Implementing Integrated Weed Management for Herbicide Tolerant Crops

CropLife INTERNATIONAL

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Acknowledgements

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Terminology

Agricultural biotechnology is a collection of modern scientific techniques which improve domesticated plants, animals, or microbes to enhance their traits with regard to ease of efficiency of production or their end use qualities and characteristics. Scientists are able to move genes (and therefore desirable traits) with greater ease and precision in ways that they could not do before using only conventional techniques such as selective breeding. Theoretically, these techniques can be used to move genes between any organisms and are used to improve or modify plants, animals and microbes.

Biotech-derived plants. Plant products derived from modern biotechnology by means of (1) *in vitro* nucleic acid techniques, including recombinant deoxyribonucleic acid (DNA) and direct injection of nucleic acid into cells or organelles; or (2) fusion of cells beyond the taxonomic family, that overcome natural physiological reproductive or recombinant barriers and that are not techniques used in traditional breeding and selection. This definition of modern biotechnology has been adopted by the Cartagena Biosafety Protocol under the Convention on Biological Diversity and the Codex Alimentarius Commission.

Conventional (or **traditional) breeding** methods are those that have been used historically prior to genetic engineering, and include mutation breeding, selective breeding, and/or tissue culture.

Conventional tillage is the common practice of cultivation to kill weeds and prepare the seedbed prior to planting a crop.

Elite germplasm are plant materials of proven genetic utility, including existing germplasm in commerce or in an advanced stage of development.

Event is a genotype produced from the transformation of a plant species using a specific genetic construct. For example, two lines of the same plant species that are transformed with the same or different constructs constitute two events.

Gene flow is the movement of genes between organisms, occurring primarily through sexual reproduction.

Genes are functional segments of a DNA molecule made up of nucleotides arranged in a specific sequence. Genes encode for specific proteins or RNA molecules.

Gene stacking is the combining of genetic traits (such as herbicide tolerance and insect resistance) in a single crop variety.

Genetically engineered plant material (also known as biotech-derived plant material) is material from plants derived through recombinant DNA techniques.

Germplasm is an individual, group of individuals, or a clone representing a genotype, variety, species, or culture, held in an *in situ* or *ex situ* collection.

Herbicide drift is the unintended movement of herbicide from the treatment area to an adjacent non-target area during herbicide application. Drift occurs in two ways: *via* physical means at the time of application; and *via* volatility which occurs after application, such as vapour moving off leaves on hot/humid days. Herbicide drift can result in costly crop damage to neighbouring susceptible crops.

Herbicide tolerant crops are varieties developed to survive herbicides that would normally have destroyed the crop. Farmers can use herbicide tolerant crops to apply highly effective, broad spectrum, post emergence herbicides for weed control without damaging the crop. Herbicide tolerant crops may be derived from conventional plant breeding, mutation breeding, or through genetic engineering.

Integrated weed management (IWM) is a strategy for weed control that considers the use of all available weed control techniques, including preventative measures, monitoring, crop rotations, tillage, crop competition, herbicide rotation, herbicide mixtures, biological controls, nutrition, irrigation, burning, *etc.* IWM does not solely rely upon herbicides for weed control.

Isolation distance is a space between fields that is used to minimise pollen flow and agrochemical drift between crops.

Mutation breeding involves the treatment of organisms with chemicals or ionising radiation to produce random changes in their DNA (mutations) with the hope of finding useful traits.

No-till or **Zero-till** indicates direct seeding into the soil through the previous year's crop residue. Instead of using cultivation to kill weeds prior to seeding, the growers use a pre-planting knockdown herbicide application, such as glyphosate or paraquat. Compared to conventional tillage, zero-till reduces soil erosion, conserves moisture, improves soil structure, increases organic matter, and reduces fuel use.

Plant breeding is the process of crossing plants with the aim of moving desirable traits (carried on genes) from one plant to another to improve plant varieties.

Recombinant DNA techniques are scientific procedures used to join (recombine) DNA segments. This technology makes it possible to take a gene from any species and place it into almost any other species.

Resistance describes the inherited ability of a plant to survive and reproduce following exposure to a dose of herbicide normally lethal to the wild type.

Rotation is the practice of growing different crops in succession on the same land.

Tolerance has been used interchangeably with "resistance" when referring to crops that have been altered to make them resistant to herbicides. The use of the term tolerance should not be applied to weeds, which are described as "herbicide resistant weeds". (See Resistance.)

Transformation is the process of incorporating DNA into an organism's genome. There are several methods to do this in plants, of which *Agrobacterium*-mediated transformation and biolistic transformation are most commonly used.

Transgenic plants (or biotech-derived plants) have genetic material from another organism inserted into them, or their own genes modified, so that the plant will exhibit a desired trait, such as herbicide tolerance. This is usually achieved through recombinant DNA techniques.

Trial site is a field planted with experimental plants.

Weed resistance is the evolved capacity of a previously herbicide-susceptible weed population to withstand a herbicide and complete its life cycle when the herbicide is used at its normal rate in an agricultural situation.

Weed shifts are a change in the weed spectrum that can result from a change in management practices. Almost any change in management practice can result in a change in the weed spectrum at a specific location.

Volunteer crop plants are plants of the same species as the crop that may germinate and grow in the subsequent seasons from viable plant material remaining in the soil.

Weed spectrum describes the collection of weed species that exist on a given site. The weed spectrum may be narrow (one or two species) or wide (hundreds of different species), and is dependent on many factors, such as climate, soil fertility, competition from other plant species, and management practices.

1. Executive Summary

Herbicides have revolutionised weed control in farm cropping systems since the 1940s by increasing the farmer's ability to control unwanted plants that might compete with crops for light, nutrients and water. The development of herbicide tolerant crops has been a major advance in weed control. These crop varieties are able to tolerate exposure to specific herbicides that would normally kill them.

Integrated weed management is equally applicable for all types of farming systems.

Herbicide tolerant crops may be derived from conventional breeding techniques, such as mutagenesis and tissue culture, or through biotechnology genetic modification techniques. Biotech-derived herbicide tolerant crops have been grown in North America since 1996 and include soybean, canola, maize, cotton, alfalfa, rice and sugar beets. These herbicide tolerant crops offer the farmer some distinct advantages in combating weeds, which may include simplified weed control, better weed control, reduced crop injury, less expensive weed control, less herbicide carryover, control of existing resistant weeds, reduced tillage, and reduced environmental impact. However, herbicide tolerant crops may also present some management challenges, such as weed shifts, herbicide resistant weeds, yield performance, gene flow, herbicide drift and volunteers.

Over-reliance on a single herbicide without the use of an integrated weed control approach can lead to species shifts and the establishment of herbicide resistant weeds. The weed shifts and herbicide resistance management challenges associated with herbicide tolerant crops are a function of how the associated herbicides are used. In this context resistance development is no different than for other herbicides used in crops to which there is natural selectivity.

Integrated weed management (IWM) is a strategy for weed control that considers the use of all economically available weed control techniques without relying on only one of these. Weed control mechanisms include preventative measures, monitoring, crop rotations, tillage, crop competition, herbicide rotation, herbicide mixtures, biological controls, nutrition, irrigation, burning, *etc.* Herbicide tolerant crops are a relatively new weed management practice used to enhance integrated weed management programmes. They have proved effective in crop production and stewardship programmes such as integrated weed management have been encouraged to help prevent the development of herbicide resistant weeds, which could negate the use and value of herbicide tolerant crops.

Importantly, integrated weed management is equally applicable for all types of farming systems and growers are encouraged to implement these strategies for conventional and biotech-derived crops.

Over-reliance on a single herbicide without the use of an integrated weed control approach can lead to species shifts and the establishment of herbicide resistant weeds.

M. Koch

2. Introduction

Agriculture began about 12,000 years ago with the cultivation of barley, lentils, wheat, and peas in an area known as the Fertile Crescent in present day Iraq (Bakker, 1980). These early farmers identified and selected useful traits (*e.g.*, large spikes, higher yield, non-shattering seed pods) and began the process of genetically modifying our crop plants. Over the last 100 years there have been steady increases in crop production in the developed world through breeding programmes and the application of new farming technologies. Plant breeders have used selection to identify improved characteristics in many staple crops.

Since the beginning of crop production man has sought ways to control weeds. Weeds are a major problem, because when left uncontrolled they can cause over 80% yield loss. Major strides in weed control have been made over the last 60 years primarily due to the introduction of modern herbicides, beginning with the synthetic auxins such as 2,4-D. Herbicide tolerant crops became the next major advance in weed control and much has been written about the pros and cons of herbicide tolerant crops (James, 2006b). Bearing in mind that integrated weed management is relevant to all types of crop farming, it is the aim of this manual to present the benefits and challenges of growing herbicide tolerant crops, along with information on how to integrate them into an overall weed control programme. Before getting into the details of integrated weed management it is necessary to provide background on weeds, herbicides, and herbicide tolerant crops.

Weeds are a major problem, because when left uncontrolled they can cause over 80% yield loss.

2.1. STEWARDSHIP

Since the earliest days of plant biotechnology, researchers and technology providers have focused on stewardship practices to help ensure the safety of biotechnology products and to promote the responsible use of this technology. CropLife International[1] and its members are committed to the responsible management of every product through each stage of its life cycle, from inception, through research and product development, to commercialisation, and eventually to product discontinuation. The plant science industry is committed to ensuring compliance with science-based regulations worldwide and promoting responsible use of the technology.

The plant science industry recognises that stewardship is a global issue.

CropLife International promotes a life cycle approach to the management of plant biotechnology products. The overall aim of this stewardship approach is to maximise the benefits and minimise any risk from using plant biotechnology products. The plant science industry is committed to promoting full and effective stewardship at the field level, and believes that the appropriate management and use of its products is a fundamental element of sustainable agriculture and optimising benefits while protecting the environment and public health.

The plant science industry also recognises that stewardship is a global issue. That is, development and production may occur in a different country or region than a product's eventual use, so appropriate tools need to be in place to ensure management of the whole product cycle. While stewardship efforts must be globally harmonised, they must be locally applied and relevant to individual regions and their regulatory frameworks.

CropLife International and its network of regional associations have established a guiding philosophy of proactive self-regulation, through which technology providers can work responsibly to protect people, animals, and the environment in order to help ensure a sustainable, healthy, abundant, and accessible food supply. The plant science industry is committed to doing its part to promote safety and trust in the world's food supply, and to support smooth trade transactions in the agricultural community. In order to meet this commitment, the plant biotechnology industry has developed and implemented initiatives supporting product stewardship, quality management systems, and compliance with government regulations for biotech-derived plants.

CropLife International and its regional member associations host training workshops around the world on a variety of stewardship topics, such as compliance management for confined field trials, insect resistance management, integrated weed management, product launch stewardship and product discontinuation. In addition, CropLife International fully supports the Excellence Through Stewardship®[2] industry-coordinated initiative that has been implemented to

[1] CLI Life Cycle Product Stewardship. http://www.croplife.org/public/life_cycle_product_stewardship

[2] http://www.excellencethroughstewardship.org/

promote the global adoption of stewardship programmes and quality management systems for the full life cycle of biotech-derived plant products.

2.2. HERBICIDE TOLERANT CROPS

Herbicide tolerant crops are now well established in North America and many other cropping regions of the world (James, 2010). The rapid adoption of herbicide tolerant crops is evidence that this technology offers many advantages. Herbicide tolerant crops often provide simplified and better weed control at a lower cost and with reduced crop injury. They also are important components of reduced or zero tillage systems which conserve moisture, reduce soil erosion, improve soil structure and carbon content, and reduce fuel use. Herbicide tolerant crops have been particularly useful in allowing the use of new modes of action for the control of existing herbicide resistant weeds. However, as with all new technologies, there are real and perceived challenges to the introduction of herbicide tolerant crops. An increase in weed resistance and weed shifts are two of the most prominent concerns.

Herbicide tolerant crops have been particularly useful in allowing the use of new modes of action for the control of existing herbicide resistant weeds.

2.3. INTEGRATED WEED MANAGEMENT

Integrated weed management describes a weed control strategy that considers all available weed control techniques and combines them to provide economic and sustainable weed management. Integrated weed management does not rely solely on herbicides for weed control, as it includes techniques such as preventative measures, tillage, herbicides, crop competition, biological controls, nutrition, irrigation, burning, *etc.* Herbicide tolerant crops are a relatively new and powerful addition to the integrated weed management toolbox.

There is potential for gene flow between related crops and weeds, and from volunteers of the current 54 herbicide tolerant crops that may require different management in subsequent seasons (Cerdeira & Duke, 2006). In some cases, herbicide tolerant crops have been perceived by growers as a total weed control solution which may result in over-reliance on a single herbicide for weed control. The result of reliance on one herbicide for weed control is often weed shifts and the evolution of herbicide resistant weeds. This is true whether utilising herbicide tolerant crops or conventional varieties. When weeds develop resistance, farmers are faced with greater management complexity and often higher weed control costs. To reduce the appearance of herbicide resistant weeds and weed shifts, it is imperative that growers draw upon a wide range of weed control practices to complement the use of their herbicide tolerant crop technology. The integrated use of a wide array of weed control practices is known as Integrated Weed Management and is widely encouraged for both conventional and biotech-derived herbicide tolerant crops.

Integrated weed management considers all available weed control techniques and combines them to provide economic and sustainable weed management.

This manual provides guidelines for incorporating herbicide tolerant crops as a successful tool in Integrated Weed Management Programmes.

3. Background on Weeds and Herbicides

3.1. WEEDS

Weeds are plants that grow where they are not wanted and negatively impact on human activities. Their undesirable qualities are considered to outweigh their good points. Plants may be considered weeds if they:

- Impact on crop production by
  - Reducing crop yields through competition for nutrients, moisture, and light;
  - Reducing crop quality through contamination of the crop with weed seed or plant material;
  - Reducing crop yields through production of chemicals toxic to the crop (allelopathy);
  - Disrupting crop harvesting by clogging harvesting equipment; and
  - Harbouring insects and diseases of crops as alternate hosts;
- Pose a health risk
  - Directly to humans by being poisonous, such as water hemlock and poison ivy;
  - To livestock by being toxic, such as tansy ragwort;
  - Through creating unsafe conditions
    - By blocking visibility, which may present a traffic hazard; and
    - By presenting a fire risk;
- Out-compete and displace native vegetation; and
- Lower property values when they are aesthetically unpleasing.

This training manual focuses on weeds that impact crop production. These weeds are typically plants that spread easily in crop fields or in disturbed areas. A plant's "weediness" is a measure of its success in colonising and displacing other species (Baker 1965; Williamson, 1994). While any plant can be considered a weed, weeds often:

- Grow rapidly;
- Are highly competitive;
- Produce a large amount of seed;
- Survive and produce seed under a wide range of environmental conditions;
- Have seed dormancy; and
- Have special adaptations to assist in seed or vegetative dispersal.

Weeds are plants that grow where they are not wanted and negatively impact on human activities.

M. Koch

3.1.1. Types of weeds

Weeds can be classified in numerous ways. Sometimes weeds are classified as broadleaves (dicotyledonous plants) and grasses (monocotyledonous plants). Another common way to classify weeds is by their lifespan – annuals, biennials, and perennials.

Annual weeds

Annual weeds complete their lifecycle within a year. There are two types of annual weeds: summer annuals and winter annuals.

- Summer annual weeds emerge in the spring or early summer, grow during the summer, and set seed in late summer before being killed by frosts. Some common summer annual weeds are barnyard grass (*Echinochloa crus-galli*), green foxtail (*Setaria viridis*), goosegrass (*Eleusine indica*), common lambsquarters (*Chenopodium album*), pigweed (*Amaranthus sp.*), purslane (*Portulaca oleracea*), and ragweed (*Ambrosia sp.*).
- Winter annual weeds germinate in the fall and begin growth. They over-winter as small plants and grow vigorously in the early spring, *e.g.*, wild mustard, marestail/horseweed, pennycress.

Biennial weeds

Biennial weeds live for two years. In the first year they usually store up energy in short fleshy root systems and in the second year draw upon the stored reserves to grow rapidly and produce seed, *e.g.*, Canada thistle, field bindweed or quackgrass, and common mullein.

Perennial weeds

Perennial weeds live for two or more years. There are three categories of perennial weeds, simple perennials; creeping perennials; and bulbous perennials. While simple perennials reproduce only by seed, creeping perennials can reproduce by seed but also by creeping roots, creeping above ground stems (stolons) or creeping underground stems (rhizomes). Bulbous perennials reproduce by seed and by underground bulbs, *e.g.*, dandelion, goldenrod, poison ivy.

3.1.2. Impact of weeds on crop production

Weeds compete with crops for resources, light, nutrients, and soil water. Compared to other crop pests (insects, fungi, *etc.*), weeds have the greatest impact on crop yield and if left uncontrolled can result in more than 80% yield loss. Weeds account for over 25% yield loss in developing countries despite an average of 10 to 50 hours per acre of hand labour expended on weed control (Akobundu, 1991). In 1992 losses from weeds were evaluated at more than U.S.$ 8 billion per year in the USA (Bridges and Anderson, 1992; Reigner, 2005) despite growers spending more than U.S.$ 7 billion per year on herbicides and cultivation to control weeds (Chandler, 1991; Gianessi and Reigner, 2006).

Weeds account for over 25% yield loss in developing countries despite an average of 10 to 50 hours per acre of hand labour expended on weed control.

Oerke (2002) estimated the impact of weeds on six major crops globally – wheat, rice, maize, potatoes, soybean and cotton. He used Food and Agriculture Organization (FAO) data from 19 regions throughout the world and found that weeds had the potential to reduce crop yields by 23-40% and actually caused between 7-11% yield loss even after weed control practices such as herbicides or tillage had been used (Table 1).

Clearly weeds still have a major impact on crop production despite significant time and resources devoted to their control. There are many methods employed for weed control but herbicides are by far the most widespread and effective method in use today.

Table 1. Estimated loss potential of weeds and actual losses from weeds in six major crops worldwide from 2000 to 2001. Figures indicate the average, and the range (in brackets), of loss from weed control from 19 regions. Adapted from Oerke, 2002.

Crop	Attainable Production (M tons)	Potential Loss Due to Weeds (M tons)	Actual Loss Due to Weeds (M tons)
Wheat	785	23 (18-29)	7.7 (3-13)
Rice	933.1	37.1 (34-47)	10.2 (6-16)
Maize	890.8	40.3 (37-44)	10.5 (5-19)
Potatoes	517.7	30.2 (29-33)	8.3 (4-14)
Soybeans	244.8	37 (35-40)	7.5 (5-16)
Cotton	78.5	35.9 (35-39)	8.6 (3-13)

3.2. HERBICIDES

Since the introduction of agriculture, humans have battled weeds in an effort to reduce crop and livestock losses. Physical control of weeds such as hand weeding and primitive forms of tillage dominated early weed control. The Romans first introduced chemical weed control (approx. 300 BC) when they applied salt and olive oil to control weeds in crops and along roads after they noted that the ground became barren beneath their olive oil presses. In the 19th and 20th Centuries inorganic compounds such as sulphuric acid, copper and iron sulphate, lead arsenate, copper nitrate and sodium arsenate were used to control broadleaf weeds in cereal crops. In 1880 sprayers were developed to deliver a mist of herbicides. It was not until the 20th Century that the production of effective and selective herbicides was recorded. Synthetic herbicides (*e.g.*, 2,4-D, MCPA) were developed during World War II and eventually first marketed for weed control in 1944. These synthetic auxins revolutionised weed control and gave companies the impetus to research and develop the large array of herbicides on the market today.

Herbicides are heavily regulated in most countries and developers need to obtain approvals from many different regulatory agencies.

Triazine herbicides ushered in a new era of pre-emergent weed control in maize and other row crops, as well as vineyards and orchards (LeBaron *et al.*, 2008). Simazine was the first triazine to be used commercially in 1956. It was developed by J. R. Geigy in Switzerland and approved for use on maize, asparagus, grape rootstocks and rights-of-way. In 1958, the herbicide atrazine, also developed by Geigy, was first registered for weed control in maize in the USA. Atrazine was, and still is, an extremely successful herbicide because it is broad spectrum, low cost, and allows flexible timing of applications. Even today, with more than 60 other herbicides registered for maize in the USA, more than two thirds of the maize crop is treated with atrazine. Other herbicide modes of action followed and today there are over 300 herbicide active ingredients across 27 modes of action. However, of these 300 active ingredients 79% fall into only eight herbicide modes of action.

3.2.1. Herbicide development

Agricultural companies now spend U.S.$ 50 to 200 million to develop and register each new herbicide. Herbicides are heavily regulated in most countries and frequently need to obtain approvals from many different regulatory agencies. The primary government agencies responsible for herbicide regulation in most countries are environmental protection agencies, departments of agriculture and the food and drug agencies. New herbicides must be registered with the appropriate regulatory authority in each country. This requires a wide range of tests and a thorough safety and efficacy review prior to obtaining registration of a new product. Herbicides must be registered for use on different crops, with each registration requiring a range of safety information. The costs for herbicide registration are extensive and increase with each crop for which the herbicide will be registered.

Discovery

Novel compounds must be synthesised, put through initial screening in the laboratory or greenhouse, patented, and analysed. A great deal of cost is expended to determine the physio-chemical properties of the active ingredient molecules (environmental fate, weed/crop selectivity, metabolism studies, *etc.*).

Formulation

The product must be formulated so that it will be stable under a wide range of conditions, can be readily taken up by plants, and does not present significant exposure risks to end-users and the environment. The product also must be able to be manufactured cost effectively.

Toxicology

Herbicide registration requires a battery of toxicological tests that are analysed and submitted to regulatory agencies for review. These agencies require a wide range of base studies that include acute and long-term effects, chemical properties, effects on endangered species, fate in the environment, persistence, *etc.*

Marketing

Once the product is close to registration companies must begin planning a product launch campaign. This includes acquiring and training personnel for sales and marketing, and developing an advertising campaign for the new product.

Major crops targeted

For economic reasons, companies pursue herbicides that have utility in high volume crops, such as maize, wheat, soybean, and rice in order to help recoup the high expense of herbicide development. If the herbicide has been successfully launched in one of these high volume crops then eventually companies may pursue registration of their new product in minor crops or for non-crop situations.

Herbicide application

Herbicides can be applied at a number of stages through the cropping cycle. The most common application times are given in the adjacent text box. Optimal application times are determined by the type of crop and the type of herbicide.

Herbicide application times

Pre-plant
The herbicide is applied onto the bare soil surface and/or onto emerged weeds prior to planting. Pre-plant herbicides are often broad-spectrum herbicides, able to control a wide range of plants.

Pre-plant incorporated
The herbicide is applied prior to planting and is incorporated into the soil to reduce herbicide loss by volatilisation or photo-degradation.

Pre-emergence
Pre-emergence herbicides are applied to the soil after planting but prior to the emergence of the crop. These herbicides generally require rainfall or irrigation to move the herbicide into the soil for maximum activity.

At cracking
These herbicides are applied as the crop emerges or "cracks" the soil surface. Selectivity is gained by the fact that there is limited uptake of the herbicide in the terminal bud of the crop.

Post-emergence
Post-emergence herbicides are applied over the top of the crop and the weeds. The crop must have sufficient tolerance to the herbicide for this practice to work. Post-emergence herbicides are generally applied soon after weed emergence, as larger weeds are more difficult to control. Most herbicide tolerant crops are sprayed post-emergence.

Directed post-emergence
Some crops, such as cotton, have woody stems that limit uptake of herbicides. This allows farmers to direct herbicides at the weeds at the base of the crop, avoiding the higher foliage and growing tips of the crop.

Shielded (hooded) Post-emergence
Hooded sprayers may be used to hold herbicide sprays within the hooded area and so shield crops from non-selective herbicides during spraying.

3.2.2. Herbicide mechanism of action

Herbicide mechanism of action (also called 'site of action') and herbicide mode of action are often used interchangeably, however the herbicide mechanism of action is only one portion of the herbicide mode of action. The herbicide mechanism of action is the biochemical pathway that a particular herbicide acts upon to kill a weed. Herbicide mode of action covers all of the interactions of a herbicide from its absorption, translocation, metabolism, and mechanism of action within the weed.

To be effective, a herbicide must make contact with the weed, be absorbed into the plant, and be translocated (transported) to the mechanism of action at sufficient concentrations to kill the weed. Once the herbicide reaches the site of action it must alter the targeted cell process, *e.g.*, cell division, protein synthesis, photosynthesis, fatty acid synthesis, pigments synthesis, *etc.* An understanding of a herbicide's mode and mechanism of action is important for the correct selection and application of herbicides. This also helps farmers to prevent herbicide injury symptoms and herbicide resistance development.

Herbicide mechanism of action is very important in management of herbicide resistant weeds, because weeds that have evolved resistance to a specific herbicide are often cross-resistant to other herbicides that have the same herbicide mechanism of action. A herbicide coding system has been issued to assist in developing herbicide resistance management strategies. The letters and numbers in brackets are the classification codes issued by HRAC (Herbicide Resistance Action Committee) and WSSA (Weed Science Society of America). In a combination, such as A/1, the first is the HRAC code and the second is the WSSA code. These codes indicate different mechanisms of action and can be used by the farmer or advisor as a tool to choose mixtures or rotations of active ingredients with different mechanisms of action. A key component of managing for resistance is to avoid the repeated use of a single herbicide group with the same mechanism of action year after year. A brief introduction to the most common herbicide mechanisms of action is provided in the text box and in Appendix 1, which contains a comprehensive list of herbicides and their mechanisms of action.

An understanding of a herbicide's mode and mechanism of action is important for the correct selection and application of herbicides.

Common herbicide mechanisms of action

(A/1) Inhibition of acetyl CoA carboxylase (ACCase)
ACCase inhibitors are herbicides that control grass weeds by inhibiting an enzyme called acetyl CoA carboxylase which results in the inhibition of long chain fatty acid biosynthesis in grasses. ACCase inhibitors have a high risk for the selection of herbicide resistant weeds. Resistance develops by altered target sites in the weeds and/or by increased breakdown of the herbicide.

(B/2) Inhibition of acetolactate synthase (ALS)
ALS inhibitors bind to the acetolactate synthase enzyme which prevents the formation of the branch chain amino acids valine, leucine, and isoleucine. ALS inhibitors have a very high risk for the selection of herbicide resistant weeds. Resistance develops by altered target sites in the weeds and/or by increased breakdown of the herbicide.

(C1/5) Inhibition of photosynthesis at photosystem II (PS II)
Photosystem II inhibitors block electron transport in photosystem II of photosynthesis by binding to the D1 quinone protein QB of the electron transport chain. The diverted electrons produce free radicals that destroy membranes. Photosystem II inhibitors have a high risk for the selection of herbicide resistant weeds. Resistance develops most frequently by altered target sites in the weeds, but increased breakdown of the herbicide has also been reported.

(D/22) Photosystem-I-electron diversion (PS I)
Photosystem I herbicides, also known as the bipyridiliums, are herbicides that act as electron interceptors of the light reactions of photosynthesis within photosystem I and thus inhibit photosynthesis. These herbicides are known as membrane disrupters because the end result of the diverted electrons is to create superoxide radicals that disrupt membrane integrity and cause leakage of the cell contents into intracellular spaces. Bipyridiliums have a moderate risk for the selection of herbicide resistant weeds.

(E/14) Inhibition of protoporphyrinogen oxidase (PPO)
Protoporphryn IX inhibitor herbicides cause protoporphyrin IX to accumulate in the cytoplasm where it reacts with light and oxygen to create toxic oxygen species that cause membrane degradation. PPO inhibitors are expected to have a low risk for the selection of herbicide resistant weeds.

(F1/12) Inhibition of carotenoid biosynthesis at the phytoene desaturase step (PDS)
These herbicides inhibit the production of carotenoids (pigments) by blocking the conversion of phytoene to carotene. The end result is bleaching of the plants. Carotenoid inhibitors have a low risk for the selection of herbicide resistant weeds.

(F2/27) Inhibition of 4-hydroxyphenyl-pyruvate-dioxygenase (4-HPPD)
HPPD inhibitors also inhibit carotenoid production but they do so by impeding the production of plastoquinone, a key co-factor in carotenoid biosynthesis. The inhibition of HPPD stops the production of vitamin E in susceptible plants and the inhibition of carotenoid production leads to bleaching of new leaves. HPPD inhibitors have a low risk for the selection of herbicide resistant weeds.

(G/9) Inhibition of EPSP synthase
Glyphosate binds to the 5-enolpyruvylshikimate-3-phosphate (EPSP) synthase enzyme resulting in the inhibition of the formation of the aromatic amino acids phenylalanine, tryptophan and tyrosine. EPSP synthase inhibitors have a low risk for the selection of herbicide resistant weeds.

(H/10) Inhibition of glutamine synthetase
Glutamine synthetase inhibitors inhibit the conversion of the amino acid glutamate plus ammonia to the amino acid glutamine. This leads to the accumulation of toxic levels of ammonia in susceptible plants, which in turn inhibits photosynthesis causing lipid peroxidation of cell membranes in the presence of light. Glutamine synthetase inhibitors have a low risk for the selection of herbicide resistant weeds.

(K1/3) Microtubule assembly inhibition
Microtubule assembly inhibitors (also known as dinitroanilines) inhibit tubulin formation in cells, which prevents the completion of cell division (mitosis) and thus prevents shoot elongation and the lateral root development in emerging weeds. Dinitroanilines have a moderate risk for the selection of herbicide resistant weeds.

(N/8) Inhibition of lipid synthesis – not ACCase inhibition
These herbicides are also known as the thiocarbamates. Their mechanism of action is not completely clear. They are known to decrease the production of lipids (leading to destabilisation of cell membranes and cessation of cell division or enlargement), inhibit the plant hormone gibberellic acid (leading to plant growth reductions) and can affect chromosome and general nuclei development in the shoot cells of susceptible seedlings. Thiocarbamates have a low risk for the selection of herbicide resistant weeds.

(O/4) Action like indole acetic acid (synthetic auxins)
Synthetic auxins mimic the internal plant hormone IAA (indole-3-acetic acid), also known as an auxin. They cause uncontrolled growth in susceptible species, leading to twisting, leaf cupping, and stem splitting that eventually leads to the death of the plant. Synthetic auxins have a low risk for the selection of herbicide resistant weeds.

Importantly, "low risk" for the selection of herbicide resistant weeds does not mean "no risk". For instance, glyphosate is a low risk herbicide, but given the large area treated with glyphosate 16 weed species have evolved resistance to this herbicide to date.

3.2.3. Herbicide selectivity

Prior to crop emergence, non-selective herbicides, such as glyphosate, paraquat and others, can be applied to kill the majority of emerged weeds. However soil applied residual herbicides or post-emergence herbicides must be chosen for their selectivity, so that they kill weeds without injuring the crop. Narrow spectrum (selective) herbicides often do not provide control of all weed species, making it necessary to use more than one herbicide on a field.

The ideal situation is to have a herbicide that does not harm the crop but controls all of the weeds. This was rarely the case prior to herbicide tolerant crops. Now, by mutation breeding or genetically engineering, a crop can be engineered to tolerate a broad spectrum herbicide. In this way weed management is greatly simplified as a single herbicide can be sprayed over the field throughout the growing season (in accordance with the growth stages identified on the label).

A key component of managing for resistance is to avoid the repeated use of a single herbicide group with the same mechanism of action year after year.

3.3. HERBICIDE RESISTANT WEEDS

The evolution of herbicide resistant weeds is an ongoing challenge in modern agriculture. The introduction of herbicide tolerant crops provides opportunities to use different herbicide mechanisms of action to control existing populations of herbicide resistant weeds. However, these new herbicide mechanisms of action may be at risk if farmers do not practice sound integrated weed management practices. This is the same risk confronting the use of all herbicides whether or not crop tolerance is derived from biotechnology, conventional breeding or natural selection mechanisms. This section provides an overview of the origins of resistance, the mechanisms of resistance, and the current status of herbicide resistant weeds globally. Management of herbicide resistant weeds is covered in later sections.

The evolution of herbicide resistant weeds is an ongoing challenge in modern agriculture.

3.3.1. Origins of resistance

Herbicide resistance is the evolved capacity of a susceptible weed population to withstand a herbicide application and complete its lifecycle when the herbicide is used at normal rates in an agricultural situation. Weed populations may naturally contain herbicide resistant individuals at very low frequencies as a result of rare random genetic mutations. (Herbicides do not cause mutations.) The frequency is dependent on the weed species and the herbicide mode of action. For some herbicides, such as the ALS inhibitors, the frequency of resistant individuals prior to herbicide application may be as high as 1 in 10,000, meaning that ALS inhibitors are prone to a rapid development of resistance. For others, such as EPSP synthase herbicides (*e.g.*, glyphosate), the resistance frequency has been estimated to be less than 1 in a billion. Repeated use of the same herbicide or herbicide mode of action, in the absence of other weed control methods eventually enriches the frequency of these rare mutations to a point where they predominate and cause herbicide failure. Herbicide resistant weeds can then easily spread as contaminants in crop seed and by machinery, water, animals, and wind.

Weed populations may naturally contain herbicide resistant individuals at very low frequencies as a result of rare random genetic mutations.

3.3.2. Mechanisms of resistance

Resistance populations develop from rare random genetic mutations that may exist in individuals within a population. These rare, random genetic mutations provide the weed with a mechanism to resist (tolerate) herbicides. Weeds may resist herbicides through:

- Target site resistance as a result of a modification of the herbicide binding site (usually an enzyme), which prevents a herbicide from binding. If the herbicide cannot bind to the enzyme then it does not inhibit the enzyme and the plant survives. Target site resistance is the most common resistance mechanism. Most but not all cases of resistance to ALS inhibitor, ACCase inhibitor, dinitroanaline, and triazine herbicides are due to modifications to the site of action of the herbicide;

- Enhanced metabolism when the weed develops an enhanced ability to metabolise herbicides into non-toxic or less toxic compounds;

- Decreased translocation which reduces the movement of the herbicide to the site of action;

- Sequestration which stores the herbicide or its toxic metabolites in the cell vacuole, on cell walls, or on tissues remote from the site of action.

From a herbicide resistance management perspective it is important to note that weeds can exhibit cross-resistance and multiple resistance.

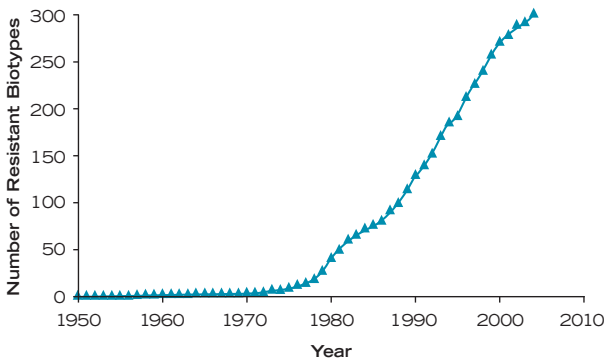
- Cross-resistance occurs where a single resistance mechanism confers resistance to several different herbicides classes within a mode of action group. The most common type of cross-resistance is target site cross-resistance, where an altered target site confers resistance to many or all of the herbicides that target that same site.

- Multiple resistance occurs when two or more resistance mechanisms occur within the same plant, often due to sequential selection by different herbicide modes of action (Heap and LeBarron, 2001), thus resulting in resistance to two or more herbicide modes of action.

3.3.3. Current status of resistant weeds globally

The "International Survey of Herbicide-Resistant Weeds" (ISHRW http://www.weedscience.org) recorded approximately nine new cases of herbicide resistant weeds annually, from 1978 to 2009 (Figure 1) (Heap, 2008). The tailing off of new cases in the last two years reflects the two years of research needed to confirm resistance, thus some cases investigated in 2007 to 2009 may not be shown in the data.

Figure 1. The increase in new cases of herbicide resistant weeds globally (Heap, 2008).



The importance of resistance cases is based on estimates made by researchers. These estimates are prone to a very wide margin of error, but still give an indication of the number of sites and hectares affected. Many of the 332 cases of herbicide resistance recorded in 59 countries are scientific curiosities rather than major agronomic problems. Of the top 25 most widespread and economically important herbicide resistant weed species ten are grasses, and six are pigweed species (*Amaranthus*

spp.). The most problematic species worldwide is *Lolium rigidum*, which has been identified as resistant in 18 countries. It has evolved resistance to nine modes of action, occurs in six cropping regimes (crop and rotation programmes), infests over 9,000 farms and 840,000 hectares. *Avena fatua*, *Amaranthus retroflexus*, *Chenopodium album*, and *Setaria viridis* (Figure 2) are sequentially the next most often reported herbicide resistant weeds globally.

Some herbicide modes of action are more prone to the problem of resistance than others and details of this are given in Appendix 1.

Some herbicide modes of action are more prone to the problem of resistance than others.

3.4. DEVELOPING HERBICIDE TOLERANT CROPS

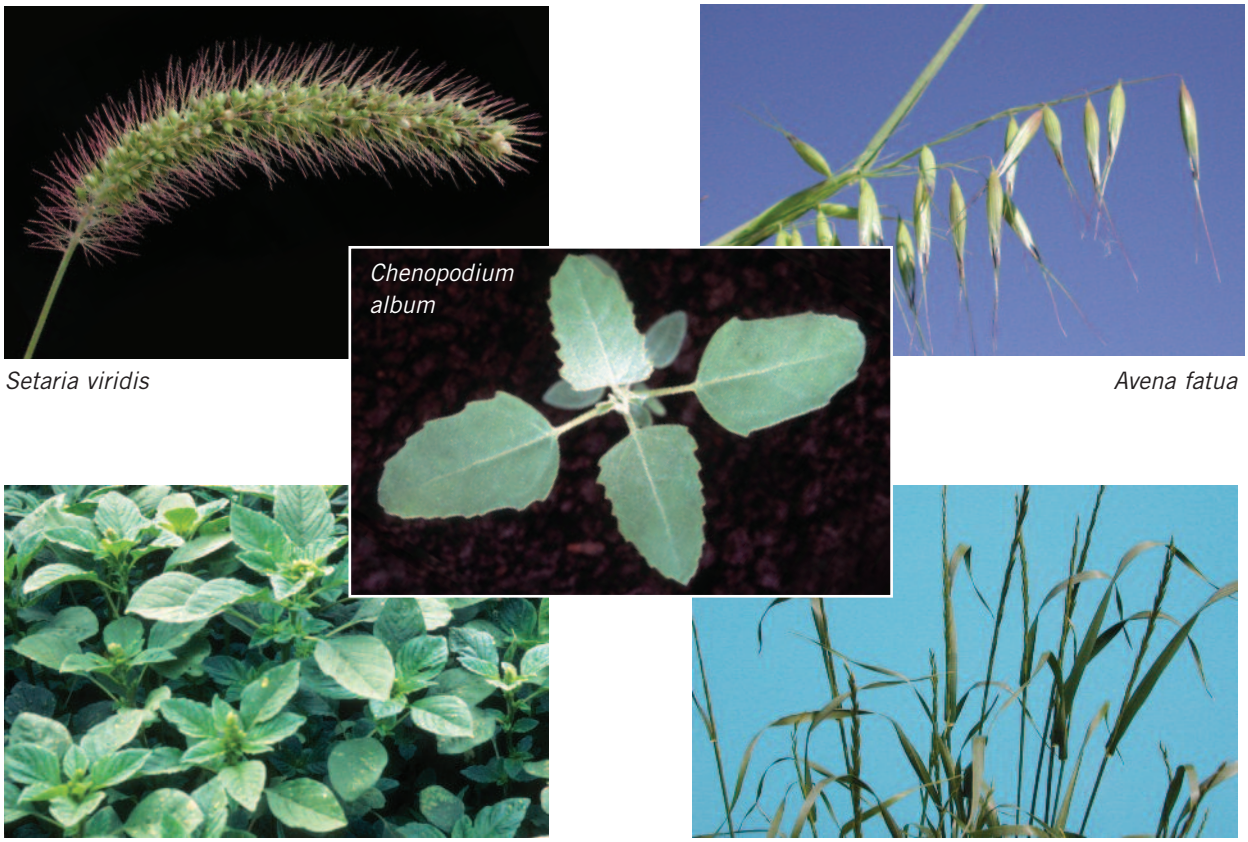
Herbicide tolerant crops contain traits that allow them to survive certain herbicides that previously would have injured or destroyed the crop along with the targeted weeds. This allows farmers to use herbicides more effectively and, in some cases, to use less herbicide. Herbicide tolerant crops have been created through conventional breeding techniques or through gene transformation.

Herbicide tolerant crops contain traits that allow them to survive certain herbicides that previously would have injured or destroyed the crop along with the targeted weeds.

3.4.1. Conventional herbicide tolerant crops

Conventional herbicide tolerant crops have generally been derived from human imposed mutations and classical plant breeding. Conventional herbicide tolerant crops are often referred to as non-genetically modified, although this term is misleading, as the new resultant varieties have had their genetics altered. Use of cell tissue culture, irradiation, chemical mutagens, and wide crosses that involve embryo rescue are methods that plant breeders have utilised to create new plant varieties, and these methods are considered part of "classical" or "conventional" breeding techniques and, thus, accepted as normal. The most common method to produce conventionally bred herbicide tolerant crops is to use a chemical mutagen to produce genetic variability that may contain herbicide tolerant individuals. Examples of conventional herbicide tolerant crops include triazine tolerant canola, sulphonylurea tolerant soybeans, and imidazolinone tolerant wheat, maize, rice, canola, sunflower and lentils (Tan *et al.*, 2005).

Figure 2. Some important weed species.



Setaria viridis *Avena fatua*

Amaranthus retroflexus *Lolium rigidum*

Photos Dr. Ian Heap

Conventional herbicide tolerant crops have generally been derived from human imposed mutations and classical plant breeding.

3.4.2. Biotech-derived herbicide tolerant crops

Biotech-derived herbicide tolerant crops have been genetically engineered through the use of recombinant DNA (rDNA) techniques. Genetic engineering alters the genetic constitution of individual cells by selectively removing, inserting, or modifying individual genes or gene sets using rDNA technology. The term "genetically modified organism" (GMO) is used to describe biotech-derived crops, but does not include herbicide tolerant crops produced through mutations and crossing.

There are two primary methods that have been employed to introduce genetic material into plant cells. They are *Agrobacterium*-mediated transformation and microparticle bombardment.

Agrobacterium-mediated transformation

The soil-borne bacterium, *Agrobacterium tumefaciens*, is able to use genetic engineering processes to transfer parts of its DNA into plant cells. The advantage for the bacterium is that the genetic material it inserts into plant cells causes the plants to produce complex nutrients (opines) which only this bacterium can use as a food source (Tempe and Schell, 1977). The inserted DNA also contains plant hormone genes that cause the infected cells to proliferate, resulting in a tumour called crown gall. Research into this phenomenon eventually led to the first published transgenic plant (tobacco) that expressed foreign genes (Fraley *et al.*, 1983). Since then there have been many additional crops and other plants (maize, tomato, potato, banana, alfalfa, canola, rice, soybean, sugarcane, wheat, *etc.*) that have been genetically transformed through rDNA technology (Hammond *et al.*, 1999; Cheng *et al.*, 1998).

Agrobacterium-mediated transformation of plant tissue is preferred over microparticle bombardment, because it results in higher transformation efficiency, fewer rearrangements, and a low copy number of the transgenes (newly inserted genes). However, the inserts may, in some instances, include bacterial DNA sequences which may complicate the characterisation and safety assessments of the biotech-derived events.

Microparticle bombardment

A useful alternative to *Agrobacterium*-mediated transformation is microparticle bombardment, a technique used to deliver DNA directly to the host genome. Particles (gold or tungsten) are coated with DNA containing the gene(s) of interest and then fired into plant cells with the hope that a small percentage of DNA dissolves off the particles and becomes integrated into the host genome. This is a less efficient method of producing stably transformed plant cells compared to *Agrobacterium* transformation, but its advantage is that it can be used on most plant species and only inserts sequences that were on the original DNA segments.

Biotech-derived herbicide tolerant crops have been genetically engineered through the use of recombinant DNA (rDNA) techniques.

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4. Tools for Integrated Weed Management

Integrated weed management tools are applicable to conventional and biotech-derived crops. In some cases agronomist refer to the term 'diversity' in describing best practices for managing resistance. This term denotes the need to employ multiple herbicides and/or management practices rather than rely just on a single practice. Growers are encouraged to adopt those integrated weed management tools that best suit their farming systems and growing environment.

Growers are encouraged to adopt those integrated weed management tools that best suit their farming systems and growing environment.

4.1. PREVENTING THE SPREAD OF WEEDS

Prevention is an important but often overlooked part of integrated weed control. Weeds are naturally dispersed by wind, water, birds and animals and it is difficult to do much about the natural dispersion of weed seeds. However, human activities account for a very large proportion of weed seed spread, and this can be significantly reduced with appropriate planning. Prevention of weeds through proper sanitation is an effective method of weed management.

Weeds are easily spread by farm machinery, vehicles, and livestock. To reduce the spread of weeds from field to field farmers can:

- Clean farm machinery with compressed air or a pressure washer before moving equipment between fields. This will reduce the spread of weed seed. Pay particular attention to harvesting equipment which can spread very large amounts of weed seed if not cleaned. Cleaning equipment between fields is especially important if a field contains herbicide resistant or noxious weeds.
- Cover grain trucks with tarpaulins to prevent the weed seed blowing off the top onto roadsides and adjacent fields.
- Use certified seed to prevent the import of weed seed onto your property from your seed source.
- Control weed seed nurseries along fence lines, farm roads, irrigation ditches, and stockyards. The success of an IWM programme is often dependent on the control of weeds around the margins of the fields.
- Ensure hay is weed free. Hay is a common source of weed seeds and an effort should be made to certify that it is weed free before importing it to a farm.
- Clean livestock prior to moving them. Livestock can spread weeds via hair, feet, and in their digestive tracts. Impound livestock in a holding area for 24-48 hours prior to turning them out on new fields to allow weed seed in their digestive tracts to pass. It is important to control the weeds in the livestock feed and bedding grounds to prevent them becoming a nursery for weed seeds that will re-infest fields.
- Mow infested crop areas prior to weed seed maturation. In many cases small patches of weeds can be mowed before seed set to reduce major weed seed increases in future years.
- Reseed disturbed soil around the farm. Weeds will take over any disturbed soil that is left bare. The best way to prevent weed infestations is to establish desirable vegetation on the soil immediately after it is disturbed.

Prevention of weeds through proper sanitation is an effective method of weed management.

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4.2. MONITORING WEED POPULATIONS

Monitoring of weed populations allows farmers to make decisions about crop rotations and weed control practices that will be most effective in specific fields. Monitoring fields is a key component of an integrated weed management system. The systematic collection of data on the distribution of weed species is useful in the short term for making immediate weed management decisions to avoid crop losses. In the long term these records provide a basis for evaluating the effectiveness of weed control programmes and help managers make sound decisions in the future.

Monitoring fields is a key component of an integrated weed management system.

Not all growers have sufficient time or resources for detailed monitoring and recording of weeds, however, all growers are encouraged to devise a monitoring and recording system that best suits their resources.

4.3. CULTURAL CONTROLS

Cultural controls such as crop rotations, improving crop competitiveness, tillage, mowing, and burning can all be effective weed control strategies to use in an integrated weed management programme.

Cultural controls such as crop rotations, improving crop competitiveness, tillage, mowing, and burning can all be effective weed control strategies.

4.3.1. Crop rotations

Certain weed species often thrive in specific crops because they are well adapted to the planting dates, tillage patterns, and competition of the crop. For instance, perennial weeds are often associated with perennial crops, and annual weeds associated with small grain annual crops. Monoculture, when only one species is grown in a field either in a single year or over several years, can result in a build up of weeds that are adapted to the same growth requirements as the crop. A good crop rotation can be a way to destabilise and disrupt weed populations so that they do not become a severe problem. Crop rotation involves the alternation of different crops on the same land. More diverse crop rotations are better for disrupting the life cycle of weed populations. Different crops will often require diverse planting dates, tillage and herbicide practices, and will be different in their competitive ability. It is these variations in cultural practices that will disrupt the weed germination and growth cycles. Alternation of small grain crops with perennial forages or row crops can have a significant effect on keeping weed populations in check. Alternating between winter and summer crops is also a good crop rotation strategy to combat weeds. Crop rotations reduce the build up of weed populations and prevent major weed species shifts. Another benefit of crop rotation is the opportunity to use different herbicide modes of action which slow the development of herbicide resistant weeds.

4.3.2. Crop management

A competitive crop is one of the least expensive methods of managing weed populations. The first plants to emerge and grow vigorously will be the plants that will dominate and utilise the resources of light, water, and nutrients (Cousens *et al.*, 1987). The aim of crop management is to ensure that the crop is the plant that dominates by establishing a vigorous and dense crop. This can be achieved by ensuring optimum conditions (soil, moisture, temperature, nutrition, *etc.*) for crop germination and emergence, along with using competitive crop varieties at optimum seeding rates. Elimination of weeds prior to sowing a crop, along with the use of either pre-emergence or early post-emergence herbicides, will give the crop a good head start over the weeds.

Vigorous seed and competitive varieties

Sowing vigorous seed is of great advantage to the competitive ability of a crop against weeds (Stobbe *et al.*, 1991). Using vigorous seed is even more important if the crop is being sown when conditions for germination and seedling growth are poor.

Stale seedbed

A stale seedbed technique can be used to give a crop an advantage over weeds. A good seedbed is prepared and allowed to sit until a flush of weeds appears. These weeds are then controlled by a non-selective herbicide such as glyphosate or paraquat. Soon thereafter, the crop is sown into the "stale seedbed" with as little disturbance as possible to reduce the stimulation of new weed seed germination. When done properly, this technique can be very effective at reducing the first flush of weeds in an emerging crop.

Row spacing

The aim of altering row spacing for weed control is to get the crop to cover as much area as possible as fast as possible. As a general rule, narrower row spacing and higher seeding rates will result in a more rapid canopy cover, which is beneficial in competing with emerged weeds and suppressing further germination of weeds. This must be balanced against the increased seed cost of narrower row spacing and the need to find an optimum seeding rate.

Seeding at an optimum rate

There are a number of factors that must be considered when trying to estimate an optimum seeding rate. If seeding rates are too high it is possible that inter-plant competition (between crop plants) may end up reducing final yields, particularly under dry conditions. For effective weed control, the ideal situation is to have the most rapid canopy cover possible, which will make the crop strongly competitive with weeds (Harker *et al.*, 2003). Unfortunately, most recommended crop seeding rates have been developed under weed free conditions. If weed pressure is known to be high, and herbicide effectiveness limited, then it is prudent to increase seeding rates to make the crop more competitive with weeds.

Seeding time

Weeds species have different moisture, light, and temperature requirements for germination. For instance, weeds such as wild oat (*Avena fatua*) and wild mustard (*Sinapis arvensis*) germinate early in cool soil conditions, while foxtail (*Setaria sp.*) and pigweed (*Amaranthus sp.*) require warmer conditions to germinate. Farmers can take advantage of this by rotating crops that are seeded at different times of the year. For example, if farmers have problems with weeds that germinate in cool soil temperatures then they may wish to rotate from an early crop to one that is planted later, such as maize. This will provide enough time prior to seeding to use tillage or a knockdown herbicide to control the flush of early weeds.

Seeding shortly after seedbed preparation

There is a significant competitive advantage for crops that emerge before or with the weeds as opposed to crops that emerge after weeds. For this reason it is critical to seed crops as soon as possible after the last seed bed preparation or knockdown herbicide, otherwise weed seed in the soil may begin germinating even before the crop is sown, giving the weeds a head start on the crop. O'Donovan *et al.* (1997) have shown that crops that emerge early compete better with weeds and result in lower yield losses from competition. Crops that compete better with weeds also reduce weed seed production. Early crop emergence can be achieved by shallow seeding of vigorous crop seed into moist firm soil.

Shallow seeding and good "on row" packing

Seeding as shallow as moisture conditions allow will make for more rapid emergence of the crop, and give it a better competitive advantage over the weeds. Ideally, equipment should allow for accurate placement of seed without a large variation in seeding depth. On-row packing that compacts soil along seeding rows is helpful in ensuring a uniform and rapid crop emergence, as the compact soil provides better seed/soil moisture contact for the crop seed whereas the loose soil between rows is less ideal for weed seed germination.

Nutrition

Crops and weeds compete for nutrients (nitrogen, phosphorous, potassium, *etc.*), and some studies have shown that added nutrients are beneficial to crops if applied directly onto crop rows rather than broadcast. Nutrients themselves may benefit the crop or the weed, depending on the species involved (Reinertsen *et al.*, 1984; Kirkland and Beckie, 1998; Blackshaw, 2004). There are many cases where the weeds are better able to utilise nitrogen than a crop, making them more competitive than they would be without the added nitrogen. For instance, wild oat (*Avena fatua*) (Carlson and Hill, 1986) and green foxtail (*Setaria viridis*) (Peterson and Nalewaja, 1992) have been shown to utilise added nitrogen better than wheat, which gave them a competitive advantage over wheat in plots treated with added nitrogen. Nutrition also influences weed seed germination, for example, nitrates are known to stimulate seed germination in some weed species.

Soil conditions

There are certain situations where amending soil conditions may help reduce the competitiveness of weeds. For instance some weeds, such as wild oat (*Avena fatua*), prefer low pH soils and increasing the pH on these soils will give crops a better chance against wild oat. Other weeds may grow better in high pH soils. Thus knowledge of the soil, weed biology and ecology will help when planning to use an integrated weed control strategy.

Intercropping

Intercropping is the practice of growing a smother crop in between the rows of the main crop. The smother crop, as the name suggests, can be effective at smothering out weed competition. This can be of great advantage if the farmer is faced with troublesome weeds for which he has no other effective control strategy. However, it needs to be noted that the smother crop itself is competing with the main crop for water and nutrients, and at some early stage in the season it may need to be killed by a herbicide to prevent continued competition with the crop.

Cover crops

Cover crops have recently become popular in regions of the maize/soybean belt in the USA. Bare soil provides fertile ground for weed growth, thus a cover crop is planted to help prevent a weed invasion. Cover crops are usually fast growing and sometimes produce chemicals which inhibit growth of other plants (allelopathic properties). Ryegrass, cereal rye, red

clover, buckwheat, and oilseed radish have all been used successfully as cover crops (Yenish and Worsham, 1993; Easdale, 1996). One caution is to ensure that the cover crop does not become a weed itself. For farmers in the American Midwest, growing annual ryegrass (*Lolium multiflorum*) as a cover crop in the fall may provide effective weed control, however their reliance on the herbicide glyphosate to remove the annual ryegrass in the spring may eventually result in glyphosate resistant annual ryegrass. The appearance of glyphosate resistant annual ryegrass on their land would be much worse than dealing with their current weed spectrum.

Limitations of competition

Good crop competition is an integral part of an integrated weed management programme. No one cultural control strategy is likely to give satisfactory weed control, however these strategies can greatly enhance weed control when used in combination, such as combining tillage and herbicide applications.

4.3.3. Tillage systems

There are many advantages and disadvantages of using tillage for weed control. When done strategically, tillage can be an effective way to reduce weed populations. However tillage exposes bare ground which can lead to soil erosion, depletion of organic matter, a decrease in water infiltration and damaged soil structure. In addition, it is costly and provides the perfect environment for new weed growth. These negative aspects of tillage have led farmers to reduced or even adopt zero tillage practices. An understanding of weed biology and ecology is critical in the planning of strategic tilling for weed control.

For annual weeds, tillage is aimed at depleting seed reserves and preventing seed production. Tillage aids in weed control in a number of ways. Light tillage will often stimulate germination of weed seedlings, making them available for killing by knockdown herbicides or subsequent tillage. Tillage can uproot seedlings, causing their death through desiccation, or through complete burial of above-ground parts.

> When done strategically, tillage can be an effective way to reduce weed populations.

For perennial plants, the aim of tillage is to deplete the food reserves stored in roots and other underground storage structures. Sequential removal of above-ground matter through tillage or mowing may eventually deplete perennial plant food reserves. Follow-up tillage is essential, as tillage often cuts perennial plants into more propagules, which if left unchecked, will give rise to new plants. Tillage exposes perennial roots to extremes, such as drying, or frost, which may kill weeds. Tillage also damages underground parts of plants and leaves them susceptible to bacterial and fungal attack.

Tillage prior to sowing a crop is often aimed at stimulating weed germination, so that seedlings may be killed with subsequent tillage, or with a knockdown herbicide prior to weed seed set and prior to sowing. Deep tillage, such as the use of mouldboard ploughs, often has the effect of burying weed seeds below a point where they can not emerge if they germinate. However, many weed species have mechanisms to become dormant if they are buried deeply, and if ploughed back up again they will germinate and compete with the crop.

Rotary hoes are very effective at uprooting small weed seedlings. Rotary hoes also are good at mixing soil and can be effective at mixing soil applied herbicides.

Conventional tillage

Conventional tillage uses more than one tillage operation to prepare a seedbed for a crop. This results in less than 30% crop residue remaining on the surface after the completion of the tillage sequence, which can result in soil erosion, loss of soil organic matter and damaged soil structure. While conventional tillage has disadvantages, it is one option in the integrated weed management tool box to destroy weeds prior to planting crops.

Spring tillage. The aim of spring tillage is to destroy the first flush of weeds prior to sowing the crop. Spring tillage may also be used to stimulate a flush of weeds to be subsequently killed with another type of tillage or a non-selective herbicide prior to seeding the crop. The type of tillage equipment used can have a major impact on weed populations. As an example, for weeds that have rhizomes, such as quackgrass (*Elymus repens*) and Johnsongrass (*Sorghum halepense*), using a disc for tillage is more likely to just cut up the rhizomes and spread them, making for a denser weed stand. Spring toothed harrows are more appropriate for these weeds, as they are more likely to pull the rhizomes to the surface where they desiccate and die.

Fall tillage. Fall tillage is aimed at killing biennial and perennial plants by depleting their food reserves. It also stimulates the germination of weed seed and the seedlings will be killed by poor growing conditions and, in some cases, frost.

Inter-row cultivation. Shallow inter-row cultivation is effective at controlling small weed seedlings. Tines are most effective for inter-row cultivation. This form of cultivation is often used in conjunction with herbicide

applications on the row. Soil should not be thrown into the rows during cultivation as it will be a source of new weed seedlings, even if the row itself has been treated with herbicide. Row shields attached to cultivators may be useful in shielding the crop from damage and coverage by soil. More than one cultivation will be needed to control weed seedlings that emerge soon after inter-row cultivation.

Pre-emergent or "blind" harrowing. Effective control of annual weeds among large seeded crops, such as peas, wheat, soybean and corn, can be accomplished by lightly harrowing after the crop has been planted, but before the shoot has emerged. Timing and uniform crop emergence is critical in this practice to avoid damage to the crop. This practice has been used successfully for control of annual broadleaf weeds in cereal and row crops. Dry, warm and windy conditions are ideal for desiccation and killing weed seedlings dislodged during harrowing. In some situations post-emergence harrowing can be done with a weeder harrow with spring tines that are gentle enough to do minimal damage to the crop. Speed and pressure settings are very important to limit crop damage. This method has been used successfully in maize, soybeans, cereals, and some vegetable crops.

Conservation tillage

Minimal tillage. In some soil and climatic conditions it is not practical to eliminate tillage entirely. Minimal tillage is the use of a minimal amount of primary and/or secondary tillage to meet the crop production requirements. Minimal tillage results in fewer tillage operations than conventional tillage.

Zero tillage (also called 'no-till'). Zero tillage occurs when a crop is planted directly into the soil with no primary or secondary tillage after harvest of the previous crop. This is done through the use of a special planter that prepares a narrow, shallow seedbed immediately surrounding the planted seed. Some zero tillage planters use drills to plant and fertilise seed below the residue of the previous crop. There are many production and environmental benefits to zero tillage, including a reduction in:

- soil erosion;
- organic matter loss;
- damage to the soil structure;
- moisture loss, and
- fuel usage.

Herbicide tolerant crops enable growers to use zero tillage together with herbicide treatment and this helps to achieve more sustainable agriculture.

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4.3.4. Mowing

When cultivation is impossible or undesirable, and the area is too large to hand weed, then mowing may be a useful option for limiting weed seed production. Weeds should be mowed prior to seed set and as close to the ground as possible to maximise the depletion of resources in the weed roots. Sequential mowing may be necessary to exhaust food reserves in the roots of perennial weeds. The best time to mow perennial weeds is just prior to flowering, as this is when the food reserves in the roots are at their lowest and viable seed will not be set.

Mowing may be a useful option for limiting weed seed production.

4.3.5. Burning

Burning was once a common weed control practice in many cropping systems around the world. However, burning is no longer as common, because it has numerous drawbacks, including air pollution, depletion of organic matter, and soil erosion issues. However, when weed seeds have already been set, burning may be effective in destroying them. Effective burning depends on the duration and intensity of the heat produced, in combination with the moisture content and location of the weed seed. Optimally, the weed seed to be burnt would be dry and located on the soil surface or still on the plant, as weed seeds below the soil surface may not be affected by burning.

4.3.6. Allelopathy

Some crops produce chemicals that exude from their roots or leach from their stubble residue and inhibit the germination and/or growth of small-seeded weeds. This chemical suppression is known as allelopathy. Barley and rye are two crops that are highly competitive partly due to their ability to produce chemicals that suppress weeds (Barnes, 1983).

4.4. BIOLOGICAL CONTROLS

Insects, nematodes, fungi, viruses, birds and animals all have been used as biological weed control agents. To date the most successful biological weed control has been the use of insects on weeds of rangeland and other non-crop areas near crop fields. The insects control weeds by defoliating the plant, boring into its stems or roots, eating seed, or forming galls in the seed head. There are a few cases where biological control has provided weed control in cropping systems. Sheep have successfully been used in cereal production for control of rigid ryegrass (*Lolium rigidum*) populations in Australia. Geese were once used for weed control in mint in the USA. However, biological control does not yet play a major role in the control of weeds in most cropping systems.

In South Africa since 1913, the Plant Protection Research Institute has released more than 90 species of biocontrol agents to help control 47 weed species. Of these, about 20% are so effective that no other control measures are required (*e.g.*, prickly pear control with cochineal beetle); about 30% have

substantially reduced the required rates of conventional control methods; approximately 45% of projects are still too recent for evaluation, and less than 10% of projects have had no effect. This success rate has been recognised by the international community (PPRI, 2001).

4.5. HERBICIDES

Herbicides are covered extensively in Appendix 1. They are one of the primary methods of weed control in any integrated weed management programme. These agrochemicals form the backbone of many integrated weed management programmes, because they are the most cost effective and efficacious method of weed control in the integrated weed management toolbox. Herbicides are considered by some to be the most environmentally damaging method of weed control, but with responsible use this is not the case.

As outlined earlier, it is important to use herbicide modes of action in sequences, mixtures or rotation to avoid the selection of herbicide resistant weeds and to prevent or minimise weed shifts. Herbicide mixtures, sequential applications and rotations are ways to combine herbicide modes of action and are effective resistance management strategies. Ideally, each component of a herbicide mixture should have different modes of action, a high level of efficacy, and be effective against key problem weeds.

Herbicides are considered by some to be the most environmentally damaging method of weed control, but with responsible use this is not the case.

4.5.1. Herbicide tolerance

Inserting the tolerance for certain herbicides into specific crops (James, 2010) has provided a new weed control mechanism for farmers. These crops are a powerful addition to the integrated weed management toolbox. They can be used to control existing herbicide resistant weed problems, such as those resistant to ALS inhibitor, ACCase inhibitor, and triazine resistant weeds. Herbicide tolerant crops already provide the backbone for many weed control programmes. However, over reliance on traits that have the same herbicide mode of action, plus a lack of integrated weed management, can result in weed shifts and the development of herbicide resistant weeds. Herbicide tolerant crops are covered comprehensively in the next section.

Each component of a herbicide mixture should have different modes of action, a high level of efficacy, and be effective against key problem weeds.

K. Koch

5. Herbicide tolerant crops

Herbicide tolerant crops contain traits that enable them to survive certain herbicide applications that previously would have destroyed the crop along with the targeted weeds. This allows farmers to use more effective herbicides at optimal application rates which can reduce the amount of herbicide needed. Herbicide tolerant crops have been created through conventional breeding techniques and through gene transformation.

5.1. HISTORY OF HERBICIDE TOLERANT CROPS

All of today's major food crops are genetically different to their ancestors. These changes have been selected by man and induced by mutation to increase yield, make them resistant to insects and diseases, and improve their flavour. Traditionally these genetic changes have occurred through natural selection or selective breeding by humans. Selective breeding involves crossing of plant varieties to combine desirable traits from both parents. This is a very slow process, as incorporating a new trait into a good variety often entails crossing it with a variety that has many undesirable traits. Once a desirable trait has been identified in the progeny, years of backcrossing are needed to eliminate the undesirable traits. Selective breeding is also limited to gaining traits from closely related plants that can be cross bred with the crop (Shelton *et al.*, 2002). Plant breeders introduced these new conventionally modified crops into agricultural production with little, if any, assessment of the environmental consequences of their release. Even so, there have been few problems with the release of conventionally bred, new crop varieties.

Many crops are able to withstand one or more of the herbicides on the market today, and this has been the basis of selective weed control over the last 60 years. However, these selective herbicides do not provide broad spectrum weed control. Since the introduction of modern herbicides plant breeders have endeavoured to create, by a number of different approaches, crop varieties that are tolerant to broad spectrum herbicides. The first introduction of a conventionally bred, herbicide tolerant crop was triazine tolerant canola in 1981.

Biotechnology has enabled breeders to incorporate desirable traits into crops from a wide range of organisms, without the drawback of incorporating additional undesirable traits. However, these improvements need to comply with stringent environmental and food safety requirements. In 1996 the first biotech-derived herbicide tolerant crop (glyphosate tolerant soybean) was introduced commercially and was rapidly adopted in the USA, Argentina and other soybean producing countries. In 2010 herbicide tolerance remained the dominant trait in biotech-derived crops and herbicide tolerant soybean the dominant biotech-derived crop in world agriculture, grown in 11 countries (James, 2010). Glyphosate tolerant soybean accounted for 50% of the global biotech-derived crop area (73.3 million hectares), followed by maize (31%), cotton (14%), and canola (5%) (James, 2010). Since 1996, the acreage of biotech-derived crops has grown by over 10% per year and is projected to continue to grow at this rate (James 2006a). In 2010 there were 148 million hectares of biotechnology derived traits, with an estimated market value for biotech-derived seed of US$ 11.2 billion (James, 2010).

5.2. CONVENTIONAL HERBICIDE TOLERANT CROPS

Conventional herbicide tolerant crops have been derived mostly from human induced mutations and classical plant breeding. The use of cell tissue culture, irradiation, chemical mutagens, and wide crosses that involved embryo rescue are some of the methods that plant breeders have utilised to create new plant varieties. These methods are considered part of "classical" or "conventional" breeding techniques and the crops developed with them are widely grown without opposition. Conventional herbicide tolerant crops are often referred to as non-GM, although this term is misleading, as the resultant varieties have been modified by mutagenesis. The most common method to produce conventionally bred, herbicide tolerant crops is to use chemical mutagenesis to produce genetic variability that may include herbicide tolerant individuals. Examples of conventional herbicide tolerant crops include triazine tolerant canola, sulphonylurea tolerant soybeans, and imidazolinone tolerant wheat, maize, rice, sunflower, lentils (Tan *et al.*, 2005).

Triazine tolerant canola was not widely adopted, because triazine herbicides did not provide broad spectrum weed control, the trait was not introduced into high yield varieties, and the trait itself resulted in a yield reduction. In North America triazine tolerant canola only gained slightly over 1% of the market share and has since declined, because of the release of more attractive herbicide tolerant canola varieties. Triazine tolerant canola did gain significant market share in Australia (90%), primarily because it is a solution for controlling multiple herbicide resistant rigid ryegrass (*Lolium rigidum*) in a canola rotation. Even so, triazine tolerant canola continues to have a yield disadvantage of 10-15% and about 3-5% lower oil content than conventional varieties, but is accepted by farmers because it allows canola to be

grown where it otherwise could not be cultivated. Imidazolinone tolerant wheat, maize, rice, sunflower and lentils are the most widely adopted conventional herbicide tolerant crops. These crops have been modified through conventional breeding techniques (chemical mutagenesis) to allow them to tolerate imidazolinone herbicides.

5.2.1. Imidazolinone tolerance

Imidazolinone herbicides include imazapyr, imazapic, imazethapyr, imazamox, imazamethabenz and imazaquin (Shaner and O'Connor, 2000). They control a broad spectrum of grass and broadleaf weeds. Mutagenesis and selection were used to create imidazolinone tolerant maize (*Zea mays L*), wheat (*Triticum aestivum L*), rice (*Oryza sativa L*), oilseed rape (*Brassica napus L*) and sunflower (*Helianthus annuus L*). These crops were developed using conventional breeding methods and commercialised as Clearfield® crops, from 1992 to the present day. Imidazolinone herbicides inhibit the enzyme acetolactate synthase (ALS) in plants, which catalyses the first step in the biosynthesis of the essential, branched chain, amino acids isoleucine, leucine, and valine. When conventional plants are treated with an imidazolinone herbicide, the herbicide binds to the ALS enzyme and inhibits its activity, which results in decreased protein synthesis and death of the plant.

Tolerance to imidazolinones can be conferred by a single amino acid substitution, which can alter the ALS binding site in such a way that the herbicide no longer inactivates the ALS enzyme.

The lentil line RH44 was developed to tolerate imidazolinone herbicides by exposure of lentil cultivars to ethyl methanesulphonate (EMS), a chemical mutagen known to induce point mutations in plant genetic material. Following mutagenesis, whole plants were treated with imidazolinone herbicides to select for lentils with mutations that conferred tolerance to the imidazolinone herbicides.

5.2.2. Cyclohexanedione tolerance

Sethoxydim tolerant maize is another example of herbicide tolerant crops developed using conventional plant breeding techniques. Sethoxydim is a cyclohexanedione herbicide that controls grass weeds in broadleaf crops by inhibiting the enzyme acetyl-CoA-carboxylase (ACCase). This is a key enzyme in the fatty acid biosynthesis pathway, and thus is necessary for the synthesis and maintenance of cell membranes, and the incorporation of fatty acids into triacylglycerides for plant energy storage.

Sethoxydim tolerant maize was derived from a somaclonal variation (genetic changes resulting from the plant regeneration process) that developed in maize embryo tissue when grown in tissue culture media containing sethoxydim. From the surviving somaclonal variant cells, plants were regenerated and, through conventional plant breeding backcrosses, eventually the maize hybrid DK404SR was developed. The mutation that confers sethoxydim tolerance expresses a modified version of the ACCase enzyme that functions normally, but is not inhibited by sethoxydim.

5.3. BIOTECH-DERIVED HERBICIDE TOLERANT CROPS

In 1996 the first commercial biotech-derived herbicide tolerant crop, glyphosate tolerant soybean, was introduced in the U.S. Other glyphosate tolerant crops soon followed and resistance to other herbicides such as glufosinate and ALS tolerance. The U.S. has remained the world leader in development and adoption of biotech-derived crops. Herbicide tolerant biotech-derived crops account for approximately 80% of biotech-derived crops grown globally (James, 2007; Brookes and Barfoot, 2006). Most are glyphosate tolerant, followed by glufosinate tolerant and ALS-inhibitor tolerant varieties.

An advantage of herbicide tolerance genes is that they are good marker genes for the selection of rare transformed plants among many untransformed tissue culture plants. As such, these genes have been added to some crops purely to aid selection of transformed plants and not specifically to confer herbicide tolerance. Problems have arisen in approval of these crops where the selection herbicide is not registered for use on the crop. In some cases, the herbicide tolerance gene has been removed or inactivated to obtain approval for the biotech-derived event.

5.3.1. Glyphosate tolerance

Glyphosate is a broad-spectrum herbicide that is effective against grass and broadleaf weeds. It is currently the most widely used herbicide globally. The primary target of glyphosate is the 5-enolpyruvylshikimate-3-phosphate synthase (EPSPS) enzyme, which glyphosate inhibits. EPSPS is an enzyme present in all plants and is involved in the synthesis of the aromatic amino acids tyrosine, phenylalanine, and tryptophan (in the shikimate biochemical pathway). Glyphosate inhibits EPSPS in susceptible plants and without aromatic amino acids the plants cannot survive. Since the introduction of biotech-derived glyphosate-tolerant soybean, glyphosate tolerance has been added to commercial canola, cotton, maize, alfalfa and sugar beets (Dill, 2005; Dill *et al.*, 2008). Although not currently registered, there are a number of additional glyphosate tolerant crops under development, including rice, wheat and bentgrass.

There have been three main biotechnology strategies to confer glyphosate tolerance in transgenic plants:

- The first is to use a bacterial gene that produces a mutant form of EPSPS which is not susceptible to glyphosate. Many crop species have been genetically transformed to express a glyphosate tolerant version of the EPSPS enzyme, called CP4, from a strain of *Agrobacterium tumefaciens*. The CP4-EPSPS enzyme has a reduced binding affinity for glyphosate, and functions normally in the presence of glyphosate, thus conferring tolerance to the crop.

- The second is to produce larger quantities of the EPSPS enzyme in an attempt to compensate for the disabled enzymatic activity caused by the presence of the herbicide. This is done by over expression of the EPSPS gene resulting in larger quantities of the EPSPS enzyme. The CP4-EPSPS gene also causes an increase in the production of EPSPS.

- The third mechanism is to increase the degradation of glyphosate by introducing a bacterial gene, called glyphosate oxidoreductase (*GOX*), which produces an enzyme that causes glyphosate degradation. *GOX* was isolated from the bacterium, *Ochrobactrum anthropi* strain LBAA.

These tolerance mechanisms can be stacked into the same plant for increased tolerance to glyphosate and to decrease the chance of trait breakdown in the crop. For example, the two enzymes CP4-EPSPS and GOX in combination provide glyphosate tolerance to GT200 canola.

Once the trait for glyphosate tolerance is introduced into plants by transformation, conventional plant breeding techniques are used to incorporate glyphosate tolerance into agronomically useful varieties. To date glyphosate tolerance has been transferred to over a thousand commercial soybean varieties through conventional breeding techniques.

5.3.2. Glufosinate tolerance

Glufosinate ammonium is a broad spectrum, post-emergence, contact herbicide. Whilst glufosinate ammonium is chemically synthesised, the active ingredient in glufosinate (L-phosphinothricin) was first isolated from the fermentation of two *Streptomyces* bacteria. The active compound, L-phosphinothricin, binds to and inhibits the enzyme glutamine synthetase (GS) in susceptible plants. The GS enzyme catalyses the synthesis of glutamine from glutamate and ammonia. The inhibition of GS by L-phosphinothricin causes an accumulation of ammonia in the plant, as well as a reduction in glutamine and the inhibition of photosynthesis, which result in the death of the plant.

Glufosinate tolerant cotton, maize, canola, soybeans, sugar beet, chicory and rice have been genetically engineered to carry the *bar* gene, which expresses the protein phosphinothricin acetyl-transferase (PAT). This protein detoxifies glufosinate by acylation of phospinothricin into an inactive compound. The *bar* gene was originally isolated from the soil bacterium, *Streptomyces hygroscopius* (Thompson *et al*., 1987).

5.3.3. Bromoxynil tolerance

Bromoxynil is a post-emergence, broadleaf herbicide that kills normal varieties of canola (*Brassica napus*). Bromoxynil tolerant canola (Oxy-235) was developed through transgenic methods to allow use of bromoxynil for weed control in canola, but this biotech-derived seed is no longer in use. The herbicide acts on susceptible broadleaf species by blocking electron flow in photosystem II, causing an accumulation of super oxide which is highly destructive to cell membranes and inhibits chlorophyll formation. This oxidation and chlorophyll inhibition result in plant death.

The bacterium *Klebsiella pneumonia* sub. sp. *ozaenae* contains a gene called *bxn*, which produces a nitrilase enzyme that hydrolyzes bromoxynil to non-phytotoxic compounds. Tolerance to bromoxynil was first achieved through isolation and incorporation of the *bxn* gene into canola (Oxy-235) using plant transformation. The *bxn* gene was transferred into other canola varieties through regular breeding techniques. Bromoxynil-tolerant cotton varieties were developed using similar techniques.

Bromoxynil-tolerant crops are not currently used commercially.

5.3.4. Sulphonylurea tolerance

Sulphonylurea herbicides bind to the enzyme acetolactate synthase (ALS), thereby inhibiting the biosynthesis of the branched chain amino acids (valine, leucine and isoleucine) and resulting in the accumulation of toxic levels of α-ketoglutarate. Tolerance to sulphonylurea comes from a gene (*als*) that encodes for an ALS enzyme that is naturally tolerant to sulphonylureas, and was isolated from the plant, *Arabidopsis thaliana*. This gene has been transferred to cotton, sunflower, wheat, flax and other crop varieties through transgenic and conventional plant breeding techniques.

5.4. CONVENTIONAL vs. BIOTECH-DERIVED HERBICIDE TOLERANT CROPS

Biotech-derived crops differ from conventional crops in two main ways:

- Firstly, through the use of biotechnology, scientists can insert genes from unrelated species into plants, opening up a much wider array of traits to be used.

- Secondly, a much smaller amount of genetic material is transferred with genetic engineering, dramatically reducing the likelihood that an undesirable trait will be transferred along with the desirable trait.

This second factor speeds up the scientific process of selecting new herbicide tolerant crop varieties. However there are additional delays in commercialising new biotech-derived varieties, because they need regulatory approvals that are not required for conventionally bred crops.

5.4.1. Pros and cons of conventional herbicide tolerant crops

The primary benefit of developing conventionally bred herbicide tolerant crops is that there are fewer regulations to register them and the public does not have a negative perception of this technology. There are two major disadvantages:

- Firstly, it is challenging for companies to deliver herbicide tolerance traits that can be transferred through conventional breeding. It should be noted that the cases of conventionally bred herbicide tolerant traits are all to herbicide modes of action that have a high risk for the selection of herbicide tolerant weeds, i.e., triazines, ALS inhibitors, and ACCase inhibitors; because it is easier to find rare mutations to these herbicide modes of action. Similar efforts using conventional breeding techniques have failed to find tolerance traits for herbicides like glyphosate and glufosinate.

- Secondly, mutated plants often contain many undesirable traits as a result of widespread and uncontrollable mutation. These unwanted traits must be removed by years of backcrossing. This is only the case with biotech-derived herbicide tolerant events when the traits are initially transferred into 'laboratory' varieties and then need to be backcrossed into commercial varieties.

Herbicide tolerant crops have been created through conventional breeding techniques and through gene transformation.

5.4.2. Benefits of herbicide tolerant crops

Herbicide tolerant crops constitute about 75% of all biotech-derived crops grown globally. These herbicide tolerant crops provide growers with flexible weed control allowing them to use a single herbicide without causing crop damage (Fernandez-Cornejo and McBride, 2002). The benefits and adoption rates of herbicide tolerant crops depend on the crop, new trait(s), and timing. Often the major perceived benefit to the grower is that they no longer have to deal with the complexity and unreliability of their previous weed control programmes, especially having to accurately identify weed species in the field and tailor herbicide programmes accordingly (Carpenter and Gianessi, 1999). While, with herbicide tolerant crops, it is possible to rely entirely on one herbicide for weed control throughout the growing season, this is not advisable as it increases the likelihood of herbicide resistant weeds developing in and around the fields.

Simplified weed control

Most herbicide tolerant crops have traits that enable them to resist herbicides that provide a wide spectrum of weed control. Therefore, it is often possible to rely on one herbicide, rather than having to combine several herbicides for effective weed control, which greatly simplifies weed management. Simplicity and flexibility (less management time) were found to be the major factors driving the adoption of herbicide tolerant soybeans by growers (Fernandez-Cornejo, 2006). Fernandez-Cornejo (2006) found that farmers who adopted herbicide tolerant soybeans did not benefit significantly from reduced weed control costs, however the farmers saved management time, which allowed them and/or their spouses to obtain a higher income from off-farm activities.

Better weed control

In many instances farmers may get better weed control when using herbicide tolerant crops as these crops allow the use of a broad spectrum herbicide. Most conventional, selective herbicides do not achieve broad spectrum weed control and more than one herbicide is required to obtain adequate weed management.

Glyphosate and glufosinate provide new modes of action in crops such as maize, soybean and canola. This has been of great benefit in controlling existing herbicide resistant weeds in these crops. In particular, triazine, ALS inhibitor, and ACCase inhibitor resistant weeds were widespread throughout the maize and soybean rotational cropping regions of the U.S., and herbicide tolerant crops have been used to help control these weeds.

Reduced crop injury

With conventional chemistry the margin of crop safety is sometimes slim, and if conditions are not perfect then crop injury may result, causing yield losses. With most herbicide tolerant crops the margin of safety is high, reducing the risk of crop injury, even if the incorrect rate is used or conditions are not perfect.

Less expensive weed control

In many cases farmers can see cost savings in their weed control when using herbicide tolerant crops. This is often due to a reduction in the number of herbicide applications, also saving the farmer in labour and equipment inputs. However, the cost of weed control is not always lower due to shifting of the cost from the herbicide itself to the technology fee charged for seed containing the herbicide tolerance trait.

Less herbicide carryover

Glyphosate and glufosinate are major herbicide tolerant crops planted globally. These herbicides have virtually no soil residual activity because they bind tightly to soil particles rendering them inactive in the soil. Thus there are no crop rotation restrictions as a result of residual herbicide activity in the soil (carryover). This allows farmers to practice integrated weed management using crop rotations.

Although adoption of herbicide tolerant crops is not necessarily associated with a reduction in herbicide use, it is usually associated with the use of herbicides that have a lower environmental impact.

Tillage reduction

Conventional agricultural practices involve cultivation prior to sowing of a crop or pasture to kill weeds and prepare the seed bed. 'No-till', also known as 'zero-till', requires replacing this cultivation with a pre-sowing knockdown herbicide application. The seed is then directly drilled into the soil through the crop residue. Special seeding equipment is required to implement no-till planting. Among the benefits of no-till are increased moisture conservation, reduced soil erosion, improved soil structure and carbon content, and reduced fuel use. The American Soybean Association conducted a survey on the tillage frequency on soybean farms and found that a significant number of farmers adopted no-till practices after planting herbicide tolerant soybeans. They calculated that the changes driven by the adoption of herbicide tolerant soybean saved over 234 million gallons of fuel and 247 million tons of topsoil (American Soybean Association, 2001).

Reduced environmental impact

Although adoption of herbicide tolerant crops is not necessarily associated with a reduction in herbicide use, it is usually associated with the use of herbicides that have a lower environmental impact (Carpenter *et al.*, 2002; Dale *et al.*, 2002; Duke and Cerdeira, 2005; Cerdeira and Duke, 2006). For example:

- With the adoption of glyphosate tolerant soybeans there was a slight increase in herbicide use per acre, however the herbicide (glyphosate) being used has a lower toxicity and persistence than the herbicides it replaces. Glyphosate has low toxicity to birds, mammals and fish; it binds to the soil rapidly preventing leaching; and is biodegraded by soil bacteria twice as quickly as the herbicides it replaced in soybean farming. All of these factors result in a lower impact on the environment.

- Shipitalo *et al.* (2008) conducted a comparative study between herbicide run off from conventional fields of maize and soybean, and fields of glufosinate tolerant maize rotated with glyphosate tolerant soybean. They found that the surface runoff of the glufosinate and glyphosate from the herbicide tolerant crops was much less than for the herbicides used on the conventional maize and soybean. They found that when soybean was grown the average glyphosate loss was one seventh that of metribuzin and half that of alachlor used on the conventional crop. When the maize rotation was grown the average loss of glufosinate was one quarter that of the atrazine used in conventional maize. The concentrations of herbicides from conventional maize and soybean (alachlor and atrazine) were more than 200 times their allowable drinking water standard in the first few runoff events after application; however the concentration of glyphosate and glufosinate were lower than their allowable drinking water standard in the first few runoff events. This study illustrates the environmental benefit of replacing residual herbicides with contact herbicides by using herbicide tolerant crops.

- Another environmental benefit of using herbicide tolerant crops is that they allow farmers to increase their adoption of minimum tillage farming (conserving soil nutrients, water, and reducing erosion).

Studies illustrate that there is an environmental benefit to replacing residual herbicides with contact herbicides when using herbicide tolerant crops.

5.4.3. Concerns about herbicide tolerant crops

As with all new technologies, there are concerns and challenges to deal with during the introduction of herbicide tolerant crops. The key challenges are the potential for weed shifts, weed resistance, altered yield performance, gene flow, herbicide drift, and volunteers. These are the same challenges experienced with weed control in non-transgenic crops.

Weed shifts

Many factors determine the spectrum of weeds found on a site, including climate, crop competition, soil fertility, other plant species, *etc.* Crop management practices have a major impact on the weed spectrum found in a field (Clements *et al.*, 1994). Changes in crop management may result in a change in the weed spectrum (the proportion of different weed species found in a field), and a change in the weed spectrum is known as a weed shift. Weed shifts have occurred in farmers' fields since the beginning of agriculture. Any change in management practice is likely to cause a weed shift if it is maintained long enough. Changes in tillage practices, cropping practices, cultural control, irrigation practices, grazing practices, *etc.* all can result in changes in the weed spectrum. Any changes in herbicide use also are likely to result in weed shifts given sufficient time.

Herbicide tolerant crops present a change in management practice and are likely to result in a shift in weed spectrums. While herbicides like glyphosate and glufosinate are broad spectrum, there are some weeds that have more natural resistance to these herbicides than others (King *et al.*, 2004; Westra *et al.*, 2004; Culpepper, 2004; Culpepper, 2006). If farmers rely on one herbicide mode of action for numerous years then there will be a shift towards weeds that have naturally higher levels of resistance to that herbicide. This type of weed shift happens if farmers rely on just one herbicide, even if the crops are not herbicide tolerant.

Crop management practices have a major impact on the weed spectrum found in a field.

Examples of weeds with naturally elevated tolerance to glyphosate are wild buckwheat (*Polygonum convolvulus*), Pennsylvania smartweed (*P. pensilvanicum*), lady's thumb (*P. lapathifolium*), ivyleaf morning glory (*Ipomea hederacea*), venice mallow (*Hibiscus trionum*), horseweed (*Conyza canadensis*), yellow sweetclover (*Melilotus officinalis*), and field bindweed

(*Convolvulus arvensis*) (Marshall *et al.*, 2000; VanGessel, 2001; Hilgenfield *et al.*, 2004).

Strategies to manage weed shifts are very similar to strategies for managing herbicide resistant weeds. Key factors in preventing weed shifts include using herbicides at the right rate and the right time, rotation of herbicide modes of action, crop rotation, the use of tank mixes and sequences of herbicides, and cultural means including tillage. If there is excessive reliance upon one herbicide in the absence of other weed management tools then there is not only the likelihood of weed shifts, but also the likelihood of selecting herbicide resistant weeds.

Weed resistance

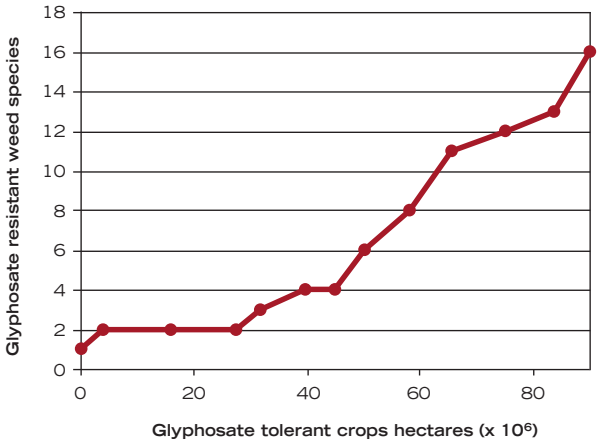
Herbicide resistant weeds are covered here in relation to herbicide tolerant crops. Whenever agricultural weed control practices remain the same, then weeds will eventually adapt and circumvent the weed control mechanisms. The repeated use of herbicides in the absence of other control measures is no exception. The occurrence of herbicide resistant weeds is dependent on the type of herbicides being used, the period they have been used for, the weed species being targeted, and many other crop management practices that farmers employ. Once weeds become resistant they can impact the profitability of a farming operation. Profitability is also affected by the cost of management practices (*e.g.*, use of multiple herbicides) to reduce the potential for resistance to develop.

Glyphosate has been used since the 1970s as a broad spectrum herbicide and its usage has steadily increased to become the largest selling crop protection product worldwide (Franz *et al.*, 1996; Baylis, 2000). The steady increase in area treated with glyphosate globally has been driven by a number of factors. Price reductions in the 1980s and 1990s and a movement towards zero tillage, which requires more glyphosate use, initiated this increase. This was followed by the introduction of biotech-derived glyphosate tolerant crops and the expiry of the herbicide's patent, which led to further large price reductions (Woodburn, 2000).

Herbicide resistant weeds have been documented since the 1970s, long before the introduction of herbicide tolerant crops (Ryan, 1970). It has also been long known that the repeated use of a single herbicide or herbicides with the same mode of action is the single most important pressure for the development of herbicide resistant weeds (Holt, 1992). Just prior to the introduction of the first herbicide tolerant crop (glyphosate tolerant soybean) there was much debate whether herbicide resistance would become a major issue. Although glyphosate was known from practical experience to be a low risk herbicide for resistance, some argued that glyphosate had been used for many years, and yet, at that time (1995) there was not a single case of a field selected, glyphosate resistant weed. Others argued that, if not managed correctly, the massive increase in area and intensity of use of glyphosate would result in glyphosate resistant weeds and threaten the sustainability of glyphosate tolerant crops (Jasieniuk, 1995; Bradshaw *et al.*, 1997).

Since the introduction of glyphosate tolerant crops there has been a steady increase in the number and spread of glyphosate resistant weeds (Figure 3). This is as a direct result of the increase in use of glyphosate on glyphosate tolerant crops.

Figure 3. The number of glyphosate resistant weeds in relation to the area of glyphosate tolerant crops (Heap, 2008).



Certainly the first appearances of glyphosate resistant weeds were not as a result of the introduction of glyphosate tolerant crops, having occurred long before these crops were introduced. Rigid ryegrass (*Lolium rigidum*) in Australia (Powles *et al.*, 1998; Pratley *et al.*, 1999; Lorraine-Colwill *et al.*, 2003), and goosegrass (*Eleusine indica*) in Malaysia (Lee and Ngim, 2000; Baerson *et al.*, 2002) were the first reported, field selected cases of glyphosate resistant weeds, and both were in orchard situations. However, horseweed (*Conyza canadensis*) was the first case of a glyphosate resistant weed appearing in a glyphosate tolerant crop (glyphosate tolerant soybean), found in Delaware and Tennessee in the U.S. (VanGessel, 2001). Glyphosate resistance in horseweed is believed to have resulted from the repeated use of glyphosate in the absence of an IWM programme. Table 2 presents the status of weeds known to have evolved resistance to glyphosate globally up until 2010.

Table 2. Weeds known to have evolved resistance to glyphosate (2010 data).

Year	Weed	Locations
1996	Rigid ryegrass (*Lolium rigidum*)	Australia, U.S., South Africa
1997	Goosegrass (*Eleusine indica*)	Malaysia
2000	Horseweed (*Conyza canadensis*)	U.S. (many states)
2001	Italian ryegrass (*Lolium multiflorum*)	Chile, Brazil, U.S.
2003	Buckhorn plantain (*Plantago lanceolata*)	South Africa
2003	Hairy fleabane (*Conyza bonariensis*)	South Africa, Spain, Brazil, U.S.
2004	Common ragweed (*Ambrosia artemisiifolia*)	U.S. (several states)
2004	Giant Ragweed (*Ambrosia trifida*)	U.S. (Indiana, Kansas)
2004	Ragweed parthenium (*Parthenium hysterophorus*)	Colombia
2005	Palmer amaranth (*Amaranthus palmeri*)	U.S. (many states)
2005	Johnsongrass (*Sorghum halepense*)	Argentina, U.S.
2005	Common waterhemp (*Amaranthus rudis*)	U.S. (several states)
2006	Wild poinsettia (*Euphorbia heterophylla*)	Brazil
2007	Crabgrass (*Digitaria insularis*)	Brazil
2007	Junglerice (*Echinochloa colona*)	Australia
2008	Liverseedgrass (*Urochloa panicoides*)	Australia
2010	Kochia (*Kochia scoparia*)	USA (Kansas)

Glyphosate resistant weeds are the most economically significant in farming systems. Glyphosate resistant Palmer amaranth has rapidly covered a large portion of the glyphosate tolerant cotton producing regions of the U.S. (Culpepper *et al.*, 2006). It is now by far the most serious glyphosate resistant weed. Glyphosate resistant horseweed is very widespread in the maize/soybean rotations in the U.S., and is relatively easy to control with other herbicide modes of action, such as synthetic auxins. Other potentially serious glyphosate resistant weeds are common waterhemp, giant and common ragweed, and Johnsongrass.

Management of herbicide resistant weeds in herbicide tolerant crops is no different than the management of herbicide resistant weeds in conventional crops:

- Use herbicide mixtures, sequences of herbicides and rotation of herbicides that have different modes of action;
- Use the full recommended rate of herbicides applied at the right time;
- Practice crop rotations to keep any one weed species from dominating. Rotations including row crops, cereals, and perennial forage crops are the most effective;
- Utilise tillage where applicable as a component of the weed management programme;
- Utilise cultural practices, reduce row spacing, maximise the crop competitiveness;
- Scout fields and monitor for resistance and weed shifts; and
- Keep accurate records.

(Mueller *et al.*, 2005; Owen and Zelaya, 2005; Young, 2006).

Management of herbicide resistant weeds in herbicide tolerant crops is no different than the management of herbicide resistant weeds in conventional crops

Yield performance

Herbicide tolerant crops may suffer from yield drag and yield lag. Yield drag is a reduction in crop yield directly attributable to the added trait or the position of the added trait in the plant genome. Elmore *et al*. (2001) discovered a 5% yield drag in glyphosate tolerant soybeans by comparing them to sister lines without the foreign gene. (The newest glyphosate tolerant traits in soybeans do not show this yield drag.)

Yield lag is a reduction in crop yield attributable to the engineered traits not being available in crop varieties that perform the best in different growing regions. As such, yield lag is specific to certain growing area–variety combinations. This was primarily a problem in the 1990s, and now that herbicide tolerant crops predominate, companies incorporate biotech-derived traits into most of their elite lines, thus yield lag is rarely an issue.

Gene flow

It is important to note that the movement of genetic material from plant to plant is a universal occurrence. Plant evolution is based on the sharing of genes, and it was the ability to harness this activity that allowed humans to cultivate selected crops and develop agriculture thousands of years ago. Therefore, gene flow in and of itself is not a problem or concern.

That said, it is possible for some crops to cross pollinate with weedy relatives and related cultivated species. Where this is possible, concerns have been raised that herbicide tolerance traits may be transferred between crop plants and weedy relatives. The rate and possibility of gene flow from biotech-derived to non-biotech-derived plants is no more likely than between other plants simply because a plant is transgenic. Introgression between crop plants and compatible weedy species already happens with conventional crops. Plant breeders have selected for disease and insect resistance through conventional plant breeding and it is likely that these traits have been transferred to compatible weedy species. It is largely unknown if these traits have greatly enhanced the fitness of the weedy relatives.

The significance of introgression between crop plants and compatible weedy relatives is primarily dependent on the nature of the weed/trait combination. Traits such as insect resistance, disease resistance, cold tolerance, salt tolerance and drought tolerance are much more likely to confer a fitness advantage to weeds in natural ecosystems than any herbicide tolerant trait, which

Because genetic modification is not an approved technology for organic farming organic farmers are not permitted to deliberately plant biotech-derived crop varieties.

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is only advantageous in the presence of the herbicide (Raybould *et al.*, 2000; Stewart *et al.*, 2003). The origin of the herbicide tolerant traits, whether they come from conventional plant breeding or genetic engineering, does not make any practical difference to the risk or consequence of transfer to sexually compatible weedy species.

Those opposed to biotechnology have spread misinformation about weeds that have acquired herbicide tolerance traits from crops, calling them "super weeds", and made false claims that they will endanger natural ecosystems. In reality herbicide tolerance traits do not confer any fitness advantage to weeds in unsprayed areas and thus will have no environmental impact on natural ecosystems (Stewart *et al.*, 2003). Indeed it is possible that a herbicide tolerance trait may confer a fitness *disadvantage* to a weed (Baucom and Mauricio, 2004), when the production of an additional protein requires additional resources from the plant and this results in a fitness penalty.

Herbicide resistant weeds can, however, present a problem in agricultural areas where herbicide selection pressure will confer a fitness advantage to a weedy species that has acquired a herbicide tolerance trait (Keeler *et al.*, 1996). The main consequence of a herbicide tolerant trait that has been transferred to a weed is that the farmer now has to contend with the resulting herbicide resistant weed. For instance, Seefeldt *et al.*, (1998) reported that imidazolinone tolerance (derived from conventional plant breeding) was transferred via pollen from wheat to jointed goatgrass (*Aegilops cylindrical*) in the U.S. Pacific Northwest. Since jointed goatgrass is a major weed in wheat, this presents a problem for farmers that wish to continue using imidazolinone herbicides for IMI-tolerant wheat production. A similar situation occurs in IMI-tolerant rice, which can cross pollinate with wild "red" rice, a major weed of rice worldwide (Langevin *et al.*, 1990).

There are a number of barriers that must be overcome before crop plants can transfer herbicide tolerance to weeds. The weed must be reproductively compatible with the crop species, usually a close relative from the same genus, and the offspring must be viable. The weed must be within physical proximity to the crop species and its flowering time must at least partially overlap with the crop species (Gepts and Papa, 2003). The presence of reproductively compatible weeds is location specific and must be determined for each crop in each growing environment. For example, for alfalfa, maize and soybean there are no weedy relatives in North America so there is no concern that herbicide tolerance genes will escape. For maize, while there are no weedy relatives, there are open pollinated varieties in Central America that can receive genes from herbicide tolerant biotech-derived crops and, while not a weed control issue, this has raised concerns about altering farmer preferred varieties and wild germplasm. Table 3 presents some U.S. data for crops that have compatible weedy relatives within physical proximity and so introgression is possible. There are no weedy relatives compatible with corn and soybeans in the U.S. and most other countries. Similar tables should be available for other agricultural growing areas.

Table 3. North American crops that have reproductively compatible weedy relatives growing within physical proximity of agricultural fields (Langevin *et al.*, 1990; Scheffler *et al.*, 1994, Hall *et al.*, 2000; Stewart *et al.*, 2003; Chen *et al.* 2004; Watrud *et al.*, 2004).

Crop	Weedy Relatives
Bentgrass	*Agrostis spp.*
Canola	Mustard species
Carrots	Wild carrot
Lettuce	Prickly lettuce
Oats	Wild oat
Radish	Wild radish
Rice	Red rice
Sorghum	Johnsongrass and shattercane
Sunflower	Wild sunflower
Wheat	Jointed goatgrass and quackgrass

Another concern raised about herbicide tolerant crops is the potential cross pollination with organic crops. This is of particular concern with biotech-derived herbicide tolerant crops, because genetic modification is not an approved technology for organic farming and, in order to maintain certification, organic farmers are not permitted to deliberately plant biotech-derived crop varieties. Organic maize and alfalfa farmers are concerned about cross pollination from biotech-derived maize crops in neighbouring fields. Cross pollination may limit their ability to market organic produce as the tests to detect biotech-derived traits are sensitive enough to detect very small quantities of cross pollination.

Herbicide drift

Herbicide drift occurs when a herbicide sprayed onto an area affects plants on an adjacent, non-target area. There is need to control herbicide drift regardless of the crop or herbicide. Herbicide drift can result in a major economic problem if the herbicide damages an adjacent susceptible crop. It can also result in environmental damage if the herbicide kills non-target plants in environmentally sensitive areas. Drift has

always been a concern for farmers; however the concern is greater when non-selective herbicides like glyphosate and glufosinate are being sprayed as post-emergence herbicides, because neighbouring crops are at a growth stage that is susceptible to these chemicals (Ellis *et al.*, 2003). An increase in use of herbicide tolerant crops is often accompanied with an increase in the need to control drift. In particular, farmers must be aware of neighbouring fields containing conventional crops and avoid drift onto these crops.

Volunteer crop plants

Volunteers are crop plants that germinate after harvest and in subsequent growing seasons. These volunteers present farmers with a problem as they compete for the resources of light, water and nutrients just as weeds do. Herbicide tolerant volunteers present farmers with an added challenge as fewer herbicides may be available to control them in subsequent plantings and they may need different control measurers. The use of certified seed, along with crop and herbicide rotations, rotation of herbicide tolerant traits, and use of cultural controls are among the best management strategies to deal with volunteers from herbicide tolerant crops.

Origin of volunteer seed

The most common origin of volunteer herbicide tolerant crops is seed that drops during harvest of the previous season's crop. Shattering of grain, seed spillage and harvest activities all allow a supply of volunteer seed to fall to the ground for the next year, and volunteers must be expected. However, there are some other unexpected ways in which volunteers may arise. Co-mingling of grain in harvest and seeding equipment can result in the adventitious presence of herbicide tolerant crop seed. The seed source itself may contain small amounts of unintended herbicide tolerant seed.

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5.4.4. Conclusions

Herbicide tolerant crops are now well established in modern agriculture (James, 2010) and they currently provide many weed control benefits, such as:

- Simplified weed control;
- Better weed control;
- Reduced crop injury;
- Lower weed control costs;
- Fewer herbicide carryover problems;
- New herbicide modes of action for control of resistant weeds;
- Environmental benefits;
- Enabling zero tillage systems; and
- Reduced fuel costs.

It is important that the herbicides associated with herbicide tolerant crops are used in combination with other weed control strategies to avoid potential problems, such as the development of herbicide resistant weeds or weed shifts.

Weeds will adapt, through resistance or avoidance mechanisms, to any farming practice that is used as a sole method of weed control. The goal of farmers should be to combine many weed management practices so that weeds are destabilised and do not have sufficient selection pressure to resist or avoid any particular management practice. To destabilise weed populations and avoid weed shifts and resistant weeds it is important to:

- Apply integrated weed management practices, i.e., use multiple herbicide modes of action with overlapping weed control spectrums in rotation, sequences, or mixtures;
- Use the full recommended herbicide rate and proper application timing for the most difficult to control weed species present in the field;
- Scout fields after herbicide application to ensure control has been achieved. Do not allow weeds to reproduce by seed or to proliferate vegetatively;
- Monitor weed management area and clean equipment before moving to a site without weed problems;
- Keep accurate field records.

For annual cropping situations, also consider the following:

- Start with a clean field and control weeds early by using a burndown treatment or tillage in combination with a pre-emergence residual herbicide as appropriate.
- Use cultural practices such as cultivation and crop rotation, where appropriate.
- Use good agronomic principles (*e.g.*, seeding rates, fertiliser placement and row spacing) that enhance crop competitiveness.

Herbicide tolerant crops are not unfamiliar; they provide the opportunity to use another herbicide mode of action in an integrated weed management programme. As with previous selective chemistries, if a single herbicide mode of action is relied upon for weed control over a long period of time in the absence of other weed control measures then herbicide resistant weeds and weed shifts will result. One way that industry can help reduce the potential for herbicide shifts and herbicide resistant weeds is to work together to develop cultivars that have tolerance to herbicides with different modes of action and spectra of control. Alternatively, individual cultivars may contain stacked genes which confer resistance to multiple herbicide modes of action. With these choices, farmers should combine herbicides with different modes of action and/or mechanical and cultural practices to avoid resistance and weed shifts. To insure long term sustainability of benefits realised with use of herbicide tolerant crops, farmers must practice diversified integrated weed management.

To insure long term sustainability of benefits realised with use of herbicide tolerant crops, farmers must practice diversified integrated weed management.

6. Developing an integrated weed management plan

It would be useful to prescribe one specific integrated weed management plan to fit each crop in each growing area, but this is not realistic. Every farm, indeed every field, needs to be evaluated on an individual basis to determine the most efficient and economical weed control programme.

Farmers need to look ahead and plan their weed control programmes for as long as practical, possibly 5-10 years, but the longer the better. Plans can always be modified as new technologies and practices become available. The aim is to craft an appropriate weed management programme that will not rely solely on one herbicide mode of action over successive years. In this way the potential risk for the selection of herbicide resistant weeds and weed shifts can be minimised. To develop an integrated weed management programme it is necessary to think strategically about how best to utilise all available weed control methods in combination to give the best overall result for each crop and each rotation. A checklist of options is a useful tool for farmers to develop.

Every farm, indeed every field, needs to be evaluated on an individual basis to determine the most efficient and economical weed control programme. Farmers need to look ahead and plan their weed control programmes for as long as practical.

This section points out some of the factors that must be considered when developing an integrated weed management plan for conventional or herbicide tolerant crops. This ordered approach has been valuable to others in developing integrated weed management plans.

The farmer needs to define long and short-term goals for the farm's integrated weed management programme.

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6.1. PURPOSE

The farmer needs to define the purpose of the weed management plan and what it will achieve. This requires creating long and short-term goals for the farm's integrated weed management programme. These goals will be established based on the level of weeds in the fields and the importance of these to local crop production.

6.2. WEED MANAGEMENT AREAS

The weed management areas need to be defined in terms of the specific boundaries of each area to be managed and the background to these areas. A management area may be anything from a portion of one field to a group of fields that have similar weeds and will share a similar resistance management strategy. The management area information should include a list of the soil types in the areas; the general topography; vegetation cover; potential impact from adjacent vegetation; *etc.*, for each area.

The final choice of weed management plan for each area needs to take into consideration the effectiveness and cost of the practices, the timing and the feasibility of implementing each plan with resources that are available to the farmer.

6.3. PROBLEM WEEDS

The farmer needs to identify the weed problems for each of the management areas. This should include listing, for each field, the three to five key target weeds and sketching maps to show the location of known weed infestations in each field. Help with the identification of weeds can be obtained on the web, or from local advisors. Importantly, the types and amounts of weedy species do not stay static. Instead, they fluctuate based on environmental factors and previous management practices. As such, farmers need to be aware of the changes and keep up-to-date with the current weed problems in production fields.

The farmer needs to identify the weed problems for each of the management areas.

6.4. EFFECTIVENESS OF CONTROL MEASURES

Before planning the next phase of control, the farmer needs to review, for each management area, the effectiveness of previous weed control efforts and to list any known or suspected herbicide resistant weeds. It is useful to record the cropping and herbicide application history for each field in the management area and to note the mode of action of each herbicide that has been used.

6.5. PLANNED CROP ROTATIONS

Looking forward, the farmer should list the potential crop rotations planned for each field and note any potential volunteer issues that might arise for each crop rotation. Five to 10 year planning is valuable. These plans can be changed and updated when needed.

6.6. CONTROL STRATEGIES AND RESOURCES

It is useful to compile a list of all practical weed management strategies and methods that are available for each field, including appropriate weed control methods in the categories of prevention, cultural, mechanical, chemical, and biological weed control practices. This list should include the known effectiveness of each practice against the target weeds in each field and any restrictions, limitations, or drawbacks that may apply to each weed control strategy (*e.g.*, herbicide carryover).

This planning documentation should include the equipment and resources needed, and the cost, for each weed control practice.

6.7. WEED MANAGEMENT PLANS

Using the information gathered above the farmer needs to prepare a weed management plan for each management area by evaluating the most appropriate weed control practices for each weedy area. The final choice of weed management plan for each area needs to take into consideration the effectiveness and cost of the practices, the timing and the feasibility of implementing each plan with resources that are available to the farmer. In addition, the management plans should include mechanisms for the prevention of new infestations and the avoidance of the development of resistance in weeds. The management of volunteer crop plants will need to be considered and safety requirements (human and crop) for the various components of the management plan, especially the consideration of practices to minimise long term, negative environmental impact.

6.8. IMPLEMENTATION

With a well informed, well researched and well reviewed plan the farmer is ready to implement weed management for his fields. Once the plans are initiated, it will be important to continue to scout the fields to assess the effectiveness of the weed control practices. Accurate records are essential to be able to evaluate effectiveness. It is best to review the effectiveness on an ongoing basis so that changes can be implemented to address what is happening in the fields. If a review of the data indicates that the weed management plan needs to be modified, these changes should be planned and implemented as quickly as possible.

6.9. REVIEW AND REVISION

Finally, prior to implementing the weed management plans, the farmer would benefit from a critical review of what is planned and any revisions, if these are deemed necessary. The critical review can be guided by the following questions:

- Do the management plans incorporate sufficient different modes of action to avoid the development of herbicide resistant weeds or weed shifts?
- Will the management plans ensure that volunteer crop plants can be controlled effectively in the subsequent crop rotations that are detailed in the plan?
- Do the management plans involve the use of weed control methods other than herbicides?
- Have all the available cultural control practices been evaluated and have those that are feasible been included in the management plans?

Without accurate records costly mistakes in application of herbicides may be made and it may be difficult to determine if herbicide tolerant volunteers will be an issue in subsequent crops.

6.10. IMPORTANCE OF KEEPING ACCURATE RECORDS

Record keeping is important and is an essential practice for the proper management of herbicide tolerant crops. Without accurate records costly mistakes in application of herbicides may be made and it may be difficult to determine if herbicide tolerant volunteers will be an issue in subsequent crops. Records should detail the whole production process from seed purchase to the final sale and delivery of the harvested crop. Some of the most important records to keep are:

- Lists of problem weeds including their prevalence in key areas;
- Effectiveness of control measures;
- Past and planned crop rotations;
- Control strategies with resources needed and resources available;
- Weed management implementation plans;
- Monitoring activities and problems identified;
- Corrective actions;
- Reviews of IWM and revisions.

Not all farmers have the time and resources for detailed record keeping, but growers are encouraged to devise documentation systems that are practical for their needs. Examples of recording forms for integrated weed management are included in this manual as a reference for growers wishing to develop their own documentation systems.

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Appendix 1. Information on Herbicides

A1. CLASSIFICATION OF HERBICIDES

Classification of Herbicides According to Modes of Action (Adapted from HRAC). The groups are the classification codes issued by HRAC (Herbicide Resistance Action Committee) and WSSA (Weed Science Society of America).

HRAC/ WSSA Group	Modes of Action and Chemical Family	Active Ingredient
A/1	**Inhibition of acetyl CoA carboxylase (ACCase)**	
	Aryloxyphenoxy-propionate 'FOPs'	clodinafop-propargyl, cyhalofop-butyl, diclofop-methyl, fenoxaprop-P-ethyl, fluazifop-P-butyl, haloxyfop-R-methyl, propaquizafop, quizalofop-P-ethyl
	Cyclohexanedione 'DIMs'	alloxydim, butroxydim, clethodim, cycloxydim, profoxydim, sethoxydim, tepraloxydin, tralkoxydim
	Phenylpyrazoline 'DEN'	pinoxaden
B/2	**Inhibition of acetolactate synthase ALS (acetohydroxyacid synthase AHAS)**	
	Sulfonylurea	amidosulfuron, azimsulfuron, bensulfuron-methyl, chlorimuron-ethyl, chlorsulfuron, cinosulfuron, cyclosulfamuron, ethametsulfuron-methyl, ethoxysulfuron, flazasulfuron, flupyrsulfuron-methyl-Na, foramsulfuron, halosulfuron-methyl, imazosulfuron, iodosulfuron, mesosulfuron, metsulfuron-methyl, nicosulfuron, oxasulfuron, primisulfuron-methyl, prosulfuron, pyrazosulfuron-ethyl, rimsulfuron, sulfometuron-methyl, sulfosulfuron, thifensulfuron-methyl, triasulfuron, tribenuron-methyl, trifloxysulfuron, triflusulfuron-methyl, tritosulfuron
	Imidazolinone	imazapic, imazamethabenz-methyl, imazamox, imazapyr, imazaquin, imazethapyr
	Triazolopyrimidine	cloransulam-methyl, diclosulam, florasulam, flumetsulam, metosulam, penoxsulam
	Pyrimidinyl(thio)benzoate	bispyribac-Na, pyribenzoxim, pyriftalid, pyrithiobac-Na, pyriminobac-methyl
	Sulfonylaminocarbonyl- triazolinone	flucarbazone-Na, propoxycarbazone-Na
C1/5	**Inhibition of photosynthesis at photosystem II**	
	Triazine	ametryne, atrazine, cyanazine, desmetryne, dimethametryne, prometon, prometryne, propazine, simazine, simetryne, terbumeton, terbuthylazine, terbutryne, trietazine
	Triazinone	hexazinone, metamitron, metribuzin
	Triazolinone	amicarbazone
	Uracil	bromacil, lenacil, terbacil
	Pyridazinone	pyrazon = chloridazon
	Phenyl-carbamate	desmedipham, phenmedipham
C2/7	**Inhibition of photosynthesis at photosystem II**	
	Urea	chlorobromuron, chlorotoluron, chloroxuron, dimefuron, diuron, ethidimuron, fenuron, fluometuron (see F3), isoproturon, isouron, linuron, methabenzthiazuron, metobromuron, metoxuron, monolinuron, neburon, siduron, tebuthiuron
	Amide	propanil, pentanochlor

HRAC/ WSSA Group	Modes of Action and Chemical Family	Active Ingredient
C3/6	**Inhibition of photosynthesis at photosystem II**	
	Nitrile	bromofenoxim, bromoxynil, ioxynil
	Benzothiadiazinone	bentazon
	Phenyl-pyridazine	pyridate, pyridafol
D/22	**Photosystem-I-electron diversion**	
	Bipyridylium	diquat, paraquat
E/14	**Inhibition of protoporphyrinogen oxidase (PPO)**	
	Diphenylether	acifluorfen-Na, bifenox, chlomethoxyfen, fluoroglycofen-ethyl, fomesafen, halosafen, lactofen, oxyfluorfen
	Phenylpyrazole	fluazolate, pyraflufen-ethyl
	N-phenylphthalimide	cinidon-ethyl, flumioxazin, flumiclorac-pentyl
	Thiadiazole	fluthiacet-methyl, thidiazimin
	Oxadiazole	oxadiazon, oxadiargyl
	Triazolinone	azafenidin, carfentrazone-ethyl, sulfentrazone
	Oxazolidinedione	pentoxazone
	Pyrimidindione	benzfendizone, butafenacil
	Other	pyraclonil, profluazol, flufenpyr-ethyl
F1/12	**Bleaching: Inhibition of carotenoid biosynthesis at the phytoene desaturase step (PDS)**	
	Pyridazinone	norflurazon
	Pyridinecarboxamide	diflufenican, picolinafen
	Other	beflubutamid, fluridone, flurochloridone, flurtamone
F2/27	**Bleaching: Inhibition of 4-hydroxyphenyl-pyruvate-dioxygenase (4-HPPD)**	
	Triketone	mesotrione, sulcotrione
	Isoxazole	isoxachlortole, isoxaflutole
	Pyrazole	benzofenap, pyrazolynate, pyrazoxyfen
	Other	benzobicyclon
F3/11	**Bleaching: Inhibition of carotenoid biosynthesis (unknown target)**	
	Triazole	amitrole (in vivo inhibition of lycopene cyclase)
	Isoxazolidinone	clomazone (WSSA group 13)
	Urea	fluometuron (see C2)
	Diphenylether	aclonifen
G/9	**Inhibition of EPSP synthase**	
	Glycine	glyphosate, sulfosate
H/10	**Inhibition of glutamine synthetase**	
	Phosphinic acid	glufosinate-ammonium, bialaphos = bilanaphos
I/18	**Inhibition of DHP (dihydropteroate) synthase**	
	Carbamate	asulam

HRAC/ WSSA Group	Modes of Action and Chemical Family	Active Ingredient
K1/3	**Microtubule assembly inhibition**	
	Dinitroaniline	benefin = benfluralin, butralin, dinitramine, ethalfluralin, oryzalin, pendimethalin, trifluralin
	Phosphoroamidate	amiprophos-methyl, butamiphos
	Pyridine	dithiopyr, thiazopyr
	Benzamide	propyzamide = pronamide, tebutam
	Benzoic acid	DCPA = chlorthal-dimethyl
K2/23	**Inhibition of mitosis / microtubule organisation**	
	Carbamate	chlorpropham, propham, carbetamide
K3/15	**Inhibition of VLCFAs (Inhibition of cell division)**	
	Chloroacetamide	acetochlor, alachlor, butachlor, dimethachlor, dimethanamid, metazachlor, metolachlor, pethoxamid, pretilachlor, propachlor, propisochlor, thenylchlor
	Acetamide	diphenamid, napropamide, naproanilide
	Oxyacetamide	flufenacet, mefenacet
	Tetrazolinone	fentrazamide
	Other	anilofos, cafenstrole, piperophos
L/20	**Inhibition of cell wall (cellulose) synthesis**	
	Nitrile	dichlobenil, chlorthiamid
	Benzamide	isoxaben (WSSA Group 21)
	Triazolocarboxamide	flupoxam
	Quinoline carboxylic acid	quinclorac (for monocots) (also group O) (WSSA Group 26)
M/24	**Uncoupling (Membrane disruption)**	
	Dinitrophenol	DNOC, dinoseb, dinoterb
N/8	**Inhibition of lipid synthesis – not ACCase inhibition**	
	Thiocarbamate	butylate, cycloate, dimepiperate, EPTC, esprocarb, molinate, orbencarb, pebulate, prosulfocarb, thiobencarb = benthiocarb, tiocarbazil, triallate, vernolate
	Phosphorodithioate	bensulide
	Benzofuran	benfuresate, ethofumesate
	Chloro-Carbonic-acid	TCA, dalapon, flupropanate (WSSA Group 26)
O/4	**Action like indole acetic acid (synthetic auxins)**	
	Phenoxy-carboxylic-acid	clomeprop, 2,4-D, 2,4-DB, dichlorprop = 2,4-DP, MCPA, MCPB, mecoprop= MCPP = CMPP
	Benzoic acid	chloramben, dicamba, TBA
	Pyridine carboxylic acid	clopyralid, fluroxypyr, picloram, triclopyr, aminopyralid
	Quinoline carboxylic acid	quinclorac (also group L), quinmerac
	Other	benazolin-ethyl

HRAC/ WSSA Group	Modes of Action and Chemical Family	Active Ingredient
P/19	**Inhibition of auxin transport**	
	Phthalamate Semicarbazone	naptalam, diflufenzopyr-Na
Z/25	**Unknown** Note: While the mode of action of herbicides in Group Z is unknown it is likely that they differ in mode of action between themselves and from other groups.	
Z/25	Arylaminopropionic acid	flamprop-M-methyl /-isopropyl
Z/26	Pyrazolium	difenzoquat
Z/17	Organoarsenical	DSMA, MSMA
Z/27	Other	bromobutide,(chloro)-flurenol, cinmethylin, cumyluron, dazomet, dymron = daimuron, methyl-dimuron=methyl-dymron, etobenzanid, fosamine, indanofan, metam, oxaziclomefone, oleic acid, pelargonic acid, pyributicarb

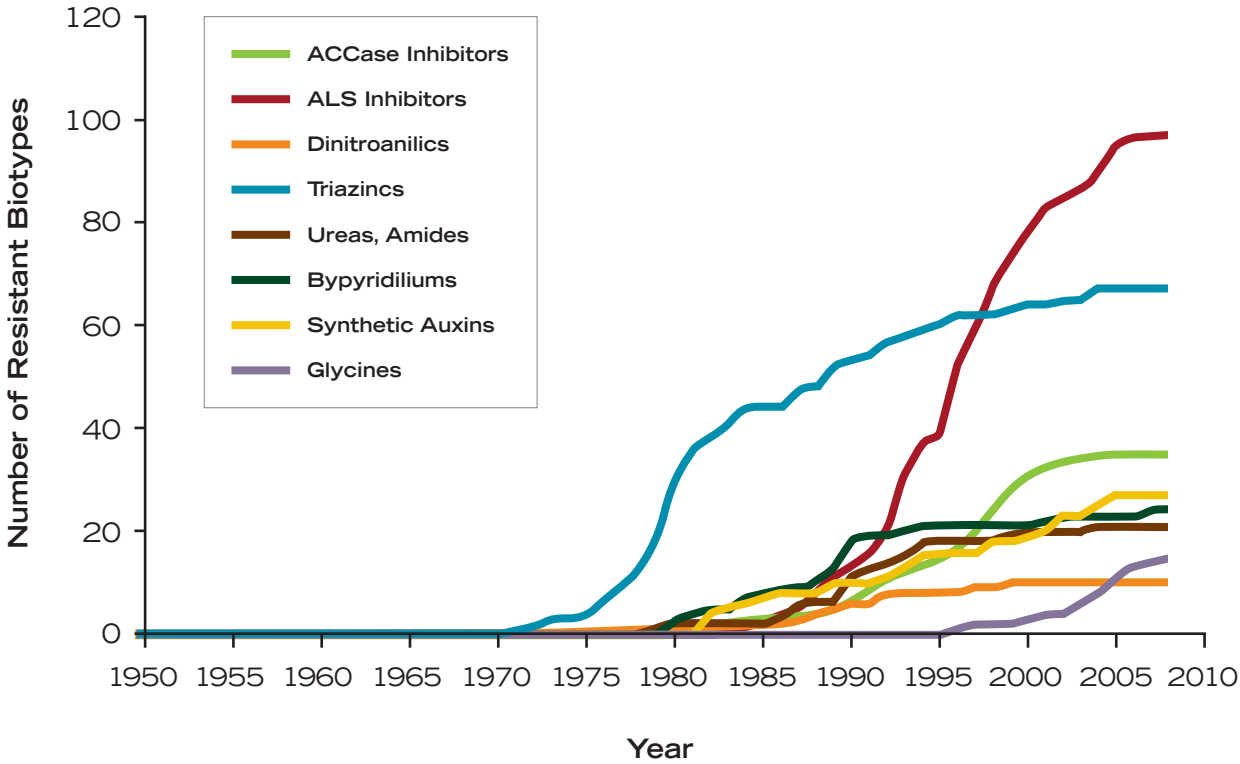
A2. FACTORS CONTRIBUTING TO RESISTANCE SUSCEPTIBILITY

Some herbicide modes of action (MOA) are more prone to the problem of resistance than others (Figure A1). The two major factors that contribute to the differences in the shape of the curves in Figure A1 are:

1. **The difference in the pre-selection proportions of resistant individuals in weed populations for each mechanism of action**. For instance, the proportion of resistant individuals in weed populations that have not been exposed to herbicides is greater for ALS inhibitor herbicides than for synthetic auxin herbicides.

2. **The total number of weeds treated by the mechanism of action**. This is a factor of the total area treated with the MOA per year, the number of years that the herbicide MOA has been used, and the number of weed species that the herbicide MOA targets.

Figure A1. The increase in new cases of herbicide resistant weeds by mechanism of action. (Heap, 2008).



ALS inhibitors

One hundred and two weed species have evolved resistance to ALS inhibitor herbicides, more than for any other herbicide MOA (Figure A1). This is partly but not solely due to the high level of natural ALS-resistant individuals in weed populations. The many different registered ALS inhibitor herbicides collectively target a very wide spectrum of broadleaf and grass species, and the popularity of these herbicides has ensured that a massive area globally has been treated with ALS inhibitor herbicides annually over the past 25 years. The ALS inhibitor herbicides still command a high market share globally and approximately five new ALS inhibitor resistant weed species per year are expected to be identified into the next decade. The ALS inhibitor resistant weeds are of major importance globally.

Triazines

Sixty-eight weed species have evolved resistance to PSII inhibitor herbicides. The number of triazine resistant weeds climbed most rapidly from 1975 to 1985, a period in which triazines dominated the herbicide market (Figure A1). In the last decade less than one new triazine resistant species per year was identified. A few factors account for the levelling off of the triazine curve:

- Most of the key weeds of maize that are targeted by triazines have already been identified as triazine resistant.
- Newer herbicides, such as the ALS and ACCase inhibitors (along with the introduction of glyphosate tolerant crops) have undoubtedly controlled some of the new cases of triazine resistant weeds.
- Farmers, extension agents, and researchers are more likely to assume triazine resistance and they do not bother to do the research to confirm the new species.

Triazine resistant weeds have moved from major importance in the 1970s and 1980s to moderate to low importance today – farmers have learned to deal with them by adding other mechanisms of action to their weed control programme.

ACCase inhibitors

Thirty-six grass weeds have evolved resistance to ACCase inhibitors. In 2001 the number of new species evolving resistance to ACCase inhibitors annually declined, primarily because there are relatively few key grass weeds left to add to the list. Even so the area infested with ACCase inhibitor resistant grasses is second only to that of the ALS inhibitors and continues to grow at a rapid rate. ACCase inhibitor resistant species are of major importance.

Dinitroanilines

Ten dinitroaniline resistant weeds have been identified, and these were of most significance in the mid-1980s to the mid-1990s. Farmers have learnt to manage most of them and their economic impact on crop production has waned.

Ureas and amides

Twenty-one species have evolved resistance to Ureas and Amides. These herbicides have been used as long as triazines but on far fewer hectares per year. Propanil-resistant *Echinochloa* species are still of major global importance in rice and account for the majority of hectares infested by weeds resistant to this mode of action.

Bypiridiliums

Together paraquat and diquat target a wide spectrum of weeds and were used extensively in the 1960s to the 1980s. Twenty-four weed species have developed resistance to bypiridiliums. In the last 15 years their importance has declined.

Synthetic auxins

Synthetic auxins have been used for longer and over a greater area than any other herbicide mode of action, yet only 28 weed species have evolved resistance to them. In addition, few of the 28 reported synthetic auxin resistant weed species have infested large areas or presented a major economic impact on crop production. Synthetic auxins are very low risk herbicides.

Glycines

Glyphosate targets a very wide spectrum of weeds, has been used for over 30 years, and has been used over a very large acreage for over 20 years. Given this, it is surprising that only 20 weeds have evolved resistance to glyphosate so far, and only a few of these cover more than 100 hectares. Glyphosate is a very low risk herbicide, yet it is clear that the number of glyphosate resistant weeds will increase commensurately with its usage. The introduction of glyphosate tolerant crops in the mid 1990s has rapidly increased the acreage and intensity of usage which will accelerate the number of new glyphosate resistant weeds identified.

Glyphosate resistant weeds currently have the least economic impact when compared to weeds resistant to the other modes of action. However, they have the potential to have the greatest economic impact in the future. Farmers manage glyphosate resistant weeds in a similar fashion to how they dealt with triazine resistant weeds. They will continue to use glyphosate and add other modes of action to their programme. This strategy effectively mitigated the impact of triazine resistant weeds because many new herbicide modes of action became available in the 1980s and 90s. Few new herbicide modes of action are being developed today, hence the high level of concern by farmers, academics and industry that this strategy may not be as effective in mitigating the economic impact of glyphosate resistant weeds in the future.

Appendix 2. Examples of IWM local and regional programmes

Use of Herbicide-Tolerant Crops as Part of an Integrated Weed Management Program, University of Nebraska, U.S.:
http://elkhorn.unl.edu/epublic/pages/publicationD.jsp?publicationId=108

Integrated Weed Management (IWM) in Australian Cropping Systems; Australian Glyphosate Sustainability Working Group:
http://www.glyphosateresistance.org.au/manual.html

Integrated strategies for managing agricultural weeds: making cropping systems less susceptible to weed colonization and establishment. Montana State University, U.S.:
http://ipm.montana.edu/cropweeds/montguides/IWM%20MT200601AG.pdf

IWM program for alligator weed in Botany Wetlands. Australia:
http://www.bettersafe.com.au/papers/Chandrasena_BotWetlands_AlligatorWeedManagement_21stAPWSS_%28Final%29.pdf

Salt Lake County Weed Control Program. Utah, U.S.:
http://www.weeds.slco.org/

Integrated Weed Management (IWM) in the CLEARFIELD Production System. CFIA, Canada:
http://www.inspection.gc.ca/english/plaveg/bio/dd/dd0873app1e.shtml#a4

IWM for Australian cotton. New South Wales, Australia:
http://www.dpi.nsw.gov.au/__data/assets/pdf_file/0006/309480/cotton-pest-management-guide-part5.pdf

Improved Weed Management with LibertyLink® Crops and Ignite® Herbicide. Australia:
http://www.lgseeds.com/content/improved-weed-management-libertylink%C2%AE-crops-and-ignite%C2%AE-herbicide

Integrated Weed Management Strategies for Turf grasses. Georgia Turf, U.S.:
http://commodities.caes.uga.edu/turfgrass/georgiaturf/publicat/PCRP2010/Integrated_Weed_Management.pdf

IWM for flaxleaf fleabane, Queensland, Australia:
http://www.dpi.qld.gov.au/documents/Biosecurity_GeneralPlantHealthPestsDiseaseAndWeeds/Flaxleaf-fleabane.pdf

IWM, Bayer Crop Science, 2009. U.S.:
http://www.bayercropscience.com/bcsweb/cropprotection.nsf/id/EN_Integrated_Weed_Management/$file/Integrated%20Weed%20Management.pdf

Serrated tussock IWM. Australia:
http://www.weeds.org.au/WoNS/serratedtussock/docs/stbpmm2.pdf

Appendix 3. Sample SOP for Implementing Integrated Weed Management

STANDARD OPERATING PROCEDURE (SOP) FOR IMPLEMENTING INTEGRATED WEED MANAGEMENT WITH BIOTECH-DERIVED HERBICIDE TOLERANT CROPS – USE OF THIS SOP IS VOLUNTARY.

Note: This Standard Operating Procedure (SOP) is intended solely as an example that may be used as an educational resource by organisations and growers that are developing integrated weed management programmes for conventional or biotech-derived herbicide tolerant crops. Growers who choose to use this SOP are encouraged to adapt it to suit their farm resources, farming practices and crop rotations.

A. DESCRIPTION OF THE ACTIVITY

A.1. To ensure good management practices for integrated weed management when growing conventional or herbicide tolerant biotech-derived crops.

B. SCOPE

B.1. This SOP covers integrated weed management measures for the production of herbicide tolerant, conventional or biotech-derived crops.

C. SOP DEVELOPER

Name of grower:
Signature:
Date:

D. TERMINOLOGY

Terms relevant in this SOP:

D.1. **Biotech-derived**: refers to crops improved through recombinant DNA techniques that alter the genetics of the crop.

D.2. **DNA**: refers to deoxyribonucleic acid, the genetic material of most living organisms.

D.3. **Grower**: refers to a farmer who purchases herbicide tolerant, biotech-derived planting material.

D.4. **Grower agreement**: refers to an agreement between the grower and the technology provider that is established at purchase of the planting material and may stipulate the integrated weed management requirements for a particular crop-trait combination in a weed management area. Many grower agreements do not have integrated weed management requirements.

D.5. **Herbicide tolerant**: refers to crops that have been developed to withstand damage from specific herbicides.

D.6. **IWM**: refers to integrated weed management and details the measures taken to delay the development of resistance to herbicides in local weed populations.

D.7. **Problem weeds**: refers to weed species that are present in large numbers, are difficult to control and appear to be increasing in number and the area they cover.

D.8. **Technology provider**: refers to the source of the planting material for the biotech-derived herbicide tolerant crop. Technology providers may require grower agreements that are implemented with seed purchase.

D.9. **Weed management area**: refers to the location where IWM is being implemented. Integrated weed management requirements may vary depending on factors present in different growing environments.

D.10. **Weed shift**: refers to changes in the types and numbers of problem weeds growing in a weed management area as a result of crop production activities.

E. GENERAL REQUIREMENTS

E.1. All growers planting conventional or biotech-derived crops that wish to implement IWM can be guided by this SOP.

F. REQUIREMENTS FOR PLANTING CROPS WITH IWM REQUIREMENTS

F.1. Prior to purchase of seed growers should read and understand the IWM requirements.

F.2. In the absence of IWM requirements, growers may choose to implement their own IWM system to help control the development of herbicide resistance weeds on their land.

F.3. Growers should choose the IWM configurations that best suit the crop rotations, weeds, farming practices and resources in their weed management area.

F.4. A Record of Integrated Weed Management should be completed for each weed-crop combination for which IWM is planned. A copy of the Record of Integrated Weed Management, with the appended map(s), should be completed within five working days following the implementation of weed management measures.

F.5. The Record of Integrated Weed Management should be retained by the grower for three (3) years after harvest to assist with further IWM planning.

G. PERFORMANCE REQUIREMENTS FOR IWM

G.1. All fields with problem weeds that will be used to produce conventional or herbicide tolerant crops should have an appropriate IWM plan in accordance with the grower guidelines for the growing area.

G.2. Appropriate weed management measures that mix modes of action, cultural practices, prevention measures, herbicides and/or biological control to prevent increase and spread of weed seed should be planned and recorded for each field with problem weeds.

G.3. The IWM measures should be suitable for the crop rotations, the local problem weeds and the resources of the grower.

G.4. The primary problem weeds should be identified, recorded and mapped for each planting area.

G.5. The conventional and herbicide tolerant crops and crop rotations planned for areas with problem weeds should be recorded.

G.6. Weed prevalence should be monitored and changes recorded to identify weed shifts and potential herbicide resistance development.

G.7. Technology suppliers should be notified when resistance development is suspected.

H. MONITORING FOR WEED RESISTANCE DEVELOPMENT

H.1. The grower should monitor weed growth in and around fields that have weed problems.

H.2. Reports and maps can be used to record weed prevalence and weed shifts and to help identify the potential development of herbicide resistance in problem weed species.

H.3. The Record of Weed Monitoring can be used to document all monitoring activities for the development of herbicide resistance in problem weeds.

I. OCCURRENCE OF WEED RESISTANCE DEVELOPMENT

I.1. The product guidelines should be followed by the grower in assessing levels of herbicide resistance in problem weeds.

I.2. The grower should notify the technology provider or agent if weed resistance development is suspected in local problem weeds.

J. CORRECTIVE ACTION IN THE EVENT OF POSSIBLE WEED RESISTANCE DEVELOPMENT

J.1. If weed control is ineffective the grower should implement different weed control measures, preventative measures, cultural practices, herbicides, and/or biological control in subsequent seasons.

J.2. If the development of herbicide resistant weeds is suspected the grower should change the weed control measures to those that use different modes of action and combine cultural, preventative, herbicide and/or biological weed control practices in subsequent seasons.

J.3. The grower should notify the technology supplier if these corrective measures fail to eliminate weeds resistant to herbicides.

J.4. Where agreed, the grower can work with the technology provider to implement treatment regimes aimed at eliminating herbicide resistant weeds in the weed management area.

J.5. The grower should facilitate the monitoring and control of weed resistance development in subsequent growing seasons.

K. MONITORING EFFECTIVENESS

K.1. Growers can facilitate assessments by technology providers of weed resistance development and IWM practices.

K.2. Growers can facilitate the access of IWM inspectors to fields and to the maps and records used for recording IWM practices.

L. CORRECTIVE ACTION IN THE EVENT OF INEFFECTIVE IWM PRACTICES

L.1. If IWM requirements are found to be inadequate, growers can work with the technology provider to identify functional IWM measures for their crops and weed management areas in subsequent growing seasons.

L.2. Modifications to IWM plans can be documented by the grower in a Record of IWM Modification, which can be retained for three (3) years after the weed problem has been corrected, to help with future IWM planning.

M. RECORD KEEPING

M.1. The Record of IWM and map for each weed management area with weed problems can be retained by the grower in an IWM Document Binder.

M.2. The Record of IWM Monitoring for each weed management area with weed problems can be retained by the grower in an IWM Document Binder.

M.3. The Record of IWM Modification for each weed management area with weed problems can be retained by the grower in an IWM Document Binder.

N. RELATED SOPS

N.1. The following SOPs must also be consulted:
[List any related SOPs]

O. REVIEW AND DISTRIBUTION

O.1. This SOP should be reviewed regularly by the grower.

O.2. Revised SOPs can be distributed to all farm managers acting on behalf of the grower, who will destroy their older copy.

P. ASSURANCE

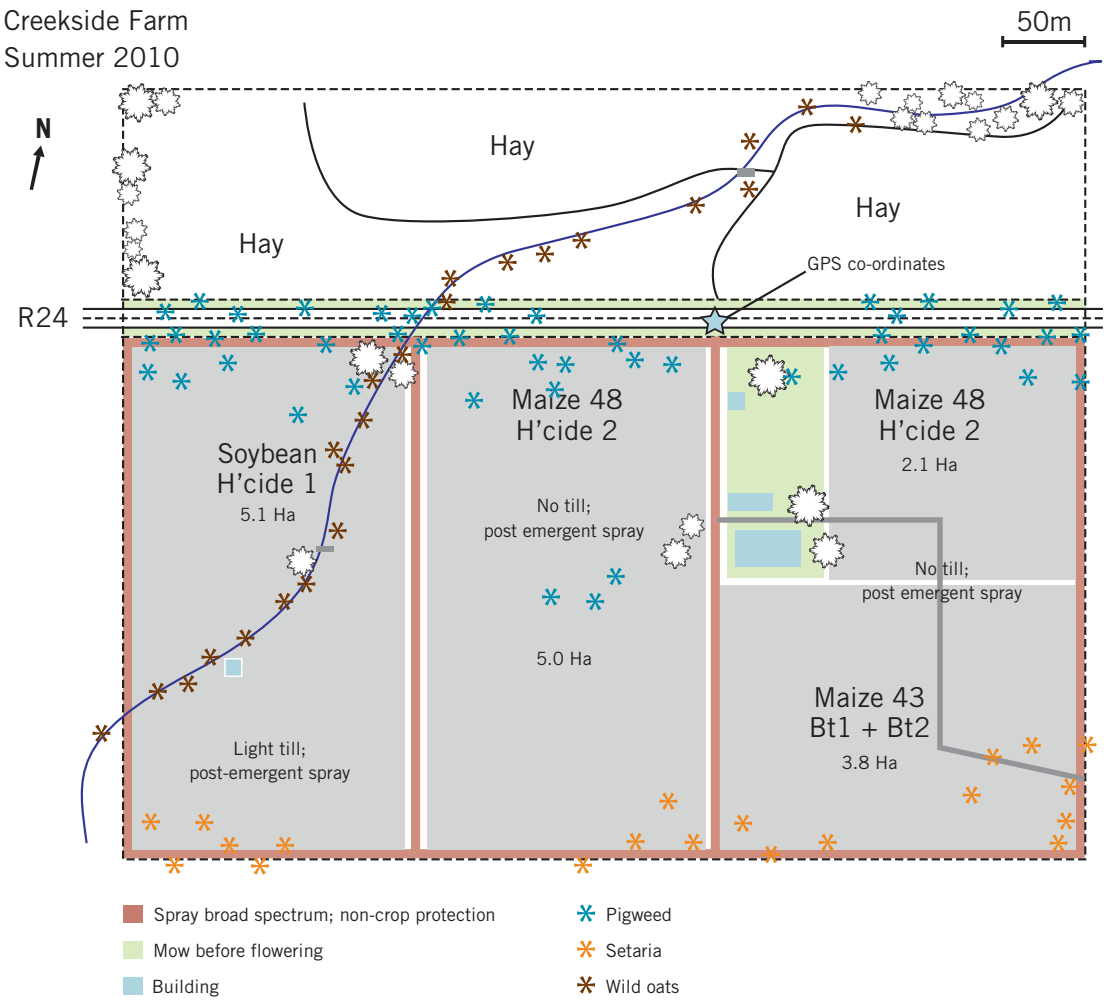
N.1. This document will be made available to all personnel responsible for implementing IWM.

Name of grower (please print):
Signature of grower:
Date:

ANNEX 1: INSTRUCTIONS FOR PREPARATION OF WEED MAPS

1. A map of problem weeds in and around growing areas used for biotech-derived herbicide tolerant crops should be prepared by the grower.
2. The map should be attached to the Record of IWM for each weed management area and retained in the IWM Document Binder.
2. Maps should provide sufficient detail to identify the fields included in the weed management area.
3. Maps should be drawn to scale and provide details on the layout of the site and approximate distances between crops and weedy areas.
4. The following items can be included on each map in the weed record file:
   a. Grower's name and contact details.
   b. Legal or descriptive land location.
   c. GPS coordinates, if available, for the entrance to the farm.
   d. Crop areas and primary weed locations.
   e. Crop identification and primary weed identification.
   f. Notes on appropriate IWM measures planned for fields and surrounding areas.
   g. Compass directions, with North at the top of the page.

Example of a map for a Record of IWM



Outline of IWM plan for mapped area

Weed management area	Herbicide tolerant crop(s)	Planned crop management (mode of action)
Creekside Farm 4502 Highway 87, Easton Contact person Alex Green, Farm Manager Tel: + 1 537 664 5878	Roundup Ready soybeans	Soil-prep light till; Roundup post emergent on soybean (G/9)
	Glufosinate resistant maize	No till; Glufosinate application post-emergence (H/10)

Major problem weeds	Planned control measures				
	Prevention	Cultural	Mechanical	Chemical	Biological
Pigweed	Clean machinery	Mow before flowering	Spring light till	Mesotrione (F2/27) + Atrazine (C1/5) in corn; Fomesafen (E/14) in soybeans	–
Setaria	Clean machinery		No till	S-metola-chlor /15) in corn and soybeans	–
Wild oats	Clean machinery	Narrow row spacing	Spring light till		–

Appendix 4. Record of Integrated Weed Management and Map

RECORD OF INTEGRATED WEED MANAGEMENT & MAP

Planting Year:

INSTRUCTIONS
Use of this form is voluntary

This **Record of Integrated Weed Management & Map** is completed to document integrated weed management that is implemented to discourage the development of herbicide resistant weeds. Growers who choose to use this form are encouraged to adapt it to their farm and farming practices.

This form and appended map(s) should be completed by the Grower within 5 working days, following the completion of planting.

The **Record of IWM & Map** should be retained by the Grower for 3 years after planting, in an **IWM Document Binder**, as a cross reference for future IWM planning.

For each weed-crop combination identified, record the crop management and cultural practices used to manage weeds.
Use an additional form if more than 5 problem weeds are identified in the management area.

PAGE 1 of 1

GROWER			FARM
Last Name	First Name	Initial(s)	Location
Street Address			GPS Coordinates
City	State/Province	Zip/Postal Code	Is a map of the growing area attached? ☐ Yes ☐ No
Telephone	Email		

LIST UP TO FIVE (5) MAJOR PROBLEM WEEDS (*only complete for number of problem weeds identified*)

1	2	3	4	5

CROP HISTORY

Previous Season Crop	Is this a herbicide tolerant crop? ☐ Yes ☐ No Herbicide:	Planting Month	Two (2) Seasons Ahead Planned Crop	Is this a herbicide tolerant crop? ☐ Yes ☐ No Herbicide:	Planting Month
Current Season Crop	Is this a herbicide tolerant crop? ☐ Yes ☐ No Herbicide:	Planting Month	Three (3) Seasons Ahead Planned Crop	Is this a herbicide tolerant crop? ☐ Yes ☐ No Herbicide:	Planting Month
Season Ahead Planned Crop	Is this a herbicide tolerant crop? ☐ Yes ☐ No Herbicide:	Planting Month	Four (4) Seasons Ahead Planned Crop	Is this a herbicide tolerant crop? ☐ Yes ☐ No Herbicide:	Planting Month

CROP MANAGEMENT PRACTICES FOR CURRENT SEASON

Crop-Weed 1	List crop management and cultural practices that will be used to combat herbicide resistance development in Problem Weed 1
Crop-Weed 2	List crop management and cultural practices that will be used to combat herbicide resistance development in Problem Weed 2
Crop-Weed 3	List crop management and cultural practices that will be used to combat herbicide resistance development in Problem Weed 3
Crop-Weed 4	List crop management and cultural practices that will be used to combat herbicide resistance development in Problem Weed 4
Crop-Weed 5	List crop management and cultural practices that will be used to combat herbicide resistance development in Problem Weed 5

FIELD MANAGER VERIFICATION (*if required*)
These activities have been carried out in accordance with standard operating procedures for integrated weed management.

Signature | Date signed

Appendix 5. Record of Weed Monitoring

RECORD OF WEED MONITORING

INSTRUCTIONS
Use of this form is voluntary

Planting Year:

This **Record of Weed Monitoring** is completed to document the impact of integrated weed management on problem weeds in the management areas where herbicide tolerant biotech-derived crops are planted. Growers who choose to use this form are encouraged to adapt it to the needs of their farms.

This record can be used to monitor up to five (5) different problem weeds in the weed management area. If more than five problem weeds have been identified then the Grower should use additional forms.

The **Record of Weed Monitoring** should be retained by the **Grower** for 3 years after planting, in an **IWM Document Binder**, as a cross-reference for future IWM planning.

PAGE 1 of 2

GROWER			FARM
Last Name	First Name	Initial(s)	Location
Street Address			GPS Coordinates
City	State/Province	Zip/Postal Code	Growing areas location(s) on the farm
Telephone	Email		

WEED MONITORING		
Problem Weed 1 Date	Population dynamics from last season to this season ☐ Declining ☐ Stable ☐ Increasing	Comments
Pre-Planting Monitoring Date	Level of Infestation ☐ Light ☐ Medium ☐ Heavy	Record all weed management control activity since previous season
Planting Monitoring Date	Level of Infestation ☐ Light ☐ Medium ☐ Heavy	Record all weed management control activity since previous monitoring
Mid-Season Monitoring Date	Level of Infestation ☐ Light ☐ Medium ☐ Heavy	Record all weed management control activity since previous monitoring
Harvest Monitoring Date	Level of Infestation ☐ Light ☐ Medium ☐ Heavy	Record all weed management control activity since previous monitoring Did Problem Weed 1 set seed? ☐ Yes ☐ No
Post-Harvest Monitoring Date	Level of Infestation ☐ Light ☐ Medium ☐ Heavy	Record all weed management control activity since previous monitoring
Problem Weed 2 Date	Population dynamics from last season to this season ☐ Declining ☐ Stable ☐ Increasing	Comments
Pre-Planting Monitoring Date	Level of Infestation ☐ Light ☐ Medium ☐ Heavy	Record all weed management control activity since previous season
Planting Monitoring Date	Level of Infestation ☐ Light ☐ Medium ☐ Heavy	Record all weed management control activity since previous monitoring
Mid-Season Monitoring Date	Level of Infestation ☐ Light ☐ Medium ☐ Heavy	Record all weed management control activity since previous monitoringn
Harvest Monitoring Date	Level of Infestation ☐ Light ☐ Medium ☐ Heavy	Record all weed management control activity since previous monitoring Did Problem Weed 2 set seed? ☐ Yes ☐ No
Post-Harvest Monitoring Date	Level of Infestation ☐ Light ☐ Medium ☐ Heavy	Record all weed management control activity since previous monitoring
Problem Weed 3 Date	Population dynamics from last season to this season ☐ Declining ☐ Stable ☐ Increasing	Comments
Pre-Planting Monitoring Date	Level of Infestation ☐ Light ☐ Medium ☐ Heavy	Record all weed management control activity since previous season

RECORD OF WEED MONITORING

Planting Monitoring Date	Level of Infestation ☐ Light ☐ Medium ☐ Heavy	Record all weed management control activity since previous monitoring
Mid-Season Monitoring Date	Level of Infestation ☐ Light ☐ Medium ☐ Heavy	Record all weed management control activity since previous monitoring
Harvest Monitoring Date	Level of Infestation ☐ Light ☐ Medium ☐ Heavy	Record all weed management control activity since previous monitoring Did Problem Weed 3 set seed? ☐ Yes ☐ No
Post-Harvest Monitoring Date	Level of Infestation ☐ Light ☐ Medium ☐ Heavy	Record all weed management control activity since previous monitoring
Problem Weed 4 Date	Population dynamics from last season to this season ☐ Declining ☐ Stable ☐ Increasing	Comments
Pre-Planting Monitoring Date	Level of Infestation ☐ Light ☐ Medium ☐ Heavy	Record all weed management control activity since previous season
Planting Monitoring Date	Level of Infestation ☐ Light ☐ Medium ☐ Heavy	Record all weed management control activity since previous monitoring
Mid-Season Monitoring Date	Level of Infestation ☐ Light ☐ Medium ☐ Heavy	Record all weed management control activity since previous monitoring
Harvest Monitoring Date	Level of Infestation ☐ Light ☐ Medium ☐ Heavy	Record all weed management control activity since previous monitoring Did Problem Weed 4 set seed? ☐ Yes ☐ No
Post-Harvest Monitoring Date	Level of Infestation ☐ Light ☐ Medium ☐ Heavy	Record all weed management control activity since previous monitoring
Problem Weed 5 Date	Population dynamics from last season to this season ☐ Declining ☐ Stable ☐ Increasing	Comments
Pre-Planting Monitoring Date	Level of Infestation ☐ Light ☐ Medium ☐ Heavy	Record all weed management control activity since previous season
Planting Monitoring Date	Level of Infestation ☐ Light ☐ Medium ☐ Heavy	Record all weed management control activity since previous monitoring
Mid-Season Monitoring Date	Level of Infestation ☐ Light ☐ Medium ☐ Heavy	Record all weed management control activity since previous monitoring
Harvest Monitoring Date	Level of Infestation ☐ Light ☐ Medium ☐ Heavy	Record all weed management control activity since previous monitoring Did Problem Weed 5 set seed? ☐ Yes ☐ No
Post-Harvest Monitoring Date	Level of Infestation ☐ Light ☐ Medium ☐ Heavy	Record all weed management control activity since previous monitoring

END OF GROWING SEASON EVALUATION

Note any weeds that may have developed herbicide resistance Has the technology provider been notified? ☐ Yes ☐ No	Note weed shifts observed	Identify the problem weed species to manage in the next season

Evaluation of IWM plan, including suggested modifications for next season to improve or maintain control

FIELD MANAGER VERIFICATION (*if required*)

These activities have been carried out in accordance with standard operating procedures for integrated weed management.

Signature

Date signed

Appendix 6.
Record of Integrated Weed Management Modification

RECORD OF INTEGRATED WEED MANAGEMENT MODIFICATION

INSTRUCTIONS
Use of this form is voluntary

Planting Year:

This **Record of IWM Modification** is completed to document modifications to Integrated Weed Management plans for specific management areas. Growers who wish to use this form are encouraged to adapt it to meet their farm needs.

This form should be completed by the **Grower** within 5 working days of the decision to modify the Integrated Weed Management plan.

The **Record of IWM Modification** should be retained by the **Grower** in the IWM Document Binder for 3 years after planting, as a cross-reference for future IWM planning.

PAGE 1 of 1

GROWER

Last Name	First Name	Initial(s)

Street Address

City	State/Province	Zip/Postal Code

Telephone	Email

FARM

Location

GPS Coordinates

Weed management area location(s)

PROBLEM IDENTIFICATION

Identify the weed(s) for which IWM modification is needed:

Discussion summary

Is herbicide resistance suspected?

☐ Yes ☐ No

If yes, enter details of communication with technology provider or agronomic advisor

Date:

Name:

Affiliation:

Contact Details:

MODIFICATION

Detail the modification and the proposed IWM measures to be implemented over the next four (4) planting seasons

Crop Rotation 1	Proposed weed management and cultural control
Crop Rotation 2	Proposed weed management and cultural control
Crop Rotation 3	Proposed weed management and cultural control
Crop Rotation 4	Proposed weed management and cultural control

FIELD MANAGER VERIFICATION (*if required*)

These activities have been carried out in accordance with standard operating procedures for integrated weed management.

Signature	Date signed

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