

ENVIRONMENTAL BENEFITS OF ROUNDUP READY® COTTON**Angus N Crossan and Ivan R Kennedy****The University of Sydney****Sydney, Australia**

Since its introduction in 2000 Roundup Ready® cotton has been rapidly adopted by Australian cotton growers. This paper presents risk assessment methods, used in conjunction with field sampling, to determine the change of environmental hazard associated with the use of Roundup Ready cotton and associated increase use of glyphosate. It was found that herbicides typically used on Roundup Ready® cotton crops pose a lower risk to the environment than herbicides commonly used on conventional cotton crops. In addition, there is evidence that the weed control programs used with Roundup Ready cotton allow reduced tillage and fewer precautionary applications of residual herbicides, providing further environmental benefits. The field results confirm that it is possible to achieve both economic and environmental benefits from the use of this genetically modified crop.

Modern agriculture relies on effective weed control. Applications of chemical herbicides are still the most cost effective means of weed control available to farmers in industrialised nations. A challenge for contemporary agriculture is meeting competitive demands for economic production, while at the same time improving farming practices to reduce risks to human health and ecosystems.

Most cotton in Australia is grown on about 1200 independent family farms in the northern inland river regions of New South Wales and Queensland, of average farm size 490 hectares. While Australia is a relatively small producer, it is the world's third largest exporter of cotton. Australian farmers are highly productive, typically growing one and a half tonnes of cotton fibre per hectare, approximately two and a half times more than average world yields. Australia produces about 3 million bales of cotton annually. This compares with China's production of 20 million bales and 17 million bales produced in the USA.

Cotton plants are grown over the Australian summer (November-March) where the plants prefer hot days with low humidity and long hours of sunshine for good crop production. The growing season for cotton from planting to picking is approximately 160 days. Cotton has many uses, the most common being the production of fibre or lint, for fabric manufacture. Cottonseed is crushed to extract a premium vegetable oil which is used for frying food such as fish and chips, snack-foods and crisps. The hull of the seed is used for livestock feed. Cottonseed oil was one of the world's first vegetable oils; it is cholesterol-free and high in mono-saturated fats that help lower cholesterol levels (www.cottonaustralia.com). It also contains high levels of antioxidants (Vitamin E) that contribute to its long shelf life.

Herbicides deliver large benefits to cotton production by controlling weeds, which in turn improves crop yield and prevents weed seeds and plant material from contaminating the harvest. However, herbicides do have the potential to be harmful to aquatic ecosystems, potentially affecting plants that provide food and habitat for fish and other aquatic animals, and sometimes being directly toxic to these animals. Therefore, it is undesirable for herbicides to be leached into water courses or transported away from target crops and fields in water.

There are two main classes of herbicides, residual and non-residual. Residual herbicides, which include pre-emergent herbicides, are classified by their longevity in soil and subsequent longer-term action. Residual herbicides present a higher risk to an ecosystem, because they remain active over a longer period of time. They can also reduce subsequent crop yields as a result of their residual effect when their application is poorly managed. Conversely, non-residual herbicides are short-lived in the environment; they are either degraded rapidly or are soon inactivated by soil contact.

Roundup Ready cotton, which can tolerate early season use of the herbicide Roundup® (glyphosate), became available to the Australian cotton industry in 2000. The acceptance and uptake of Roundup Ready technology has

been remarkably swift. Within two years of its introduction, approximately 40% of all cotton grown in Australia was Roundup Ready®. The percentage of Roundup Ready cotton grown in Australia exceeded 40% for the 2003/04 cotton season. The rapid adoption of Roundup Ready® technology, has led to changes in herbicide use patterns by cotton growers. Growers potentially decrease use of residual herbicides and increasingly use glyphosate. Glyphosate, a non-residual herbicide, has now been used in Australia for many years with favourable results for weed control with many crops, but it was timely that an Australian study should examine the potential environmental impact of these changes to herbicide use in cotton production.

The fate of pesticides and other chemicals applied on cotton farms depends on many factors. In general, such farm chemicals may be dispersed in the environment by transport processes such as aerial drift, volatilisation, run-off in surface water, leaching into ground water, or degrade by *in situ* chemical, photolytic or biological degradation, reducing the chemical concentration.

Compared to other chemicals used in cotton production, herbicides are relatively water soluble. High water solubility may indicate that a herbicide will be more susceptible to run-off and leaching into subsurface water. There is evidence that some herbicides, for example diuron, can be detected in ground water as a result of subsurface drainage (Goody *et al.*, 2002). Similarly, herbicides are sometimes detected in samples taken from riverine ecosystems, either as a result of overspray or run-off (DIPNR, 2003a; DIPNR, 2003b; DIPNR, 2003c; Beernaerts *et al.*, 2003). The transport of herbicides from target areas in cultivated paddocks can be minimised by good management, for example practices recommended by the BMP (Best Management Practice) initiative of the Australian Cotton Industry (Shaw, 2000; Williams and Williams, 2000).

Herbicide tolerant crops can give environmental benefits by allowing a shift to conservation tillage practices (Cannel and Hawes, 1994); farmers can reduce the extent of soil cultivation required to control weeds and prepare the soil for planting. Specifically, herbicide tolerant crops allow farmers to reduce the use of pre-emergent herbicides that need to be incorporated into soil and to rely on post-emergent herbicides such as glyphosate directly applied on weeds instead. It has been suggested that the shift to post-emergent control of weeds may promote no-till and conservation tillage practices that can decrease soil erosion and water loss and increase soil organic matter and total nitrogen (Cannel and Hawes, 1994; Feng *et al.*, 2003).

This paper outlines the findings of a recent field study that examined possible benefits from the use of Roundup Ready® cotton in Australia. The study compared the ecological risk from herbicide systems for weed control used with cotton varieties incorporating a genetically modified (GM) trait-tolerance to the herbicide glyphosate with that associated with the use of other herbicides used in conventional cotton production.

The aim of the study was to compare the risk of herbicide use in cotton production before and after the availability of Roundup Ready cotton.

The process involved both desktop risk assessments, based on models, and a comprehensive field trial with environmental sampling. The data obtained were used to validate the accuracy of the desktop calculations. In order to understand and assess the differences between herbicides, risk should always be based upon the ratio of the quality of the pesticide used (exposure) and a value to indicate the action specific to that dose of chemical (effect), such as indicated in the equation below:

$$\text{Risk} = \frac{\text{Exposure}}{\text{Effect}}$$

Glyphosate has a low affinity for organic matter (represented by a low K_{ow} value, which is a measure of the distribution of a substance between an organic solvent and water) and high water solubility; roughly three times the

water solubility of common table salt (sodium chloride). At first sight these data suggest that glyphosate could be prone to leaching. However, numerous studies have reported that glyphosate is likely to be immobile in the environment because it binds tightly to soil (Giesy *et al.*, 2000). Low soil mobility, together with relatively low persistence and human and aquatic toxicity render glyphosate as potentially one of the least environmentally hazardous herbicides to non-target organisms. This statement is supported by quantitative risk assessment using several scientific analyses. Glyphosate is certainly considered safer for human health and the environment than most of the herbicides currently used for cotton production (IOGTR, 2000).

The Roundup Ready cotton field project was initiated by Monsanto in 2001 to objectively test predictions of reduced environmental risk through the introduction of Roundup Ready technology to Australia. The project was managed by the consulting firm, Maunsell Australia Ltd., with assistance from scientific research groups in CSIRO Land and Water and The University of Sydney.

The field study undertaken at Auscott Midkin in the Gwydir Valley (northern New South Wales, Australia) consisted of four trial fields. All four fields were sown with Roundup Ready® Cotton (*Sicot 189RR*). The four fields, with slope gradients of 1:1400, were uniform light to medium grey cracking soils of 50-60% clay content. Soil organic carbon levels were measured as 0.8-1.2%, and pH levels were within the range of 7.5 to 8.6. Two fields were subjected to typical conventional herbicide programs over the 2001/02 growing season whilst the other two were subjected to typical glyphosate-dominated herbicide programs (Table 1). Other herbicides used in the study, for comparative purposes, included 2,4-D, diquat dibromide, diuron, fluometuron, paraquat dichloride, pendimethalin, prometryn and trifluralin. The use of glyphosate in a post emergence 'knockdown' application is not possible on a conventional cotton variety but was made possible here through the planting of the glyphosate tolerant *Sicot 189RR* variety on all four fields. The ability to rate the relative risk of individual herbicides was not affected by the application of glyphosate for knockdown in the conventional program fields.

Table 1: Herbicide applications on the four fields used in the field experiment. Figures in brackets indicate application rates of active ingredient in kg ha⁻¹

| Fields (Herbicide Program) | Herbicide Applications – 2001/02 Australian Cotton Season ^a | | | |
|----------------------------------|--|--|---|---|
| | Knockdown | Pre-Emergence | Knockdown | Layby |
| 24 (Roundup) | - | Diuron (1)/Trifluralin (2.3) (early Sept) | Glyphosate (1.5) (end Oct) | Glyphosate (1) (mid Dec) |
| 29 (Conventional) | - | Diuron (1)/Trifluralin (2.3) (early Sept) Fluometuron/ Prometryn (early Oct) | Glyphosate (1.5) (late Oct) Glyphosate (1) (early Nov) | Fluometuron (1.5)/ Prometryn (1.5)/ Diuron (1) (early Dec) |
| 83 (Roundup) | 2/4-D (0.9)/ Glyphosate (1) (mid Aug) | Diuron (1)/Trifluralin (2.3) (mid Sept) | Glyphosate (1.5) (mid Oct) | Glyphosate (1) (mid Dec) |
| 84 (Conventional) | 2/4-D (0.9)/ Glyphosate (1) (mid Aug) | Diuron (1)/ Pendamethalin (3) (mid Sept) Fluometuron (1.7)/ Prometryn (1.7) (late Sept) | Glyphosate (1.5) (mid Oct) | Fluometuron (1.2)/ Diuron (0.8) (mid Dec) |

^a All herbicide applications occurred in 2001

A comprehensive set of soil, sediment and water samples were collected for chemical analysis as part of the field project. These data were used for partial validation of the modelled values as well as to formulate a probabilistic risk assessment.

The data for the analyses of glyphosate and diuron in topsoil (0-5 cm) are summarised in Figures 1 and 2. The residues of glyphosate found in soil were consistent with application rates and the field study conditions, which were typical of Australian cotton growing practices. Both diuron and glyphosate were detected in topsoil soon after herbicide application in the cotton growing season (Figure 1). However, near harvest towards the end of the season no glyphosate residues in soil were detected and there was only a low range detection of diuron (0.022 mg/kg).

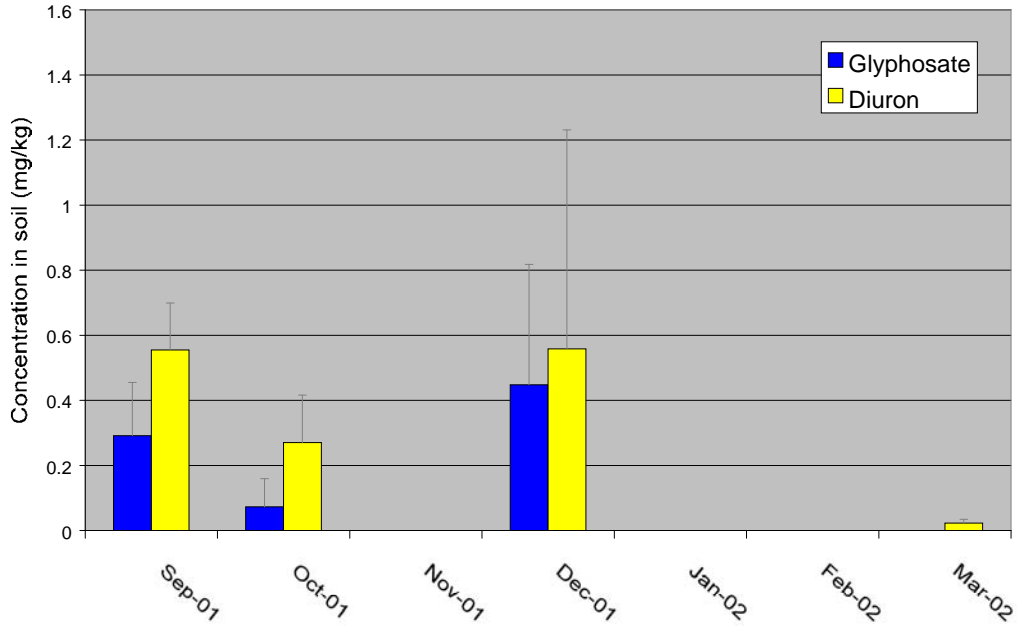


Figure 1: Concentrations of glyphosate and diuron in soil throughout the 2001-02 cotton growing season; averaged results from four experimental fields, standard deviation shown by the error bars.

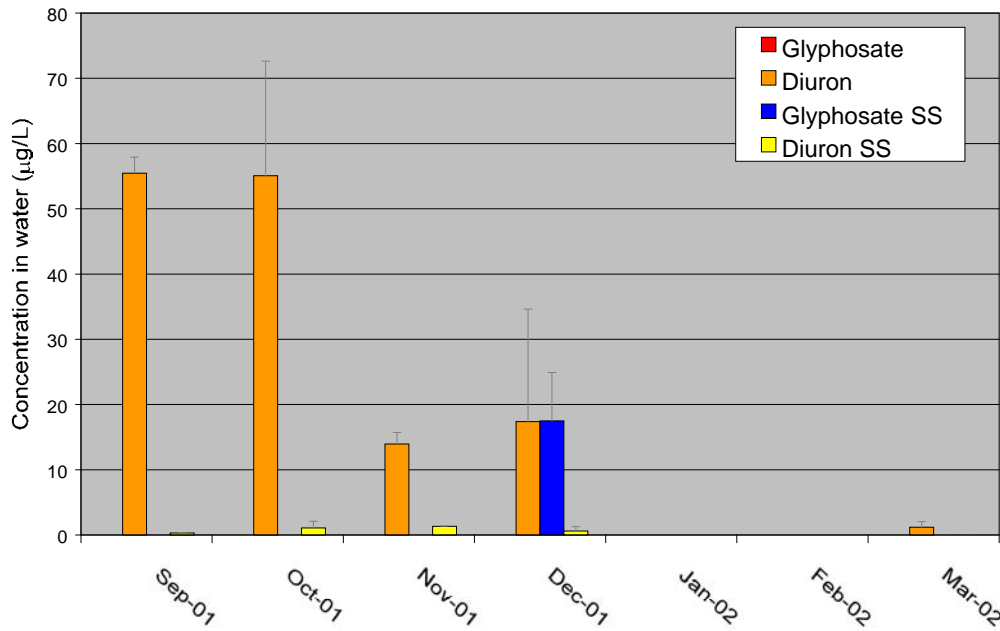


Figure 2: Concentrations of Glyphosate and Diuron in runoff water and suspended sediment (SS) presented for each month from four fields; standard deviation shown by error bars.

No glyphosate was detected dissolved in runoff water at any stage (Figure 2), with a small number of detections in suspended sediment soon after application of the herbicide. By contrast, diuron, which has a lower binding affinity for the soil, was detected in runoff water at comparatively high concentrations early in the season soon after application. By the end of the growing season the diuron concentrations detected were significantly lower, in accordance with the decreasing concentrations in soil. The values of diuron detected were consistently higher than the ANZECC interim guideline for ecosystem protection of $0.2 \mu\text{g L}^{-1}$ (a low reliability guideline, because of a

limited data set; ANZECC, 2000). Because of its low toxicity, the ANZECC guidelines for glyphosate are $370\mu\text{gL}^{-1}$, and these were not exceeded by a wide margin in any of the samples, including those with sediments.

Two approaches to modelling, the Pesticide Impact Rating Index (PIRI) (Kookana *et al.*, 1998) and the use of fugacity (a calculation of chemical movement through multiple environmental phases) modelling (Mackay, 2001 and Sanchez-Bayo *et al.*, 2002), were used to do desktop calculations of the expected concentrations and fate of the herbicides glyphosate, 2,4-D, diquat dibromide, diuron, fluometuron, metolachlor, paraquat dichloride, pendimethalin, prometryn and trifluralin in various environmental compartments, including runoff and groundwater.

These two approaches to risk assessment provided separate appraisals of the likely risk to selected species in the ecosystem by glyphosate compared to the use of other herbicides. The results from PIRI, which are not presented here, showed that GM herbicide-tolerant scenarios would result in less risk than the conventional herbicide weed control programs assessed. These results were supported by the risk analyses presented below, calculating the risk associated with individual herbicide use.

Relative risk (RR) was expressed by comparing the toxic exposure of the herbicides of two common wetland species, rainbow trout (*Oncorhynchus mykiss*) and water flea (*Daphnia sp.*) following recognised risk assessment framework (Norton *et al.*, 1992; Suter II, 1993; US EPA, 1998; Sanchez-Bayo *et al.*, 2002). The field results were used to determine the probability of exposure and the likely level of exposure are given by the median value of all data collected (Table 2). Glyphosate was not detected in runoff water; therefore the detection limit was used for this assessment.

Exposure (X): Estimation of exposure is a key aspect of determining risk and knowledge of the concentrations (C) of pesticides in the ecosystem is essential to determine exposure. The following equation (2) was used to determine exposure (X):

$$X = C P^{t_{1/2}} (\text{BCF}) \quad (2)$$

The probability of exposure (P) is determined by the frequency of positive values 'n(+)' for each chemical compared to the number of samples in the data set "N". The half-life ($t_{1/2}$) is included to represent persistence and "BCF" refers to the bioconcentration factor in organisms (Chiou *et al.*, 1977).

A summary concentration calculations used for the ecosystem risk assessment is shown in Table 2. The median data were used to determine the exposure as they are considered to give a more realistic representation of the runoff data for risk assessment purposes. Averaged data are often skewed too low and are therefore not useful for sensible ecosystem management. As shown in Table 2 glyphosate had the lowest probability of detection. In the case of glyphosate a negative BCF factor is specified because of its extremely low affinity for organic matter. This value is obtained from a negative logKow was disregarded for the exposure calculations contained in Table 2.

Risk (R): Applying the information generated on exposure (X) and toxicity (Tox), $\text{Tox} = \text{LC}_{50}$ (Tomlin, 1999-2000) to the following equation (3) allows computation of the risk to the ecosystem:

$$R = X/\text{Tox} \quad (3)$$

The results of the risk assessment are presented in Table 3. The risk categories were assigned high ($R > 10$), medium ($10 > R > 1$), low ($1 > R > 0.01$) and negligible ($R < 0.01$) and were applied to obtain relative distribution within the results of the risk assessment.

Table 2: Median herbicide concentration in runoff water calculated from the field trials and determination of exposure of each chemical to the ecosystem

| Chemical | Median (μgL^{-1}) | Probability (P) = n(+)/N | Half-life ($t_{1/2}$) | BCF | X = C * P * $t_{1/2}$ *BCF |
|-------------|--------------------------------|--------------------------|-------------------------|--------|----------------------------|
| Glyphosate | <50 ^a | 0.33 ^b | 22 | (-2.6) | 363 |
| Diuron | 43.68 | 1.00 | 60 | 3.2 | 8255.5 |
| Fluometuron | 11.9 | 1.00 | 85 | 2.7 | 2761.4 |

| | | | | | |
|---------------|------|------|----|-----|-------|
| Prometryn | 2.09 | 1.00 | 60 | 3.4 | 423.9 |
| Pendimethalin | 1.91 | 1.00 | 21 | 5.2 | 209.8 |
| Trifluralin | 0.42 | 0.89 | 25 | 4.9 | 45.6 |

^a using a concentration of 50 µg L⁻¹ (aquatic limit of reporting) and disregarding negative BCF

^b sediment only

Table 3: Relative risk scores and categories of the herbicides used in the field trial scenarios

| Chemical | Risk Quotient | | | |
|---------------|---------------|------------|----------------|------------|
| | Trout | Category | <i>Daphnia</i> | Category |
| Glyphosate | <0.0004 | Negligible | <0.0004 | Negligible |
| Diuron | 7.5 | Medium | 0.2 | Low |
| Fluometuron | 0.05 | Low | 0.3 | Low |
| Prometryn | 0.08 | Low | 0.01 | Low |
| Pendimethalin | 4.2 | Medium | ID | - |
| Trifluralin | 1.1 | Medium | 0.08 | Low |

ID Insufficient data

The summary of results in Table 3 (above) show that glyphosate presents the lowest risk to the species assessed, with a risk quotient many orders of magnitude lower than applications using other commonly used herbicides. Thus, from this analysis, increasing amounts of glyphosate applied could be applied without much effect on the degree of risk.

This project used fugacity modelling (Mackay, 2001) to assess a variety of theoretical herbicide scenarios to compare and contrast ecological risk of a range of potential herbicide applications. The main purpose of the fugacity model was to produce an estimation of the concentration of herbicides in runoff for a larger range of herbicides than could be included in the field study. When possible these concentrations were validated by the analysis of the samples collected during the field study. The complete set of runoff data obtained from the fugacity modelling were used to assess the risk of the theoretical herbicide treatments based upon the toxicity of the two wetland species as detailed previously. A hazard quotient was determined for each herbicide and given a score to compare relative risks.

The results from the theoretical scenarios presented in Figure 3 showed good agreement with the risk categories determined for the actual field experiment scenarios (Table 3). Diuron and trifluralin consistently gave high risk to trout and low and medium risk respectively to *Daphnia*. The fluometuron assessment indicated high and medium risk existed for *daphnia* and trout respectively. The theoretical scenarios allowed metolachlor, pyriithiobac-sodium and clethodim to be assessed and these results showed that the risk of using these chemicals at the indicated rates was very low. The risk associated with the use of glyphosate was consistently found to be negligible.

Whilst desktop approaches are useful to indicate likely risks, risk assessments using real data provide a more reliable basis for management decisions.

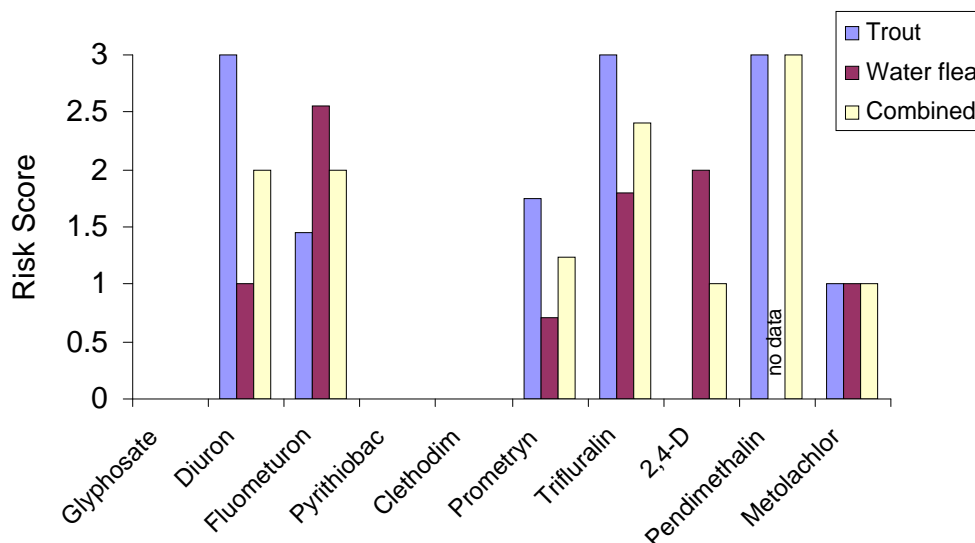


Figure 3: Risk score for each herbicide; presented as averages of all scores from all scenarios

Another means of assessing risk is to use the frequency of residue detection to calculate the probability of exceeding water quality guidelines. This can give a better understanding of the actual impacts from herbicide use. Probabilistic risk assessments are considered the ultimate development and most recent form of ecological risk assessment (ECOFRAM 1998, Solomon *et al.*, 2000). A probabilistic approach was developed from data obtained in the Roundup Ready field project by calculating the frequency of exposure using the range of environmental concentrations found in data from the field study.

Table 2 shows this probabilistic risk assessment used to calculate probabilities of exceeding the ANZECC water quality guidelines under usual cotton farming practices. It is clear that the probability of exceeding the water quality value of glyphosate is extremely low. No guideline values for fluometuron, prometryn or pendimethalin could be obtained and therefore MRL values for cotton seed and oil seed were used to enable a limited comparison.

Table 4: Comparison of probabilities that use will result in runoff water exceeding the nominated guideline value.

| Chemical | Guideline ($\mu\text{g L}^{-1}$) | Probability of exceeding guideline value |
|-----------------------------------|------------------------------------|--|
| Diuron (ID ^b) | 0.2 | 0.80 |
| Trifluralin | 2.6 | 0.58 |
| Fluometuron (MRL ^a) | 100 | 0.08 |
| Prometryn (MRL ^a) | 100 | 1.0×10^{-05} |
| Pendimethalin (MRL ^a) | 50 | 3.0×10^{-06} |
| Glyphosate | 370 | 1.9×10^{-10} |

^a Where no ANZECC/ARMCANZ (2000) guideline values were prescribed MRL values were used.

^b Refers to the ANZECC/ARMCANZ (2000) "Insufficient Data" condition and therefore a value with greater sensitivity is prescribed.

This suggests the precautionary guideline value for diuron would be exceeded eight times out of ten. In contrast, a cotton farmer is five hundred times more likely to win a lottery jackpot (with a probability of one in 10 million) than exceed the guideline value for glyphosate (probability one in five billion $\sim 1.9 \times 10^{-10}$).

In addition to the reduction in environmental risk outlined above, Roberts (1998) study at Bellata compared conventional herbicide strategies with a glyphosate-tolerant strategy. It found that, provided the variety cost plus glyphosate cost did not exceed the current weed control strategy costs, there would be a definite gain. Thus, cost competitive technology was predicted to be taken up by growers resulting in economic and environmental gains. This was believed to be largely a result of the use of post-emergent herbicides to improve the ability to control weeds without the costs of cultivation combined with greater flexibility in crop rotation from reduced need for the use of residual herbicides.

Since the availability in Australia of Roundup Ready cotton, studies have examined actual costs of the use of the technology (Taylor, 2003). For low weed pressure scenarios a yield benefit of \$225 per hectare was obtained. Flow on costs, including labour and associated spray costs, gave a total benefit of \$395 per hectare, including the license fee (Taylor, 2003). These economic benefits are one explanation for the extremely rapid uptake of the Roundup Ready technology in the Australian Cotton industry.

Roundup Ready weed control technology can give farmers more options for the control of weeds and allows farmers to tailor their approach to the specific agronomic restraints of each farm. Herbicide-tolerant crops allow a shift to conservation tillage, providing other environmental benefits. Conservation tillage practices decrease soil erosion, increase water and nutrient retention and increase soil organic matter.

The technology affords growers the freedom to wait until the growing season before making herbicide application decisions. This avoids precautionary use of potentially unnecessary and environmentally more risky pre-season residual herbicides. The grower must decide to pay for the Roundup Ready trait at the time of seed purchase, however if the crop fails prior to a planting audit at the end of November, no payment is required. Thus, the financial risk is lower than relying on non-refundable pre-emergent herbicides to control weeds.

To facilitate the introduction of more environmentally sustainable pesticides and to meet the challenges facing modern agriculture, improved practices need to be adopted. Improvements often require a change in technology. Such changes can be controversial, especially where perceptions may not be informed by scientific methodology. Changes in herbicide technology also give rise to a change of weed spectrum or "species shift". There is evidence that the introduction of glyphosate has changed the weed spectrum within Australian cotton properties, favouring glyphosate tolerant, small seeded, biannual and perennial weeds (Charles *et al.*, 2004). The benefits of glyphosate, as with any new technology, need to be managed within an integrated weed management program. Assessment and integration of all new technology should be conducted on a case-by-case basis and include measurements of economy, environment and efficacy.

As this study shows it is prudent to validate risk assessments using the field data collected from monitoring programs. This enables the confirmation of any assumptions made during the assessment. The field data were used to validate the model calculations and to provide a greater understanding of the environmental behaviour of the chemicals studied. Data collected in the laboratory are never equivalent to the more realistic measurements obtained from the field. Correctly interpreted, the data collected from coordinated monitoring programs can contribute to the responsible management of agrochemicals.

The Roundup Ready field project has provided valuable information regarding the environmental fate and transport of glyphosate in Roundup Ready cotton systems. From both field measurements and desktop modelling tested by field measurements, it was shown that the glyphosate herbicide, due to its low toxicity and low mobility, presents an extremely low risk of contamination and rates very well against other herbicides.

The use of glyphosate in combination with other low risk herbicides for weed control with Roundup Ready cotton provides an opportunity to significantly reduce the risk of off-site herbicide contamination in cotton production. Therefore, by choosing herbicide programs that contain "lower risk" herbicide options, it is possible to minimise risk to the environment as well as provide growers with good crop performance and economic benefits.

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