AFPP – VINGT ET UNIÈME CONFÉRENCE DU COLUMA
JOURNÉES INTERNATIONALES SUR LA LUTTE CONTRE LES MAUVAISES HERBES
DIJON – 8 ET 9 DÉCEMBRE 2010

ADDRESSING THE DEVELOPMENT OF GLYPHOSATE RESISTANT WEEDS IN SUSTAINABLE AGRICULTURE

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SUMMARY
Monsanto is committed to sustainable agriculture and the use of techniques to meet current needs as those of future generations. The herbicide tolerant crop systems contribute to the key goals of sustainability which are to produce more, conserve more while improving grower's lives and feeding a growing world population. Experience has demonstrated that the benefits of the glyphosate tolerant crop systems are preserved by the adoption of proactive management practices to address the potential for the development of resistance to glyphosate as well as other herbicides within the system. The objectives of this article are to review the world wide status of glyphosate resistant weeds and to share the knowledge gained from the use of the Roundup Ready® system across the world areas.

Key words : Weed resistance, glyphosate, Roundup Ready®, sustainable agriculture.

RÉSUMÉ
GERER LE DEVELOPPEMENT D'ADVENTICES RESISTANTES AU GLYPHOSATE DANS L'AGRICULTURE DURABLE
Monsanto s'engage dans l'agriculture durable et dans l'utilisation de techniques répondant aux besoins actuels comme à ceux des générations futures. Les systèmes de cultures tolérantes aux herbicides y contribuent dans les trois dimensions que sont productivité, environnement et amélioration de la qualité de vie des agriculteurs. L'expérience montre que les bénéfices des systèmes de cultures tolérantes au glyphosate sont préservés par l'adoption de pratiques intégrées limitant le potentiel de développement d'adventices résistantes au glyphosate comme à d'autres herbicides. Cet article présente la situation mondiale du développement d'adventices résistantes au glyphosate et reflète l'expertise acquise de l'utilisation des systèmes Roundup Ready® dans le monde.

Mots-clés : Adventice résistante, glyphosate, Roundup Ready®, agriculture durable.

INTRODUCTION

Controlling weeds is paramount for optimum crop production. Unlike insect pests and diseases, which occur in some years and not others, weeds are ubiquitous. They return every year from millions of seeds, tubers or rhizomes, deposited in the soil from plants that survive in the field, field edges, and irrigation ditches, and spread from field to field on application and harvesting machinery. Potential crop losses from weeds have been estimated to be 30-40% of total productivity for corn, soybeans and cotton if left uncontrolled (Oerke, E.C., 2006). Implementing sustainable weed management programs are a critical part of agricultural sustainability.

Conservation tillage contributes to the long-term sustainability of farming practices and weed management using herbicides is a key component of conservation tillage (ASA, 2001). Conservation tillage has significantly reduced the loss of topsoil due to soil erosion, improved soil structure with higher organic matter, reduced runoff of sediment and fertilizer, reduced on-farm fuel use, reduced CO_2 emissions, and increased carbon sequestration in soil in the U.S (CTIC 2009; Fawcett and Towry, 2002: ASA 2001).

Modern herbicides, equipment innovations and strong benefits oriented education programs have contributed to the growth of conservation tillage in the U.S., Argentina, Brazil and other countries. U.S. growers have consistently indicated that Roundup Ready® technology has been an important innovation allowing them to shift to conservation tillage (Givens et al, 2009). Implementing best practices for weed control and herbicide resistance management are total part of sustainable agricultural systems. "Herbicide resistance" is by definition the inherited ability of a plant to survive and reproduce following exposure to a dose of herbicide normally lethal to the wild type, usually the labeled rate.

Resistance can evolve in any weed population, if it's subjected to enough selection pressure by a particular herbicide and if it contains individuals that carry specific genetic code(s) capable of rendering those individuals safe to the lethal effects of an herbicide. The application of an herbicide to weed populations does not, itself, cause a mutation in subsequent generations. Rather, over time, those biotypes that are not susceptible become dominant in the population with repeated use of the herbicide in the absence of other control methods, such as, use of herbicides with different mechanisms of action and/or use of mechanical and/or cultural methods. The development of resistant populations is common to most herbicides but the probability of resistance is not the same for all. The probability for resistance is a function of: frequency of resistant allele(s), dominance or recessive nature of the resistant allele(s), relative fitness of the resistant biotype, mechanism of resistance and frequency of the use of herbicides of the same mode of action in the absence of other control methods.

Concern about increase in resistance to individual herbicides and concern about the evolution of weed populations with resistance to multiple herbicides is leading to a need for greater adoption of proactive management programs. Monsanto in cooperation with public sector, weed scientists etc. is active in promoting the use of best management practices for sustainable weed management practices.

GLYPHOSATE RESISTANT WEEDS : GLOBAL STATUS AND CONTRIBUTING FACTORS

The number of glyphosate resistant weed species world-wide is relatively low compared to the number of weeds resistant to other chemical herbicide families, such as PS II and ALS inhibitors. As of October 2010, 20 weed species are reported to have developed resistance to glyphosate worldwide after over 35 years (Heap I., 2010).

Glyphosate resistance weed populations have evolved in three separate agricultural settings: fallow, perennial crops (orchards or vineyards), and glyphosate tolerant crops (Table I). In all three situations, a primary factor contributing to the evolution of resistance has been the sole reliance on glyphosate in the absence of other control methods over an extended period of time. In addition, the repeated use of low rates and/or applications beyond the recommended growth stage and lack of tillage have also been identified as important contributing factors. The association of the occurrence of weed resistance with reduced tillage is believed to be more the indirect effect of the over reliance on glyphosate rather than a direct cause.

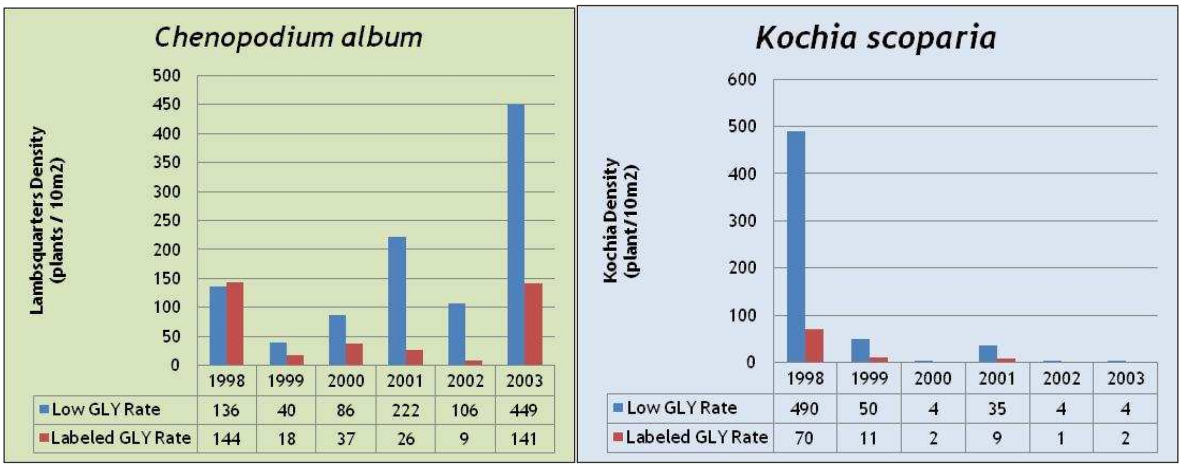
Table I : Situations of the glyphosate resistant weeds (Heap I., 2010)
Situations des adventices résistantes au glyphosate (Heap I., 2010)

Genus	**Year First Reported**	**Country**	**Situation**
Amaranthus palmeri & *tuberculatus* (syn. *rudis*)	2005	USA	RR soybeans / RR cotton
Ambrosia artemisiifolia & *trifida*	2004	USA	RR soybeans
Conyza bonariensis, *canadensis* & *sumatrensis*	2000 / 2003 / 2009	USA / S. Africa /Spain	RR soybeans / Vineyards / Orchards
Digitaria insularis	2006	Paraguay	RR soybeans
Echinochloa colona	2007	Australia	Fallow
Eleusine indica	1997	Malaysia	Orchards
Euphorbia heterophylla	2006	Brazil	RR soybeans
Kochia scoparia	2007	USA	Fallow, RR corn, RR soybeans
Lolium multiflorum, *perenne* & *rigidum*	1996 / 2001 / 2008	Australia / Chile /Argentina	Fallow / Orchards / various crops
Parthenium hysterophorus	2004	Colombia	Orchards
Plantago lanceolata	2003	S. Africa	Vineyards
Poa annua	2010	USA	Turf
Sorghum halepense	2005	Argentina	RR soybeans
Urochloa panicoides	2008	Australia	Fallow

For some species, the herbicide dose rate was found to be a factor contributing to the development of weed shifts and possibly resistance. Within weed populations, the dose rate is a factor determining weed shift. Figure 1 shows the evolution of the weed density across years for two specie, averaged over two rotations of glyphosate-resistant (GR) crops (one is continuous GR corn, and the other one is rotation of GR corn, sugarbeet and spring wheat), when continuously using glyphosate. The experiment shows that continuously using glyphosate at low rate increases the density of *Chenopodium album*, while managing the population of *Kochia scoparia*.

Figure 1 : Glyphosate-Induced Weed Shifts in Glyphosate Resistant (GR) crop rotations (average GR corn monoculture and GR corn, sugarbeet and spring wheat) (Wilson *et al*, 2007)

Changements de flore occasionnés par le glyphosate dans des rotations de cultures tolérantes au glyphosate (moyennes monoculture de maïs et rotation maïs, betterave et blé de printemps) (Wilson et al, 2007)



GLYPHOSATE RESISTANT WEEDS : MANAGEMENT PRACTICES

There are multiple options for controlling glyphosate resistant populations. A number of chemical options for use in corn, cotton or soybeans are listed in Table II. More broadly, weed management diversity is the foundation of proactive resistance management. Also, herbicide mixtures, whose components are equally effective against the target weed species, are predicted through model simulations to delay resistance longer than rotations (Diggle *et al*, 2003).

For example, when growing glyphosate tolerant corn several years in a row, one could integrate multiple in-crop weed management options through multiple herbicidal modes of action in tank mix or in sequence :

The weed control program would be based

- in year 1 on acetanilide + triazine followed by glyphosate,
- in year 2 on acetanilide followed by glyphosate + auxins
- in year 3 on acetanilide + triazine followed by glyphosate

In crop rotation systems, the various weed management options can be integrated across crops and fallow periods. For example :

- Year 1 – cultivated with wheat – Weed control based on sulfonylureas and auxins
- Year 2 – cultivated with RR soybean – Weed control based on glyphosate
- Year 3 – cultivated with RR corn – Weed control based on acetanilide, triazine and glyphosate.

These rotation templates have various options for local adaption on farm level. Additionally it is obvious that proactive management of resistance has proven more beneficial, both for agronomic and economic reasons, than the reactive management of resistant weeds.

Table II : Chemical options for managing glyphosate-resistant weeds
Matières actives contrôlant les adventices résistantes au glyphosate

Resistant Species	Options
Amaranthus spp.	Triazine, HPPD (corn) PPO (cotton) PPO, Triazines, ALS (soybeans)
Conyza	ALS, PPO (vineyards, orchards) Auxins (2,4-D, dicamba) (corn, preplant) ALS, Triazines, PPO (soybeans)
Ambrosia spp.	PPO, ALS, Triazines (soybeans) HPPD, ALS, Triazines (corn)
S. halepense *D. insularis*	ACCase, Acetanilides (soybeans, cotton) SU, Acetanilides (corn)
Lolium spp.	ACCase, paraquat, glufosinate (fallow, orchards, vineyards) ACCase, Acetanilides (soybeans, cotton) ALS, Acetanilides (corn)

MONSANTO STEWARDSHIP PROGRAMS

Robust stewardship programs are key to effectively manage weed shifts and the evolution of herbicide resistance. To develop the appropriate stewardship programs for glyphosate, Monsanto focuses significant resources on research about:

- Mechanisms of glyphosate resistance
- Weed biology and modelling of weed population dynamics
- Identification and distribution of best practices to retard development of resistance and management of existing problems
- Development of sustainable valid options

Another important component of a stewardship program is weed resistance monitoring. The objective of such monitoring is the early detection of resistance in new species and to determine the spread of resistance to new areas. Various options can be considered for this objective:

- Long-term field studies,
- Random collection of weed seed from grower's fields and grow-outs,
- Systematic monitoring of selected grower fields and recording of weeds present,
- Monitoring of grower performance issues with appropriate follow-up.

Experience to date indicates that neither long-term field studies nor systematic monitoring of grower fields and taking weed counts have been effective in providing a way for early detection. However, coordinated efforts by industry, farm consultants and universities to monitor grower performance and conducting follow up testing has been a useful way for early detection (Dubois and Plancke, 2010). The collection of weed seed from plants surviving at the end of a growing season has been useful for identifying the spread of resistance.

Grower training and education programs are also important parts of Monsanto's stewardship programs. Monsanto in collaboration with universities has implemented grower surveys in the U.S. to better understand grower attitudes toward resistance and to track grower adoption of best management practices. Table III displays the adoption rate of best practices to avoid weed resistance development to US growers. It shows that most of the practices are well adopted by the growers. The areas where improvement can significantly be gained are the cleaning of the equipment, the use of different herbicidal modes of action and supplemental tillage.

Table III : Frequency of adoption of best management practices as a result of education programs in the US (Frisvold *et al*., 2009)

Fréquence d'adoption des bonnes pratiques à la suite de programmes de formation aux USA (Frisvold et al., 2009)

Best Practices	**Always or Often**	**Sometimes**	**Rarely or Never**
Scout before	83%	11%	5%
Scout after	81%	15%	4%
Start with clean field	75%	13%	12%
Control early	89%	9%	2%
Control escapes	79%	15%	6%
Clean equipment	25%	20%	54%
New seed	94%	3%	2%
Different modes	39%	33%	28%
Supplemental tillage	21%	26%	53%
Use label rate	93%	4%	1%

Monsanto's recommendations for proactive management of resistance are in line with the general principles of herbicide resistance management of the Herbicide Resistance Action Committee (HRAC):

- Apply integrated weed management practices. Use multiple herbicide modes-of-action with overlapping weed spectrums in rotation, sequences, or mixtures.
- Use the full recommended herbicide rate and proper application timing for the hardest to control weed species present in the field.
- Scout fields after herbicide application to ensure control has been achieved. Avoid allowing weeds to reproduce by seed or to proliferate vegetatively
- Monitor site and clean equipment between sites.

CONCLUSION

Monsanto views weed management as a significant component of sustainable agriculture. Monsanto is focused on developing innovative approaches and on collaborating with public and private initiatives that promote best practices. Specifically, the principles of Monsanto's weed resistance stewardship program are :

- Commitment to follow-up on performance complaints and situations in which weed resistance is suspected
- Transparency according to a clear and open process : where resistance has been confirmed by established valid criteria, we acknowledge and communicate and recommend practices to manage the resistant weed
- Provide management solutions, information, and training to growers so they can continue to be successful with the glyphosate tolerant systems and glyphosate herbicide
- Maintain close cooperation with all outside parties involved with weed resistance (Industry, Academics, Commodity Groups, Regulators) to provide the best solutions to growers.
- Maintain a leadership position in research on glyphosate resistant weeds and best management practices
- Discover and provide new options for more effective weed control management

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