Herbicide resistance and species shift in cotton: The need for an Integrated Weed Management (IWM) approach

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ABSTRACT

The Australian cotton production system has undergone a variety of changes in the last decade. Most Australian cotton is grown using a furrow-irrigated system, with the cotton planted in rows on raised hills, 1 m apart, or on raised 2 m wide beds, with two rows per bed. Production has changed from a cultivation-based system, with large inputs of insecticides, residual herbicides and hand-hoeing, to a system reliant on minimal cultivation, the retention of stubble from rotation crops, transgenic insect and herbicide tolerant cotton varieties, permanent irrigation beds, and in some situations, few if any residual herbicides. These changes in agronomic practices have major implications for weed management in the Australian cotton system, resulting in a species shift in the weed spectrum and may lead to the development of herbicide resistant weeds. Over-reliance on glyphosate as the primary weed management tool in the farming system is of major concern. Results from field observations and experiments highlight the shift occurring in the weed species, and the necessity for using an integrated approach to manage weeds efficiently and economically. A range of herbicide combinations and rates is explored with conventional and herbicide tolerant cotton varieties. Improved crop yields and weed control were achieved with non-traditional herbicide combinations, and with systems that included post-emergence glyphosate on glyphosate tolerant (Roundup Ready®) cotton. Good yields were obtained with glyphosate alone on Roundup Ready® cotton in a single season, but strong selection pressure from a single herbicide resulted in a shift in the weed species to more glyphosate tolerant weeds, reducing the effectiveness of the treatment over time. This research shows that in order to prevent the development of herbicide resistance and reduce the impact of species shift, it is important that the cotton industry develops and embraces an integrated weed management (IWM) approach. IWM is based on the philosophy of using a range of weed management methods in combination, so that all weeds are controlled by at least one component of the weed management system. The aim of IWM is to effectively manage all weeds so as to reduce the size of the weed seed bank over time, diminishing weed pressure and decreasing the need for weed management inputs, especially the need for large quantities of residual herbicides. IWM must be implemented in all parts of the farming system, including fallows and rotation crops.

Introduction

The commercial cotton industry has grown rapidly in Australia since its establishment in north-western New South Wales in the early 1960s. The industry was established on furrow irrigated, heavy, cracking clay vertisols that were well suited to cotton production. With the growth of the industry, production expanded into other soil types and other geographical areas, and in some years there is a relatively large area of rain-fed, non-irrigated cotton.

Weed management options have also developed since the 1960s, with the introduction of a range of soil-residual and over-the-top herbicides, and more sophisticated application and cultivation equipment. These improvements have made it easier to manage weeds. Many weeds that were problematic in the 60s and 70s, are now far easier to control and are of relatively little importance. Examples of these are the grass weeds such as *Echinochloa colona* (awnless barnyard grass) and *Urochloa panicoides* (liverseed grass) that are now routinely and easily managed with the residual grass herbicides such as trifluralin and pendimethalin. *Sorghum halepense* (Johnsons grass), for example, has been largely eliminated from the cotton growing areas with the combined use of glyphosate and the residual grass herbicides. Nevertheless, a range of weeds persists that are difficult to manage even with the current range of herbicides. Perennial weeds such as *Cyperus rotundus* (nutgrass) and *Polymeria longifolia* (polymeria take-all) have persisted as major problems on many properties in spite of every effort.

Over the last decade there have been a number of changes to the cotton production system that have had an important impact on the weed management system. The cotton production system of the early 1990s was based around large inputs of insecticides, residual herbicides, hand hoeing and cultivation. The total cost of weed control was on average $187/ha of cotton, with in-crop herbicides representing 41% of this cost, and in-crop hand hoeing representing a further 36% (Charles, 1991).

Since that time there has been a strong move to adopt reduced tillage systems, with permanent beds and permanent wheel tracks, much reduced inputs of insecticides, and less hand-hoeing. Cotton is now commonly planted on 2 m wide beds, rather than the traditional style of single rows on hills 1 m apart. In some instances, cotton is being planted directly into the standing stubble of a previous cereal crop, and may be planted on a different (ultra narrow-row) planting configuration, which may have, for example, six rows of cotton planted on a 2 m bed, in contrast to the traditional two rows.

Impacts of changes to the cotton cropping system

All of these changes have impacted on the weed management system. The 'conventional' cotton cropping system of the 1990s typically involved multiple heavy cultivation passes in the fallow between cotton crops. After picking, the cotton hills were normally disced down, and the field was cross-ripped (once or twice) with a heavy tyned implement. Occasionally a field was deep-ripped using a heavy crawler such as a D8 or D9. This ripping might have followed a rotation crop rather than the cotton crop. The cotton hills were re-established at some later point, probably after further cultivation, and well before cotton planting. The well-tilled seedbed that resulted was ideally suited for the application of soil-incorporated residual herbicides. The effect of this system was to cause maximum disruption to the cotton field, effectively burying most weed seeds and killing nearly all weeds, including most tap-rooted and perennial weeds. *C. rotundus* and *P. longifolia* were two weeds that were not well controlled by this cultivation based system, but most other weeds were effectively controlled by the combination of cultivation and seed burial.

The adoption of reduced tillage systems, with permanent beds and permanent wheel tracks, has seen a large reduction in the number and depth of cultivation passes in fallows, with some substitution of herbicides, and especially glyphosate, for mechanical weed control operations. Most cultivation passes now involve a tyned implement, designed to cause minimal soil disturbance. Consequently, many weed seeds remain on or near the soil surface, in an environment that promotes their germination and establishment. Also, many perennial and tap-rooted weeds are not controlled by the lighter tillage systems. Weeds that are not controlled by cultivation and are also glyphosate tolerant are not being effectively controlled by this system.

In some situations, cotton is being planted directly into standing stubble that has been retained from a previous cereal crop. This system can greatly reduce the risk of damage to cotton seedlings from sand-blasting during crop emergence, and may reduce early-season insect damage, but the stubble mass is not normally heavy enough to act as a surface mulch to impede weed establishment. With retained standing stubble, no cultivation is possible during the 10-month period between the cereal and cotton crops. All weeds present during this time must be controlled with a herbicide. The use of standing stubble also prohibits the application of soil incorporated, residual herbicides, necessitating reliance on contact herbicides and herbicides that do not require incorporation. Even if the stubble is incorporated into the soil later in the cotton season, the presence of large quantities of stubble can cause difficulties for inter-row cultivation and the application of herbicides. Consequently, this system relies heavily on glyphosate, and group A and B herbicides (the fops and dims, and sulfonylurea herbicide groups) as the main methods of weed control, and strongly favours glyphosate tolerant weeds.

Hand-hoeing was a major input in in-crop weed control, representing 36% of total weed control costs in 1990 (Charles, 1991). Hand hoeing is a very effective way of controlling small numbers of scattered weeds, with crews of 10 to 20 people a common site in cotton fields early in the season. It is non-selective and effective in controlling nearly all species and sizes of weeds, except for some perennial weeds such as *C. rotundus* and *P. longifolia*. However, hand hoeing can be extremely expensive, is relatively slow, and it has become increasingly difficult to obtain sufficient crews during peak demand. There are also concerns regarding the health of workers who can be required to spend long hours in +40 °C temperatures and might be exposed to pesticides.

Several strategies have been adopted to reduce the need for hand hoeing. There has been a general increase in the use of residual herbicides, to reduce the numbers of weeds present in fields, and increased use of post-emergent contact herbicides to control weed escapes. More accurate inter-row cultivation equipment has been used to increase the percentage of weeds that can be effectively controlled with cultivation. Shielded applications of herbicides such as glyphosate have also been substituted for hand-hoeing. Where hand-hoeing is required, the traditional hoe is increasingly being replaced with spot spraying from purpose built rigs that allow a person to cover a field far more quickly and with improved comfort. Consequently, the move away from hand hoeing has resulted in increased reliance on herbicides for weed control.

The introduction of genetically modified, herbicide tolerant (Roundup Ready®) cotton, has allowed a quantum leap in the move to greater reliance on herbicides, with glyphosate replacing all other herbicides, hand-hoeing and most in-crop cultivation passes in some situations. Roundup Ready® cotton is normally used when planting into standing wheat stubble, where inter-row cultivation and the incorporation of residual herbicides are problematic.

Roundup Ready® cotton is also normally chosen for use with the ultra-narrow row planting configuration, where the row spacing precludes the use of inter-row cultivation (although it may be possible to cultivate the furrow, depending on the configuration used), and precludes the application of the residual herbicides that are normally applied as directed in-crop applications later in the season.

The overall impact of the changes in the cotton farming system over the last decade has been to greatly increase the reliance on herbicides, with increased use of residual herbicides and greatly increased use of glyphosate and the Group A and B herbicides. Some changes have been introduced to reduce weed control costs (such as the reduction in hand-hoeing) and improve cotton yields (such as the use of ultra-narrow row cotton), but most changes result from changes in farming practices that are not directly related to weed management issues. Many of these changes have made weed management more difficult, and have led to the emergence of new weed management problems. Some use patterns are placing strong selection pressure on weeds, selecting for herbicide tolerant weeds and are likely to eventually result in the emergence of herbicide resistant weeds in the cotton industry.

Changes in the weed spectrum in the industry

Weed populations are constantly changing, reflecting weed life cycles and the dynamics of the environment, climatic, physical and chemical. While the Australian cotton grower may endeavor to maintain a weed-free fallow and crop monoculture, this aim is never perfectly achieved. In practice, the grower tries to maintain a balance between the desire to eliminate weeds and the cost of weed control. Ideally, weed management inputs are tailored to match weed problems as they emerge, but this ideal is restricted by the limited spectrum of management tools available, none of which is individually able to control all weeds in all situations. Cotton growers, having a limited range of weed management tools, are often forced to use a similar weed management program year after year. While these weed management programs may best fit the needs of the cotton grower, it is inevitable that over time, the management program will select out those weeds that are most tolerant of the tools used. These weeds eventually come to dominate the weed spectrum, resulting in a species shift in the weed spectrum, and necessitating a change in the weed management program.

The changes in the cotton production system over the last decade have resulted in a species shift in the weed spectrum. The ten most important weeds of Australian cotton production are shown in Table 1, as indicated by weed surveys conducted in 1989 (Charles, 1991) and 2000. Many of the weeds that were important in 1989 are still of importance, with six of ten weeds common to both surveys. Of the remainder, *Xanthium occidentale* (noogoora burr) and *X. spinosum* (Bathurst burr), two of the three weeds most important in 1989, are no longer ranked in the top ten weeds. These weeds are still problematic in some situations, but are targeted by residual herbicide, cultivation and hand-hoeing inputs, and are controlled by the Group B herbicides Staple® (pyrithiobac-sodium) (both species) and Envoke® (trifloxysulfuron sodium) (*X. occidentale* only) that have become available in the last decade. *Haloragis glauca* (haloragis take-all) is relatively easily controlled with glyphosate and is no longer a major weed problem. *P. longifolia* is still very problematic where it occurs, but is not present through much of the cotton growing area. Its relative importance has diminished with the expansion of cotton production into new areas where it is not as common.

Of the four new weeds that were recorded in 2000, all are relatively small seeded weeds that are easily controlled with seed burial from heavy cultivation. *E. colona* and *U. panicoide*s were readily controlled by the residual grass herbicides trifluralin and pendimethalin, that were routinely used in 1990, but are more difficult to control in systems where these herbicides are not used, or are applied as a band, rather than a broadcast application, allowing the weeds to grow and set seed in the unsprayed area. *Sonchus oleaceous* (sow thistle) is a glyphosate tolerant weed, as were four of the top five weeds reported for 2000 (*Hibiscus trionum* (bladder ketmia), *C. rotundus*, *S. oleaceous* and *Ipomoea lonchophylla* (cowvine).

Changes in the weed spectrum on individual fields

Weed density and diversity have been monitored on growers' fields on six commercial cotton properties over the last seven seasons. Results from three of these properties are shown in Tables 2, 3 and 4. Results are averaged over three fields on each property. Surveys were undertaken twice each season, the first early in the cotton season, and the second immediately prior to picking. Weed density and diversity were recorded on two fixed transects in each field, with 10 sets of observations per transect, and each observation covering an area of 50 m^2. Transects ran diagonally across the fields. Results from the properties 'Strathgyle', 'Auscott' and 'Glencoe' are presented. Of these, Strathgyle and Auscott had adopted a reduced tillage, permanent bed strategy, while a more traditional approach with heavy cultivation was used at Glencoe. Cotton was grown in the same fields each season over the observation period at Strathgyle, whereas cotton crops alternated with cereal rotation crops at Glencoe. Auscott used a rotation of three cotton crops followed by a cereal rotation crop.

Results from the surveys varied from season to season, depending on the combination of seasonal conditions and management inputs. Fluctuations in total weed density over the six seasons at Strathgyle are shown in Figure 1. Total weed density averaged just under one weed per m^2 at Strathgyle, with no clear trend over time. A distinct change in the weed spectrum occurred over time at Strathgyle, with *I. lonchophylla* becoming by far the most prominent weed (Table 2). The density of volunteer cotton plants remained stable, but the densities of most other weeds declined over the observation period. None of the remaining weeds reported in 1995/96 were present at more than one per 100 m^2 in 2001/02. Of the weeds that were present at this density in 2001/02, all were glyphosate tolerant weeds.

The total weed density on three fields at Auscott increased more than ten-fold over the observation period, due to a large infestation of *C. rotundus* that was not adequately controlled by the reduced tillage farming system used. While this weed is not necessarily controlled by cultivation, careful attention to equipment hygiene and strategic heavy cultivation are important tools in its management. The density of other weeds remained relatively stable, although there was again an increase in the density of many of the glyphosate tolerant weeds.

The total weed density on three fields on Glencoe was initially at a much higher level than on the other properties, but declined over time. This decline appeared to relate to the use of in-crop shielded applications of glyphosate that has been used in addition to the full complement of residual herbicides, cultivation and chipping previously used on this property. Nevertheless, more weeds were present at higher densities (greater than $0.1/m^2$) at this site than as the other sites, both at the 1995/96 and 2001/02 observations. While there was a change in the density of individual weeds over time, there was no clear pattern of small seeded or glyphosate tolerant weeds. Most of the change in the weed density was due to a large decline in the populations of *C. rotundus* and *S. oleraceus*, probably due to the in-crop use of glyphosate, combined with heavy cultivation in fallows during a series of dry seasons.

Clearly, there has been a change in the weed spectrum on many cotton fields over the last decade in response to changing farming practices. The shift in favor of glyphosate tolerant weeds is most apparent on fields where glyphosate has replaced other weed management tools, and will limit the value of glyphosate in these situations. Managing glyphosate tolerant weeds in the cotton farming system is likely to be a major issue in the next decade.

Herbicide systems for managing weeds in cotton

The Australian cotton industry of the 1990's was heavily dependant on in-crop herbicides and hand-hoeing for weed control. These two inputs represented 76% of the total cost of weed control at this time (Charles, 1991). A typical herbicides system used a pre-planting, soil-incorporated application of trifluralin and diuron, with a band of fluometuron applied behind the planter. A further residual herbicide application normally occurred at lay-by (prior to canopy closure), with diuron, fluometuron or prometryn, or a combination of these being applied as a directed spray (applied to the irrigation furrow and the base of the cotton plant). All herbicides are normally applied at their maximum recommended rates.

The typical weed control approach has changed over the last decade, as has already been discussed, with much greater reliance on in-crop glyphosate, increased use of many of the residual herbicides, and a large decrease in the use of hand-hoeing. Trifluralin, which was the most commonly applied residual grass herbicide in 1989, is now less commonly used, due to its requirement for incorporation. Pendimethalin, which has a similar weed spectrum to trifluralin, requires less incorporation, and is now commonly used instead of trifluralin. However, pendimethalin is much more expensive than trifluralin and is commonly only applied on a band behind the planter, rather than as a broadcast application.

A range of additional herbicides is now available, with the registration of a range of Group A fop and dim grass herbicides, the Group B herbicides pyrithiobac sodium and trifloxysulfuron sodium, and glyphosate for use with Roundup Ready® cotton. These additional herbicides allow cotton growers to adopt a range of herbicide strategies, from a traditional, residual herbicide based strategy through to strategies based solely on non-residual herbicides.

Some of the changes in herbicide strategies have been forced by the changes in the farming system, with reduced cultivation and chipping, the retention of standing stubble etc., but other changes have been specifically targeted to address weaknesses in the weed control program. An early-season, in-crop application of pyrithiobac sodium, for example, is now routinely used on many fields to improve management of *Datura ferox* (fierce thornapple) and *Sesbania cannabina* (sesbania pea). An application of trifloxysulfuron sodium may be included to manage *X. occidentale*.

While changes in the system mean that some herbicides are substituted for others, as a pendimethalin application might replace a trifluralin application, it is not uncommon that a new herbicide, targeted at a specific problem, is used in addition to an existing herbicide program, resulting in an ever increasing assault of herbicides on a field. Generally the rates of the original herbicides are maintained at their maximum registered rate, along with the new herbicide. Such a field program might be: trifluralin + diuron pre-planting; pendimethalin + fluometuron as a band at-planting; a glyphosate post-planting, pre-crop emergence; a band of pyrithiobac sodium early post-emergence, a shielded glyphosate application in-crop and; a prometryn at lay-by.

The effect of a heavy herbicide program on weeds can be readily assessed, but the impact of the program on cotton establishment and yields is more difficult to determine. Anecdotal evidence indicates that problems with cotton seedling establishment are becoming more common when wet spring conditions occur. While these problems are often attributed to seedling diseases, it is likely that in many instances seedling ill-thrift or mortality is due to the combination of seedling diseases and herbicide damage caused by high rates of residual herbicides applied before crop establishment. In addition, experimental work and field observations have shown that cotton growth in the early part of the season is impeded by the use of heavy rates of residual herbicides. Cotton seedlings grow far more vigorously where no residual herbicides are used. The use of weed control programs that rely less heavily on high rates of pre-planting residual herbicides may overcome some cotton establishment and early-season growth problems.

A range of herbicide strategies was compared in a long-term replicated field experiment, run over five consecutive seasons, using three replicates and plots of eight rows by 50 m length. Weed density was assessed early and late season, and cotton lint yield was determined from the two central rows of each plot, harvested using a modified commercial cotton picker. Treatment differences became more pronounced over time. Results averaged over the last two seasons showed that changes in the weed management system resulted in relatively large changes in both weed density and cotton yield, with large differences between the best and worst treatments (Table 5). A range of other treatments, including glufosinate-ammonium and bromoxynil tolerant cotton varieties were included in the experiment, but are not presented here. As might be expected, there was a strong relationship between the level of weed control and cotton lint yield over the range of systems used (Figure 2), with the best yields occurring on the systems with the lowest weed densities. Nevertheless, a range of yields was achieved by the systems that gave the best weed control. Comparison of three conventional systems using residual herbicides (Systems 1, 2 and 3) showed some advantage to using diuron compared to fluometuron with the weed spectrum present on this site, but no advantage to using all three herbicides together. This result, with both reduced weed control and reduced cotton yields from a system using an additional herbicide, was consistent over a number of systems and seasons, and indicates the dangers inherent in continually adding herbicides into a system without considering the total system.

The change to a modified system, using a range of herbicides in combination, at reduced rates (System 4), resulted in greatly improved weed control and improved yields. Clearly, weed control can be improved by using a combination of herbicides, but the rates of individual herbicides must be reduced in proportion to the total amount of herbicide used.

Systems that included no residual herbicides were explored, but it proved impossible to adequately control grasses and some broad-leaf weeds in a system that relied totally on post-emergence, contact Group A and B herbicides (System 5). A number of weed species were not adequately controlled by these contact herbicides or were tolerant of the herbicides used, resulting in a rapid increase in weed numbers over time in these systems. Grass weeds, for example, should have been easily controlled by butroxydim, but were very difficult to control in practices as they continued to emerge throughout the season, and were only susceptible to the herbicide when they were small and actively growing. Three herbicide applications proved inadequate to control the grass weeds in irrigated cotton, but the cost of application precluded the use of more applications in a single season. Similarly, pyrithiobac sodium was an effective herbicide on many broad-leaf weed species, but is most effective on small weeds, was ineffective on some of the weed species present, and could only be applied twice in the season. Consequently, pyrithiobac sodium did not adequately control many of the broad-leaf weeds present.

Systems that used glyphosate on Roundup Ready® cotton gave far better weed control and yields than the conventional systems (Systems 1 to 3) or the modified System 5, whether glyphosate was used in combination with residual herbicides, or used alone (Systems 6 to 12). Use of reduced rates of the residual herbicides did not reduce weed control, but also did not improve cotton yields, contrary to expectations. This result is probably due to the ability of cotton to compensate for early season damage. It is still likely that use of reduced rates of residual herbicides will reduce problems with early season crop establishment in the long term, especially when wet conditions occur early in the season.

System 12, using glyphosate applied post-emergence with no residual herbicides, gave good weed control and the second best yields, but did not appear to be sustainable in the longer term. Most weeds were well controlled by this system, but *X. italicum* (Italian cocklebur) emerged as a problem that became progressively worse over time. Most *X. italicum* plants emerged early in the season and were easily controlled by the first glyphosate application, but some plants emerged after this application and were difficult to control when they occurred in the cotton row, as they were not apparent until later in the season when they were relatively large and emerged above the cotton. None of the available herbicides can control *X. italicum* effectively at this growth stage without causing unacceptable damage to the cotton. Inclusion of a trifloxysulfuron sodium application in the system would have improved control of *X. italicum*, but would be of limited value, as this herbicide can only be used once per season, and is only effective on seedling *X. italicum*. Plants that emerged later would still be difficult to control.

Species shift

The problem of species shift and the occurrence of new weeds is a likely consequence of any change in a weed management system that involves the substitution of one input for another input. It is almost inevitable that when a new weed management tool is used, it will not be as effective on some weeds as was the management tool it replaced. Species shift can also occur when a new weed is introduced into a system where that weed is not well controlled.

Species shift tends to be less of a problem in management systems that use a range of weed management tools, as most or all weeds are managed by some component of the management system. Species shift can be a far greater problem in systems where a single management tool replaces a range of tools. Management systems using Roundup Ready® cotton, where glyphosate may replace most herbicide, cultivation and hand-hoeing inputs are likely to result in rapid changes in the weed spectrum towards glyphosate tolerant weeds. The selection of weeds that are tolerant of or resistant to glyphosate is inevitable in situations where glyphosate is used as almost the only weed management tool. A similar scenario is likely when any management tool replaces a range of other management tools.

The simplest way to avoid problems with species shift and herbicide resistance is to use an integrated approach to weed management.

Integrated weed management (IWM) systems for cotton

Integrated weed management (IWM) is not so much a system as a framework, where all inputs into the farming system that have an impact on weeds are recognized as being part of the weed management system. These management tools are then integrated into a complementary system that optimizes the outcome for crop production and weed management. An IWM system uses a wide range of weed management tools in combination, so that all weeds are controlled by at least one component of the management system. Conversely, an IWM system recognizes the often negative impact of many weed management tools on the wider environment and other components of the farming system, and uses only those tools that are required to achieve an efficient and sustainable system. IWM recognizes the importance of the complete cropping system, including inputs in fallows, rotation crops and cotton crops, and external inputs such as the management of weeds on irrigation structures and channels, and the introduction of weeds from external sources.

The aim of IWM is to effectively manage all weeds, so as to reduce the size of the soil seed-bank over time, reducing weed pressure and decreasing the need for weed management inputs.

IWM can be conceptualized as shown in Figure 3, where inputs that were not previously considered as having importance in weed management, are recognized and collectively optimized.

Crop variety, agronomy and management is an example of such an input, the importance of which is often not fully recognised. The selection of competitive crop varieties, and the use of crop agronomy and management practices that maximize crop competitiveness, especially early in the season, can have a large benefit in weed management. The use of systemic insecticides, for example, can improve crop growth rates and crop competitiveness, but can also reduce the impact of "beneficial" insects that are negatively impacting weeds. The value of some inputs, such as insecticides needs to be "balanced", or "optimized" to achieve the best result.

The interaction of irrigations, cultivations and herbicides is an example of another area that is often not fully appreciated by farm managers, but is central to a fully developed IWM system in irrigated cotton, where most weed germinations (at least in dry seasons) are stimulated by irrigation.

Development of an IWM system is a dynamic process that must be constantly reviewed and modified as necessary to achieve the best short-term and long-term outcomes.

Weeds researchers in Australia have developed WEEDpak, a comprehensive weed management guide, specifically designed for the cotton industry, to assist Australian cotton growers to develop IWM systems that are sustainable and are tailored to meet their individual needs.

References

- Charles, G.W. (1991). A grower survey of weeds and herbicide use in the New South Wales cotton industry. *Australian Journal of Experimental Agriculture*, **31**: 387 – 392.

Table 1. *Ranking of the 10 most important weeds of Australian cotton production, as indicated by surveys undertaken in 1989 and 2000. Weeds were ranked as 1 (most important) to 10 (least important).*

Ranking	1989	2000
1	*Xanthium occidentale*	*Hibiscus trionum**
2	*Cyperus rotundus**	*Echinochloa colona*
3	*Xanthium spinosum*	*Cyperus rotundus**
4	*Physalis spp.*	*Sonchus oleraceus**
5	*Ipomoea lonchophylla**	*Ipomoea lonchophylla**
6	*Hibiscus trionum**	*Urochloa panicoides*
7	*Datura ferox*	*Sida fibulifera*
8	*Tribulus spp.*	*Physalis spp*
9	*Haloragis glauca*	*Tribulus spp.*
10	*Polymeria longifolia**	*Datura ferox*

* Glyphosate tolerant weeds

Table 2. *Changes in the weed spectrum on three commercial cotton fields on 'Strathgyle', a property growing cotton in the same fields each season. Only weeds present at more than one per 100 m² are reported. The management at Strathgyle adopted a reduced tillage, permanent bed system.*

1995/96	No./m^2	2001/02	No./m^2
Total weed density	0.53	Total weed density	0.90
*Ipomoea lonchophylla**	0.18	*Ipomoea lonchophylla**	*0.83*
Cotton	0.12	Cotton	*0.09*
Physallis minima	0.10	*Polymeria longifolia**	*0.05*
Asteraceae	0.08	*Graminetinus erubescens**	*0.01*
Amaranthus macrocarpus	0.05	*Cullen cinereum**	*0.01*
Tribulus micrococcus	0.03		
*Sonchus oleraceus**	0.03		
Solanum nigrum	0.02		

*Glyphosate tolerant weeds.

Table 3. Changes in the weed spectrum on three commercial cotton fields on 'Auscott'. Only weeds present at more than one per 100 m^2 are reported. Cotton was grown in rotational system with three cotton crops followed by a rotation crop such as wheat. The management at Auscott adopted a reduced tillage, permanent bed system.

1995/96	No./m^2	2000/01	No./m^2
Total weed density	0.56	Total weed density	6.02
*Sonchus oleraceus**	0.45	*Cyperus rotundus**	4.94
Hibiscus trionum	0.02	*Sonchus oleraceus**	0.28
*Graminetinus erubescens**	0.02	*Hibiscus trionum**	0.15
Cyperus rotundus *	0.01	*Chamaesyce drummondii*	0.08
Plantago cunninghamii	0.01	*Graminetinus erubescens**	0.05
		*Ipomoea lonchophylla**	0.03
		Sida fibulifera	0.02

Glyphosate tolerant weeds are indicated by an "".

Table 4. Changes in the weed spectrum on three commercial cotton fields at 'Glencoe', a property using a "traditional" cultivation strategy, complemented with in-crop shielded applications of glyphosate. Cotton crops were alternated with rotation crops such as wheat. Only weeds present at more than one per 100 m^2 are reported. Glyphosate tolerant weeds are indicated by an "*".

1995/96	No./m^2	2001/02	No./m^2
Total weed density	4.96	Total weed density	2.99
*Sonchus oleraceus**	2.90	*Chamaesyce drummondii*	1.04
Cyperus rotundus	1.16	*Lamium amplexicaule*	0.51
Latuca serriola	0.27	*Physallis minima*	0.46
Avena fatua	0.27	*Hibiscus trionum**	0.33
Solanum nigrum	0.15	*Sonchus oleraceus**	0.19
Rapistrum rugosum	0.04	*Cyperus rotundus**	0.15
Asteraceae	0.03	*Echinochloa colona*	0.14
*Medicago polymorpha**	0.03	*Avena fatua*	0.07
*Graminetinus erubescens**	0.03	*Portulaca oleracea*	0.05
Chamaesyce drummondii	0.02	Poaceae	0.02
Poaceae	0.02	*Graminetinus erubescens**	0.02
Plantago cunninghamii	0.02		

Table 5. *Impact of weed management systems on weed density and cotton yield. Results are averaged over two seasons. Systems 6 – 12 used a Roundup Ready® cotton variety.*

	Herbicide application (l or kg a.i./ha)						
System	Pre-planting incorporated	At planting	Early post-emergence	Mid-season	Lay by	Weeds (No./m^2)	Yield (kg/ha)
1	Trifluralin 1.1	Fluometuron 2		Prometryn 1	Prometryn 1.25	12.7	774
2	Trifluralin 1.1 + diuron 1.5			Prometryn 1	Prometryn 1.25	8.6	753
3	Trifluralin 1.1 + diuron 1.5	Fluometuron 2		Prometryn 1	Prometryn 1.25	15.5	567
4	Norflurazon 1.2	Fluometuron 0.25 + prometryn 0.25 + diuron 0.5		Pyrithiobac sodium 0.1	Prometryn 1.25	2.5	1250
5			Butroxydim 0.045 + pyrithiobac sodium 0.1	Butroxydim 0.045 + pyrithiobac sodium 0.1	Butroxydim 0.045	17.6	644
6	Trifluralin 1.1	Fluometuron 2	Glyphosate 1	Glyphosate 1	Glyphosate 1	2.3	1167
7	Trifluralin 0.56	Fluometuron 1	Glyphosate 1	Glyphosate 1	Glyphosate 1	2.0	1072
8	Trifluralin 1.1 + diuron 1.5		Glyphosate 1	Glyphosate 1	Glyphosate 1	2.3	1069
9	Trifluralin 0.56 + diuron 0.75		Glyphosate 1	Glyphosate 1	Glyphosate 1	1.6	1047
10	Trifluralin 1.1		Glyphosate 1	Glyphosate 1	Glyphosate 1	4.0	1066
11	Trifluralin 0.56		Glyphosate 1	Glyphosate 1	Glyphosate 1	2.0	1083
12			Glyphosate 1	Glyphosate 1	Glyphosate 1	4.8	1195

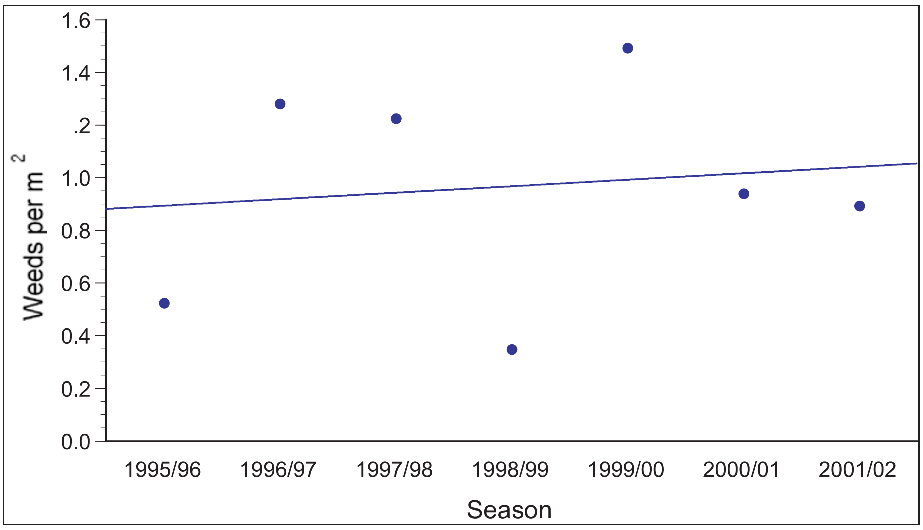

Figure 1. *Seasonal variation in the density of weeds at Strathgyle. Data were averaged over three fields, with observations taken early-season and at picking. The linear model fitted to the data indicated little change over time and was not statistically significant.*

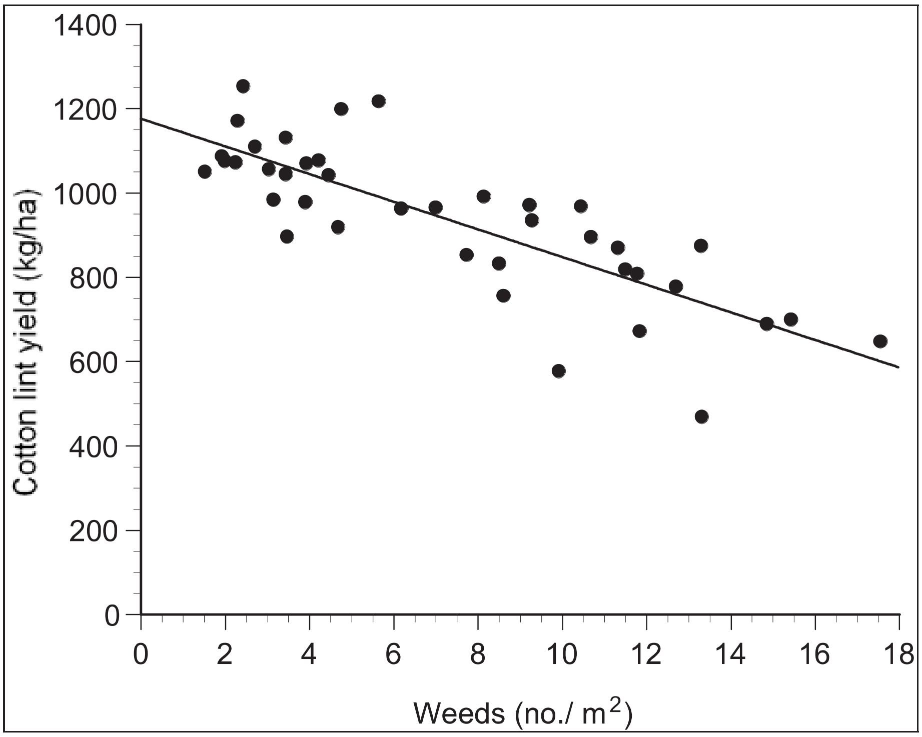

Figure 2. *The impact of weeds on cotton lint yield under a range of herbicide systems. Data points were averages of two seasons and three replicates. The relationship was: Yield = 1173 – 32.8 x Weeds/m*^{2} *$R^2 = 0.64$ P<0.001.*

Figure 3.
Components of an integrated weed management (IWM) system.