Managing herbicide resistance in cotton: the importance of the Crop Management Plan

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BACKGROUND

Many cotton growers are concerned that relying too heavily on Roundup (glyphosate) will lead to future problems with weeds becoming resistant to this herbicide. The potential for resistance is very real, as shown by the increasing resistance problems with Roundup Ready crops in the US, and emerging problems with glyphosate resistant ryegrass and awnless barnyard grass in the Australian cotton growing area.

This paper discusses these issues 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 twenty 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.

Unfortunately, 20 years later, this is no-longer the case. Cotton is now being grown with a rapidly shrinking array of weed management inputs. There are almost certainly herbicide resistant weeds in the cereal component of the cotton farming system on a number of properties, and probably also resistant weeds in the cotton component, somewhere in the industry, although they haven’t been detected yet. While these resistance problems may not have been caused by the way weeds are managed in cotton, in the end it doesn’t matter, the problem doesn’t go away just because it was caused somewhere else.

The stark reality of size of the herbicide resistance problem is brought home in an article by Werth and Thornby in these proceedings. There are now 185 different weed species resistant to a herbicide somewhere in the world. Thirty four weed species have resistance in Australia, and while most 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 in the plant. Group A & B herbicides are at high risk of developing resistance, Groups C to H are moderate risk, and groups I – Z are low 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 herbicides and ryegrass populations resistant to glyphosate (Group M). We now also have 2 confirmed awnless barnyard grass populations with resistance to glyphosate, with a 3rd suspected population and doubtless other populations yet to be detected. This season we had a suspected resistant awnless barnyard grass population in cotton. It turned out not to be resistant, but it was a wakeup call – it could have been glyphosate resistant awnless barnyard grass in cotton.

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 number 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.

So, the selection pressure on glyphosate is not overly strong in a traditional weed management system where survivors from a glyphosate spray are normally controlled by cultivation, chipping or a residual herbicide.

HERBICIDE RESISTANCE IN THE COTTON SYSTEM

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

Unfortunately, this system has its drawbacks, including expense, undesirable off-target impacts of herbicides and unavoidable damage to the cotton crop. Twenty years ago, many chipping bills were in excess of $100/ha, with bills up to $300/ha not uncommon. These bills are not affordable in the current economic climate, even if the large chipping crews are still available, which they generally are not. These issues have forced the weed management system to evolve over the years to one which is less reliant on chipping, substituting residual and contact herbicides for chipping inputs. Unfortunately, the drawbacks of off-target impacts and damage to the cotton crop remain and are accentuated by the heavy reliance on residual herbicides required. While this damage was hardly noticeable in the 2½ bale cotton crops of the 1980's, it is unacceptable in the 5 and 6 bale crops of this decade.

Fortunately, alternative weed management systems became available with the release of Roundup Ready® cotton, and more recently Roundup Ready Flex® and Liberty Link® cotton varieties. Use of these transgenic traits has allowed cotton growers to develop new, lower input, more environmentally friendly weed management systems which are conducive to higher cotton yields. The strength of these systems is that they rely on broad-spectrum, contact herbicides, with excellent crop safety (Roundup Ready Flex and Liberty Link), which are more environmentally benign than the residual herbicides they replaced and are only applied when a weed problem is present, allowing the application rate and number of applications to be tailored to match the problem/s.

The down-side with the use of the Roundup Ready trait 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 a glyphosate intensive system, which selects for glyphosate-tolerant species (a species-shift to glyphosate tolerant weeds). Many of the glyphosate tolerant species, such as rhyncho and emu foot, which were minor pests of the traditional cotton system, will increase in number in a glyphosate intensive system, eventually 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 is relatively weak selection pressure on glyphosate in a traditional weed management system, where survivors from a glyphosate spray are normally controlled by cultivation, chipping or another herbicide. However, the selection pressure on individual weed species may be stronger than it appears 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 chipping 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 from the same generation and genetically identical. Even plants in different years are likely to be from a single generation and genetically identical.

Some weeds are exposed to much stronger selection pressure in a Roundup Ready Flex system. A weed such as awnless barnyard grass, for example, is controlled to some extent by each of the residual herbicide inputs used in the traditional system. However, awnless barnyard grass may have 2 or 3 generations within a single season and each generation may 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.

However, not all weeds are at the same level of risk. The selection pressure on a weed such as Italian cockleburr (one of the Noogoora burr complex), may be 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 chipping or spot-spraying, impose no effective selection pressure on this weed.

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 option 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 input before they can 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 20 years 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

One of the biggest threats to the sustainability of the Roundup Ready system is the use of glyphosate in the rest of the farming system.

For example, where cotton is grown in a wheat rotation in an irrigated system, it would be 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 a field may receive 5 or 6 applications (or even more) over the fallow period, especially where wheat stubble is retained. This again 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, cultivation or chipping. An approach widely supported in the southern farming system is to follow a glyphosate application with a paraquat/diquat (Spray.Seed) application in 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 inputs, 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 develop in the dryland cotton farming 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.

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	Sexual	Common	Small	Long	Thornapple
risk	Sexual	Uncommon	Large	Short	Tall sedge
Low risk	Sexual	Uncommon	Small	Long	Desert cowvine
	Vegetative				Nutgrass

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 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.

CONCLUSION

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

1. Always follow the Crop Management Plan. The core principle of this plan is to ensure crops are checked after a herbicide application and any surviving weeds are controlled using an alternative weed management tool before they set seed.
2. 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 chipping, 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 chipping may still be required to control larger weeds in the plant line.
3. Adopt a double-knock or follow-up approach at least once a season for managing weeds in fallows.
4. Always control weed escapes before they set seed