuron, for example, is becoming widely used to manage glyphosate-resistant flaxleaf fleabane in Australia. After all, diuron was routinely used for over 30 years without any resistance issues to this herbicide emerging, so it seems like a good option. However, this thinking fails to recognise that diuron was not formally used alone but as one part of a whole system of residual herbicides and other tools, with the system often including diuron, trifluralin, fluometuron, pendimethalin, prometryn, inter-row cultivation and hand hoeing. To now expose glyphosate-resistant fleabane to diuron without any of the other tools is to place very high selection pressure on this weed, and is likely to see resistance emerge to diuron within only a few

years. The solution to resistant fleabane, is not to manage it with diuron, but to manage it with a range of manage tools, so that diuron is only one component of the system. Using a tank mix of diuron and Spray.Seed, for example, backed up with strategic cultivation and spot spraying with Amitrole as necessary is a much more sound approach that is likely to be sustainable in the longer-term.

Similarly, using a double-knock in fallows with glyphosate followed by Spray.Seed is a useful strategy for controlling some of the more difficult weeds. However, it is only effective as long as both glyphosate and Spray.Seed are effective. Relying solely on Spray.Seed to control glyphosate resistant weeds is a recipe for developing Group L resistance. Relying on a Group A or B herbicide to control feathertop Rhodes grass is guaranteed to fail within a few years.

The need to develop an approach to weed management that is sustainable in economic terms, in environmental terms, and in functional terms is a far bigger challenge than it may at first appear. The adoption of a glyphosate centred system doesn't cut it, and can't be patched by just adding a 2nd herbicide to manage problem weeds. Persisting with a glyphosate centred system is a sure path to failure, with dire consequences, as the US industry is now proving, with many of the more problematic weeds in the US having multiple resistance often to 4 or 5 modes of herbicidal action.

Glyphosate resistant flaxleaf fleabane is now very common and in many cases, such as this, elimination is no longer an option. There has to be a change in the whole farm system to ensure it is managed.

Using Liberty Link® cotton

With the increasing number and spread of glyphosate resistant weeds, the idea of rotating to cotton varieties using the Liberty Link technology is looking increasingly attractive. Liberty Link technology, which allows the use of glufosinate over the top of the crop, allows cotton growers to rotate to a new mode of action herbicide, glufosinate, which is a Group N herbicide. Given that most fields have little or no history of Group N use, rotating to this group is a sound concept.

Glufosinate is effective on a wide range of broadleaf weeds, including some that are not well controlled by glyphosate. Foremost of these are the vines, cowvine and bellvine. Glufosinate is very effective on these two weeds, controlling quite large plants at label rates. Using glufosinate to manage the problem of species shift to glyphosate tolerant weeds is a sound strategy and should be the option of choice in many situations.

However, glufosinate is weak on most of the grasses, including the glyphosate resistant grasses. To manage glyphosate resistant grasses in a Liberty Link crop, it is essential that a residual grass herbicide be applied prior to or at planting, Liberty herbicide be applied only to small, actively growing grasses and a layby application may also be needed. Consequently, there is little advantage to using Liberty Link technology to manage glyphosate resistant grasses. Growers having problems with glyphosate resistant grasses may be better off by adding the grass herbicides and other inputs to the Roundup Ready Flex system and concentrate on managing the weeds in their existing system.

Living with glyphosate resistance

Eliminating small patches of glyphosate resistant weeds before they spread is always the best strategy for managing resistance. How this is done depends on the size of the patch and its location. Quarantining a small part of a field and effectively sterilizing the area for a couple of years may well be the best approach to managing an outbreak of resistance.

One of the advantages in the current scenario is that all the known glyphosate resistance weeds have short seed bank longevity and don't emerge from depth. Consequently, it is possible to eliminate any of these weeds from a field by preventing all seed set over a couple of seasons, provided there has been no seed burial through cultivation.

Cultivation is a useful tool for managing these weeds, as any seed buried in the soil is effectively removed from the gene pool, but buried seed can last for far longer than will seed that remains on the soil surface. If cultivation is used to bury the bulk of the seed, it is essential that there is no

further cultivation that would bring the seeds back to the surface.

If it is impractical to eliminate the resistant plants, such as with resistant fleabane that can blow in from a neighbouring field, then there has to be a change in the whole farm weed management approach to ensure these resistant weeds are effectively managed in the system.

At risk weeds

While herbicide resistance can develop in any species, some weed species are more at risk than others. The plant characteristics which contribute to the risk of developing resistance are: method of reproduction, plant frequency (how common the weed is), seed production rate and seed dormancy (seed-bank longevity). Plants at the highest risk are those which reproduce sexually, commonly occur at high densities, produce large numbers of seeds and have little or no seed dormancy (the seed dormancy can act like a refuge, diluting the population with older, non-resistant plants). Unfortunately, weeds such as awnless barnyard grass, common sowthistle and fleabane are already problematic in a glyphosate dominant system and are at high risk of developing resistance. These plants are often present at 10s or even 100s per m^2 early in the season, can produce thousands of seeds per plant and have little or no seed dormancy, with two or three generations possible each season.

Many of the weeds which are more problematic in the traditional cotton system and tend to get more attention by managers, such as thornapples and the burrs, are at much less risk of developing resistance. They are normally present at much lower densities (1 Italian cocklebur per m^2 would be a major infestation), produce fewer seeds (a few hundred per plant), have only one generation per year, and have strong seed dormancy, prolonging the effective generation period.

Consequently, managing a glyphosate dominant system requires a mind-shift, where the most important weeds become not just those that can individually cause the greatest yield reductions (such as thornapples), but those that have the greatest risk of developing resistance (such as awnless barnyard grass). Resistance in awnless barnyard grass, for example, would be a major nuisance in cotton, requiring a cotton grower to revert to a system which included a residual grass herbicide and regular inclusion of an alternative herbicide such as Spray.Seed in fallows. This would significantly increase the cost of weed control in the system. Resistant sowthistle would be even more expensive to manage, being very difficult to control in crop and in summer fallows without reverting to hormone sprays or other products which are themselves highly problematic.

The easiest way to manage herbicide resistance is to avoid it, but if resistance is suspected, it is vital that it is identified as soon as possible. Even the best farmer can end up with herbicide resistance due to the accidental introduction of a resistant seed or plant from an external source. Dirty headers, hay and grain are all likely potential sources of herbicide resistant weed seeds. Herbicide resistance has the potential to rapidly expand from a small problem in one field to a farm-wide problem within a season or two, and has no respect for farm boundaries.

Any cotton-grower suspecting herbicide resistance in a transgenic cotton crop is required to notify the respective technology provider immediately. This is a legal requirement under the crop management plan. The TIMS committee will also be notified to ensure that appropriate action is taken as soon as possible.

Herbicide resistance is a whole-season and whole-farm problem. High weed numbers in a rotation crop, such as this sorghum, are just as much a problem as if they were in cotton.

Plant characteristics that contribute to the risk of developing herbicide resistance.

Risk	Reproduction method	Frequency	Seed production	Seed dormancy	Examples
High risk	Sexual	Common	Large	Short	Awnless barnyard grass
Moderate risk	Sexual	Common	Small	Long	Thornapple
	Sexual	Uncommon	Large	Short	Tall sedge
Low risk	Sexual	Uncommon	Small	Long	Desert cowvine
	Vegetative				Nutgrass

Always ensure survivors of a glyphosate application are controlled using an alternative tool before they set seed. Starting the season with survivors from the fallow that are setting seed is a recipe for disaster.

Summary

The best way to manage herbicide resistance is to avoid it. Herbicide resistance can be avoided by following four simple rules.

- Always follow the Crop Management Plan. The core principle of this plan is to ensure crops are checked after herbicide applications and any surviving weeds are controlled using an alternative weed management tool before they set seed.
- Ensure at least one effective alternative weed management tool is used each season on all major weeds, especially those in the high-risk category. An inter-row cultivation, combined with a light hand hoeing, is a sound strategy for avoiding selecting for resistance in-crop. Alternatively, using a directed layby residual herbicide, incorporated with inter-row cultivation, may be equally effective, although a light hand hoeing may still be required to control larger weeds in the plant line.
- Adopt a double-knock or follow-up approach at least once a season for managing weeds in fallows.
- Always control weed escapes before they set seed