How to fight weed resistance and maximize yields?

Integrated Weed Management

Your guide to the way ahead in weed control

WEED RESISTANCE COMPETENCE CENTER

Contents

1.0 Introduction

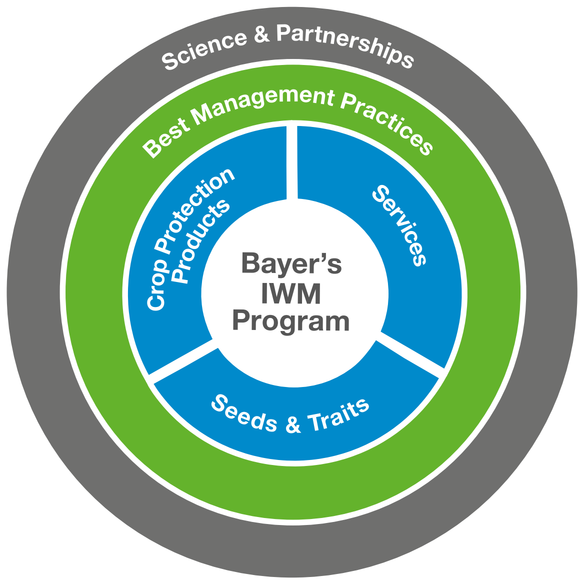
The title of this brochure, "How to fight weed resistance and maximize yields?", reflects the increasing presence of weed resistance as a permanent fixture in the management of weeds around the world. The use of properly applied herbicides at labeled rates is the most consistent, effective and economical method to control weeds. However, resistance to all herbicides is growing globally and multiple resistance (to more than one herbicide mode of action) is increasing the complexity of weed management. All stakeholders, including those on the farm and in public and private institutions, need to do more at all levels – on the farm or plantation, in industry, in distribution chains and advisory entities – to educate about resistance and to promote practices that include the integration of chemical and non-chemical management practices in order to prevent the obsolescence of current weed control measures. This revision of a previous brochure seeks to build on new knowledge and provide a guide on how to combine integrated strategies and practices that lead to sustainable weed control in an Integrated Weed Management approach, and why it is important to do so.

1.1 Why is Bayer taking stronger action on weeds?

The challenge of feeding a growing global population – over 9 billion by 2050 – is being made more difficult by the spread of herbicide-resistant weeds with their negative impact on agricultural productivity. Already today, every year weeds destroy enough food to feed 1 billion people. With resistant weeds on the rise, the loss may be even higher in future.

Farmers need a varied toolbox of available products and practices to combat the build-up of resistance. This goal is difficult to achieve in day-to-day endeavors because when a particular weed management practice is working well and is economically attractive, it is tempting to continue with it despite knowing that over-reliance on a single measure can significantly increase selection pressure, leading to resistance.

Incorporating Integrated Weed Management measures can help prevent resistance from severely impacting weed control, and may also lead to a decrease in the density of a resistant weed population. This requires, of course, that the problem is recognized, studied in detail, and addressed with a dedicated program over a longer period of time.



Bayer's Integrated Weed Management program is a holistic approach to weed control.

It is a well-balanced combination of three components to enhance farmers' productivity and secure food supplies in the long term:

1. *Outstanding* ***Integrated Weed Control Solutions***
2. *Implemented locally according to* ***Best Weed Management Practices***
3. *Based on the latest* ***Scientific Insights*** *and supported by valuable* ***Partnerships.***

In this way, Bayer CropScience is contributing to a more sustainable future of agriculture.

1.2 What is Integrated Weed Management?

Integrated Weed Management (IWM) is a fundamental program in the production systems of farmers that enables the sustainable control and management of weeds in fields using methods designed to complement each other. It involves the use of a range of diversified control techniques embracing physical, chemical and biological methods in an integrated fashion and without excessive reliance on any one method. An IWM plan needs to be defined over at least one full crop rotation in order to fully benefit from all aspects of diversification. Because of the increase in weed resistance over the past decade, IWM has been adopted increasingly as a tool for managing herbicide-resistant weeds. The purpose of IWM is to reduce weed pressure and keep weeds at low levels. The desired outcome is to put weeds off balance and thus make it easier for an herbicide to do its job — which is to protect the yield potential of a crop. The goals of an IWM plan can be simply stated as follows:

1. Suppress weed growth and biomass accumulation to limit their ability to decrease yield
2. Minimize weed seed production to limit the return of seeds into the soil seed bank
3. Deplete weed seed reserves in the soil to minimize germination in subsequent years
4. Prevent or reduce the spread of weeds to keep problems away from non-problem areas

The careful use of such methods should result in no negative environmental issues, and in fact, can deliver positive environmental results by helping to reduce soil erosion and increasing soil organic matter levels. It can also pay for itself by delivering economical weed control. It may require doing some things differently than what was done before, but IWM is a dynamic program than can be fine-tuned to almost any agricultural production system.

1.3 Bayer CropScience's commitment to IWM

Improved productivity will be accomplished by offering high-quality seeds, crop protection products and tailored services, and integrating them in complete weed management solutions. Bayer CropScience has a broad selection of herbicides in different classes for sustainable protection against weeds in major food, feed and fiber production systems worldwide.
Bayer invests heavily in research to develop new methods and possibilities of combating weeds. The herbicide research activities are concentrated at the research facility in Frankfurt, Germany, where Bayer CropScience has laboratories, production facilities and its Weed Resistance Competence Center, which was inaugurated in 2014. As our global reference center, the Weed Resistance Competence Center is developing and implementing pro-active programs to promote the sustainability of weed control. The growing resistance situation worldwide, along with its increasing complexity, is making weed control more arduous. The implementation of solutions requires a fundamental shift in thinking and acting by farmers, by advisors, by the product distribution chain, and by all of us as well.

Our Mission:
The Weed Resistance Competence Center provides the scientific foundation for understanding weed resistance and is the Bayer CropScience global reference center for weed resistance management.

The core activities of its full-time personnel cover three areas:

- Understanding weed resistance mechanisms and their evolution in the field
- Developing and testing new weed control strategies and supporting the discovery of weed control innovations
- Sharing Bayer CropScience's knowledge and weed control solutions with the entire value chain.

WEED RESISTANCE COMPETENCE CENTER

1.4 Best Weed Management Practices – Diversity is the Future

Our global initiative is called "Diversity is the Future". Diversity is the key to success in many aspects of crop protection, including diversity in herbicides, diversity in crops, and diversity in supplementary methods designed to disrupt the life cycle of weeds. In this way Bayer is contributing to sustainable agriculture.

DIVERSITY IS THE FUTURE
is a global Bayer initiative to promote best practices in weed management

Weed control basics begin with understanding what a weed is and how it can affect you, even if you are not a farmer nor work in agriculture.

2.0 Weed control basics

2.1 What is a weed?

A weed can be defined in many ways. The Webster-Miriam dictionary (Anon., 2015) defines a weed as “a plant that is not valued where it is growing and is usually of vigorous growth; especially: one that tends to overgrow or choke out more desirable plants.” This certainly refers to several attributes of weeds: not valued (where it is growing, e.g. in a field of crops), vigorous growth, and interference with the growth of desirable plants (e.g. crop plants). Those attributes contribute to losses in potential yield caused by weeds and losses that result in less food, feed and fiber being harvested and available to nourish and clothe our growing global population.

2.2 Why do we need to control weeds?

Weeds can be pretty, as in the picture of the poppies in the picture to the left (*Papaver rhoeas*). However, in this situation these plants are not wanted because they are growing in a field of barley. It might not seem like a lot of weeds are present, but the relatively light infestation can still significantly reduce yield. What you see at the field’s border may actually be much worse somewhere else in the field and cannot readily be seen from its edge. Weeds compete with crops for water, nutrients and space, and if allowed to grow taller than the crop canopy, can block light (**Figure 1**). All this competition with the crop can add up to significant yield losses over a growing season. In some cases the weeds can interfere with the harvest and cause additional yield loss. And if weeds are allowed to grow unchecked, they can reproduce and recharge the soil seed bank. The seeds of many weed species can survive in the soil for many years and cause protracted problems. A summary of monetary yield losses across many countries and for a large variety of crops through weeds (**Figure 2**) shows an average potential loss of approximately one third of the total harvest (Oerke, 2006). The average yield protection afforded by all weed control methods reduced the total loss by three-quarters. Sometimes, in addition to decreasing the crop yield, weeds can also affect the ability to harvest a crop.

Effect of weeds on crop plants

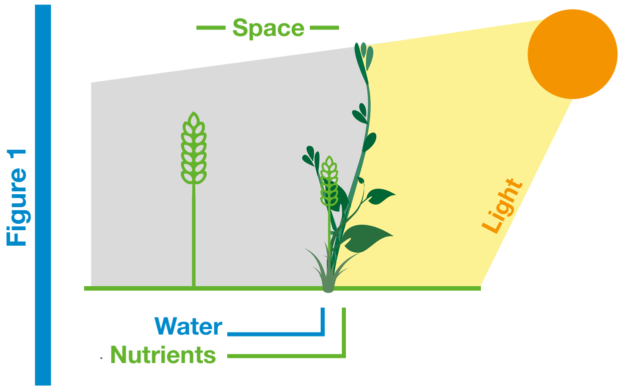


Figure 1

Picture source: http://www.bayercropscience.co.uk/your-crop/crop-diseases,-weeds-and-pests/grass-weeds/black-grass/

Average yield protection potential of weed control measures

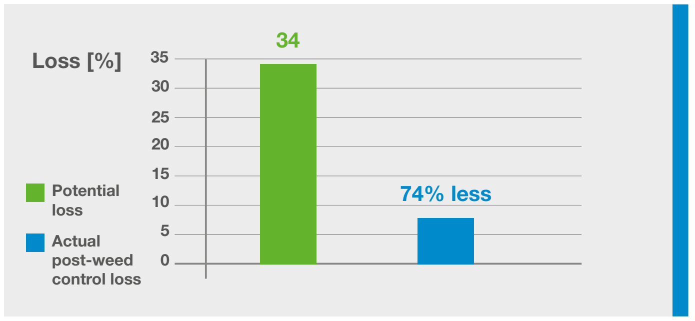


Figure 2

Source: Oerke, 2006

For example, Palmer amaranth (*Amaranthus palmeri*) in cotton (**Figure 3**) can break the tines of mechanical harvesters and thus decrease and severely slow down the harvesting process. Once harvested, weeds can contaminate the harvest with undesired seeds that result in dockage. In severe cases, a total loss of yield can be the result of allowing weeds to get the upper hand in a crop (**Figure 4**).

Palmer amaranth plants in a cotton field

Figure 3

Weeds choking out corn plants

Figure 4

The bottom line is that weeds need to be controlled in every field, every year. In addition to affecting yield, weeds can cause many other problems (Zimdahl, 2007). Weeds can cause human health issues, such as allergic reactions caused by their pollen, e.g. the reaction commonly known as hay fever. Poisonous weeds can cause allergenic reactions on exposed skin or actually result in severe injury or death if ingested. Dried weeds can also be a significant fire hazard during certain periods of the year. Certain weeds can harbor specific harmful pests (insects, diseases and nematodes). Aquatic weeds can interfere with water management. Weeds can also negatively interfere with downstream harvest processes and, surprisingly, can detrimentally impact transportation safety if they interfere with good visibility on highways or railways.

One rarely thinks about the effects of weeds on wildlife, but poisonous invasive species can also be detrimental to game animal populations, damage communities of native flora, and develop into major ecological problems if unchecked (Zimdahl, 2007).

2.3 How can **weeds** be **controlled?**

It is really simple. Weeds can be controlled economically in broad-acre agriculture through two main means: through mechanical cultivation or use of an herbicide. Other agronomic, non-chemical means of weed control can significantly reduce weed populations but rarely result in the level of weed control achieved using the first two methods. Manual weeding can be used for small-scale uses or as a complement to mechanical cultivation or herbicide use on larger fields, but is not an economically sustainable method of weed control for larger farms because it is so labor-intensive.
Weed control can be divided into preventive weed management, with the aim of decreasing the emergence or growth of weeds, and corrective weed management, with the aim of eliminating weeds once they have emerged.

Past

Present

Source: Bayer CropScience

Definition of weed control and suppression

Figure 5

Weed control		Suppression
Weed control Elimination of weed competition with **more than 80% efficacy**		**Suppression** Reduction of weed competition with **30-70% efficacy**
Annual weeds • Elimination of roots and shoots • Weed development stopped • No viable seeds	**Perennial weeds** • Elimination of above-ground plant material • Impact on below-ground organs	• Partial inhibition of growth and development • Reduction in number of viable seeds

Source: Bayer CropScience, 2014

Preventative weed management techniques include crop rotation, alternation of spring and autumn crops, and agronomic measures such as tillage, seeding time, starting with clean seed, and the use of cover crops. Corrective weed management techniques include hand-weeding, mechanical cultivation and thermal weed management (by flaming), post-harvest weed seed control, biological or biotech weed management, and chemical weed control (herbicides). These techniques will be discussed in greater detail in Section 5.

How do you define the level of weed control needed? **Figure 5** shows commonly accepted definitions of weed control and suppression. Acceptable levels of weed control are reached upon the elimination of weed competition with more than 80% efficacy. Suppression is defined as the reduction of weed competition with 30-70% efficacy. Efficacy is usually measured by assessing the reduction in above-ground biomass. However, reduction in the below-ground roots and other organs (i.e. rhizomes) is also important. However, the reduction in the number of viable seeds that are returned to the soil seed bank (defined as the sum of viable, dormant seeds in the soil, including vegetative propagules) is a more long-term oriented and robust goal of weed control. Generally speaking, the higher the level of efficacy, the better the yield protection. In the past, a great deal of emphasis was put on using economic thresholds to determine the level of intervention in weed growth. However, the high degree of competitiveness and ability of some weeds to produce large numbers of seed, e.g. Palmer amaranth, a “zero-tolerance” policy has been adopted as a management strategy to prevent such weeds from overrunning fields (Norsworthy *et al*., 2014).

The reduction of viable seeds that are returned to the soil seed bank is a more long-term oriented and robust goal of weed control.

Sun Tzu, an ancient Chinese military general, strategist, and philosopher, has been credited with underscoring the need to “understand one’s enemy”. The more you understand about him, and yourself, the better you are able to defeat him. The same goes for weeds. They are, year after year, the major enemy for crops. The objective is to disrupt the weed’s cycle and eliminate its threat to obtaining the maximum yield possible in a given field with the given inputs and subject to the conditions over the crop-growing season. In order to do so, you must understand the weed, beginning with its identity and biological characteristics. Some weeds have a much greater ability to compete (e.g. pigweeds, *Amaranthus* spp., and giant ragweed, *Ambrosia trifida*) than others (e.g. large crabgrass, *Digitaria sanguinalis*) and need to be treated differently. The same can be said for the crop. You must understand its ability to compete with the weeds present in the field and how long it takes for the crop canopy to close. Once the crop canopy is closed, the ability of weeds to affect the yield potential is severely reduced (Seavers and Wright, 1999). In short, weeds are highly adaptable to many environments and strive for survival, while crops are adapted to specific environments and bred for yield and uniformity.

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2.4 Weed identification – **why** is it important to know **your weeds?**

Know your weeds. The most important reasons for correctly identifying weeds are based on the fact that differences in susceptibility to herbicides and growth characteristics among weeds that look similar but are, in fact, different species can result in the selection of improper measures. The following list (adapted from Shrestha, 2015) states several of the reasons:

- Knowing exactly which weeds you have in your field and their biological characteristics helps you choose the correct herbicide and other complementary control measures that will work
- Different weed species can respond to management measures very differently
- Some weed species are more competitive than others and need to be treated differently
- Seed production and shattering characteristics (return to the soil bank) may differ greatly between weed species
- Weed emergence characteristics can differ greatly between weed species
- It is important to know whether a weed has an annual or perennial growth habit to help chose a management strategy – perennial weeds may require control of plant organs in the soil (e.g. rhizomes, bulbs)

2.4.1 Differences between species in inherent activity

Differences in sensitivity between plant species can be large, even if the phenotypes (weed appearance) are very similar. Let's take two Amaranthus species currently causing problems in the US, Palmer pigweed and waterhemp, as an example. **Figure 6** shows photos of the germinating weeds (Hager, 2013) and **Figure 7** shows the inflorescence and individual flowers (Hartzler, 2013) for both species, which can be difficult to tell apart. The dose-response curves for representative samples of each species in response to treatments of post-emergent applied tembotrione are shown in **Figure 9** (Bayer CropScience data, 2013). Although they look similar at the lower rates and really begin to differentiate only at the higher rates, they really are different. The calculated GR50 rates (rate at which 50% fresh weight reduction was observed) are 9 and 33 g a.i./ha (g active ingredient per hectare), respectively for the waterhemp and Palmer pigweed samples. This means that it takes approximately 3.7 times more tembotrione to get 50% fresh weight reduction of Palmer pigweed than waterhemp. When looking at the GR80 values, 15 and 91, respectively, the ratio is slightly higher at 6 times more tembotrione to get 80% fresh weight reduction. This difference can therefore have serious consequences for weed control if you misidentify the weed.

Palmer pigweed (above) and waterhemp (below) seedlings

Figure 6

Source: Hager, 2013

Palmer pigweed (left) and waterhemp (right) female inflorescence and individual flowers

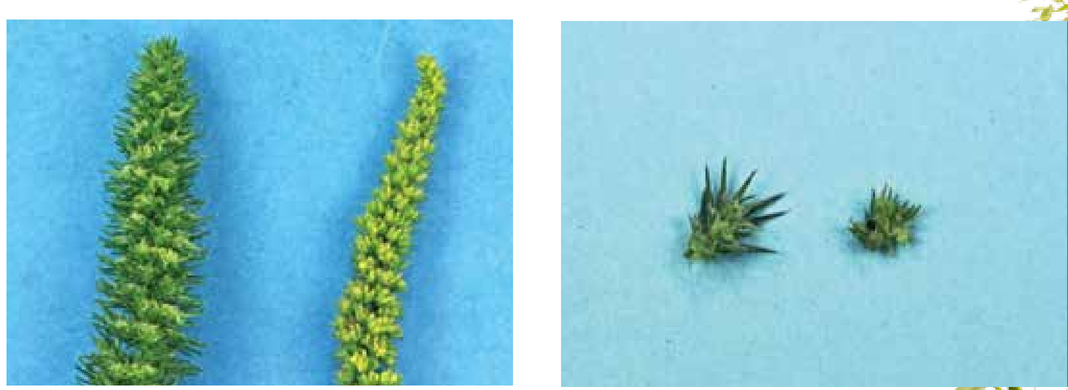

Figure 7

Source: Hartzler, 2013

Dose-response curve for Palmer amaranth and waterhemp to tembotrione

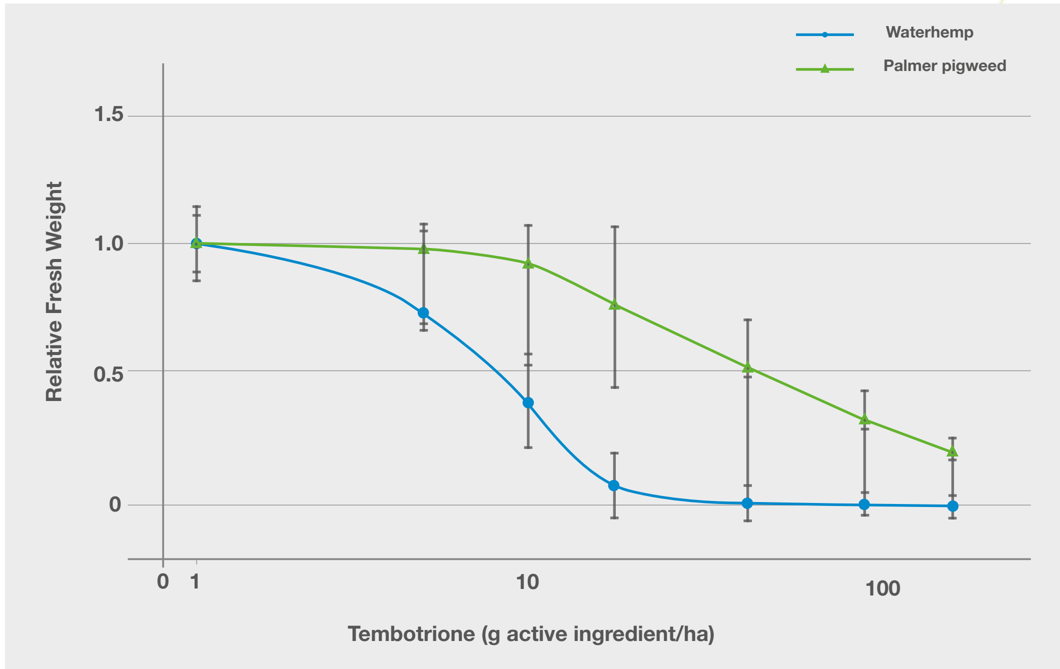

Figure 8

Source: Bayer CropScience, 2013

2.4.2 Phenotypic variability

Not only can different weed species look similar, different populations of the same species can also look different. This ability to have multiple growth forms is a desirable property for a weed since it helps it adapt to novel forms of stress (Hantsch *et al*., 2013). Phenotypic variability in weeds can be extremely large and appears to be a predictor of the invasive ability of weeds to acclimate to new environments (Mal and Lovett-Doust, 2005). Sometimes, the variability is so large that not enough is known about all the phenotypic variants and genetic tests must be implemented – at significant cost – to truly distinguish whether an accession of a weed is merely another phenotypic variant or belongs to another completely different species (Bayer CropScience unpublished data, 2015).

2.4.3 Genetic variability

High phenotypic variability seems to go hand-in-hand with high genetic variability. This leads to greater chances of a weed population surviving a new threat to its survival, such as the application of a new herbicide it has not experienced before. Only one plant has to survive and produce viable seed for the trait or traits conferring resistance to be passed on to the next generation. It is important to know the reproductive strategy of a species – whether it is self-fertilized, apomictic or outcrossing – to help guide you to the best strategy to contain the weed to a particular area. It can also help you to zero in on particular reproductive structures (e.g. seeds, rhizomes, bulbs) to measure the success of your weed control management program.

Where to get information on weed identification

Due to the regional differences in weed phenotypes, the best place to get information on weed identification is from local sources – local agricultural extension agents, company representatives, agricultural universities, public and private advisors, or from one of the increasing number of smartphone or tablet applications.

2.5 Weed biology and ecology

Once a weed has been correctly identified, it is then important to understand the biological and ecological attributes of that species as the first step to developing a management plan for that weed (Norsworthy *et al*., 2012). An incomplete understanding of the biology of a weed in a particular area is one of the continuing impediments to its management. Attributes including germination characteristics and period, growth habit and optimum growth conditions, growth rate, competitiveness, flowering and seed dispersal, and seed production are important factors that can give insights on how best to approach managing that weed. The aim of an IWM program is to disrupt the life cycle of the target weed(s) with as many approaches as is economically feasible in order to make the herbicide's job easier and decrease the selection pressure for resistance.

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2.5.1 Germination characteristics and period

Does the target weed germinate in the winter, spring, or both? Does it germinate at one time or in waves during the entire growing season? These are important considerations when designing a weed management program. For example, a majority of black grass (*Alopecurus myosuroides*) seeds germinate in the fall if moisture is sufficient, making winter crops like winter wheat more vulnerable (Moss, 2013). In the case of Palmer amaranth (*Amaranthus palmeri*), germination can occur throughout the growing season (April – October in South Carolina) and even after canopy closure, necessitating weed control strategies that cover extended periods (Jha and Norsworthy, 2009).

2.5.2 Growth habit and optimum conditions

It is very helpful to know if the weed is an annual or perennial, whether it grows over the winter or is a summer plant. It is harder to control a winter annual in a winter crop and likewise a summer annual in a spring crop. A rotation of crops counter to the season of driver weeds is one of the best strategies to put weeds off balance (Leighty, 1938). For example, if facing an annual grass in a winter cereal crop, it is easier to combat this in a spring crop, given the opportunity to use a cover crop during the winter to reduce the opportunity for the weed to grow freely, or to use a non-selective burn-down treatment to significantly reduce weeds prior to planting.

Does the weed grow prostrate or vine up the crop structure? Does the weed form rhizomes or other underground reproductive structures that might impede complete control? Is it a C4 plant that is much more able to handle higher temperatures and thus outcompete a C3 crop under these conditions? It helps to understand the biology of the target weeds to find each weed's weaknesses and exploit them, and avoid its strengths with other tactics.

2.5.3 Growth rate

The growth rate of weeds can differ greatly between species and thus play a major role, particularly when planning post-emergent applications. Timely applications on weeds at the optimal growth stages are sometimes difficult to achieve due to the weather. Knowing how much time one might have before weeds grow out of the optimal treatment stage can be valuable in deciding how urgent it is to complete an application.

2.5.4 Competitiveness with crops

Weeds naturally compete with crops for water, nutrients, space and light. Certain weeds are much more competitive than others and need to be managed more closely. As described in **Figure 9**, emerged weeds should be removed before the end of Period 1 (maximum weed-infested period) to prevent reductions to crop yield. Period 2 is the critical period for weed-crop competition and needs to be maintained weed-free. Weeds emerging later during Period 3 do not normally significantly affect crop yield, except for vining weeds or others that may interfere with harvest operations. After closure of the crop canopy, the crop generally can effectively suppress major weed growth. However, it is important to keep populations from growing at the very end of the season in order to prevent additional contributions to the soil seed bank. This is particularly relevant for resistant populations.

2.5.5 Weed-free period for a crop

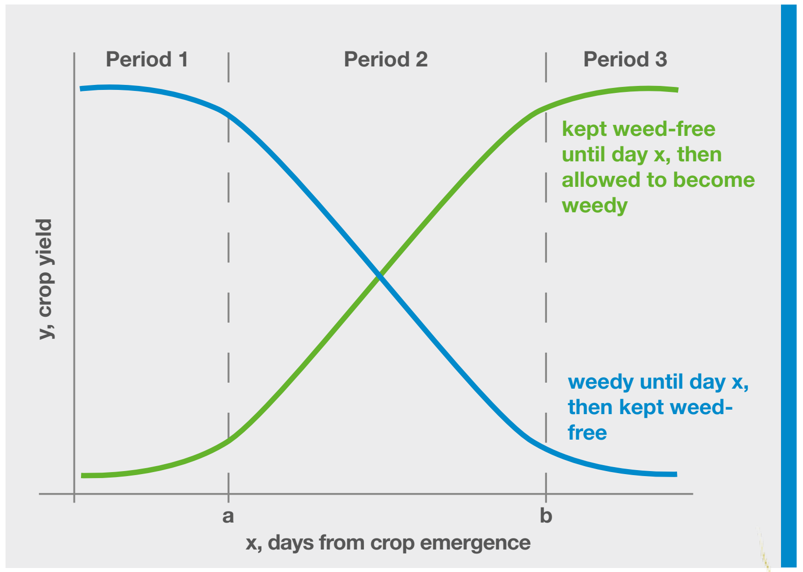


Figure 9

Figure credit: Ed Zaborski, University of Illinois (adapted from Altieri, 1995)

2.5.6 Weed size for optimal control

The weed size for optimal control by any post-emergent herbicide is generally small – 15 cm or less. Younger weeds tend to be more susceptible to herbicides than older weeds. In the case of a contact herbicide or one that does not translocate to a great degree, they are generally less effective on larger weeds because the developed foliage can obstruct the growing points, which must be completely covered by the herbicide application in order to reach maximum efficacy.

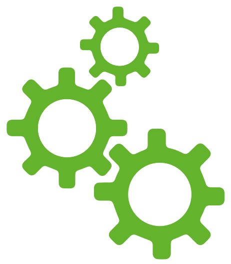
2.5.7 Seed production and dispersal

Prolific seed production coupled with a high degree of competitiveness in many of the Amaranth species highlights the need for reducing the seed returned to the soil seed bank to as near zero as possible in this group of weeds (Barber *et al.*, 2015; Davis *et al.*, 2015; Nordby *et al.*, 2007). Seed production has an indirect influence on resistance evolution by changing the mathematics. The higher the seed production, the greater the chance of finding an individual with the mutation(s) conferring resistance.
It is also helpful to understand how seeds are dispersed in order to control their spread within a field and between fields. The distribution of weeds in a field is generally found to be non-uniform and has been described as “an important source of inefficiency in weed management” (Cardina *et al.*., 1997). Keeping an eye on the “bad patches” within a field is one way of determining whether a potential problem is emerging.

2.5.8 Vegetative propagation

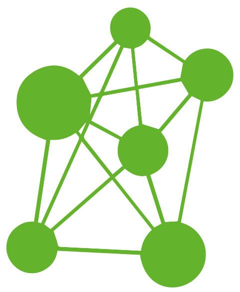
Some weeds, such as Johnsongrass (*Sorghum halepense*), can propagate vegetatively as well as through seed production (Paterson *et al*., 1995). Their rhizomes can be moved through soil tillage operations (Thill & Mallory-Smith, 1997).

2.6 How **herbicides work**



Herbicides are chemicals that kill plants or arrest their growth through various mechanisms. They can block the function of a target protein leading to the accumulation of a product that is toxic, as in the case for glufosinate ammonium, which inhibits glutamine synthetase and leads to an accumulation of ammonia (Devine *et al.*, 1993). This results in severe biochemical changes, which ultimately releases reactive oxygen species that destroy lipids and membrane integrity. Consequently, glufosinate acts very quickly. A sulfonylurea (or other herbicide inhibiting ALS, acetolactate synthase), on the other hand, can work very slowly because it blocks the production of an essential product. In this case inhibition of the ALS enzyme that is responsible for production of the branched-chain amino acids leucine, isoleucine and valine is the mechanism of action (Duggleby *et al.*, 2008). The lack of these essential amino acids stops plant growth and eventually leads to death.

2.6.1 Basic biochemical mechanisms



The modes of action of herbicides are loosely classified by the Herbicide Resistance Action Committee (HRAC) into those affecting light processes, cell metabolism or growth, and/or cell division (HRAC, 2010). The progression of herbicide activity has been summarized in the following steps by Délye *et al.* (2013): penetration into the plant (shoot or root), translocation to the site of action, accumulation at the site of action (specific concentration of intact herbicide molecules required for activity), binding to the target protein, and the ensuing damage, cell and plant death. Further information can be found in the following sources: Devine *et al.*, 1993; Powles & Yu, 2010; WSSA, 2014. The general classification of herbicides into categories and groups according to the site of action according to HRAC (Menne & Köcher, 2007; HRAC, 2010) is presented in **Table 1**. There are 21 different known sites of action, with another broad group containing individual compounds whose site of action is as yet unknown.

HRAC Classification of Herbicides according to Site of Action

Table 1

Category	Group	Herbicide Site of Action
	C1, C2 & C3	Inhibition of photosynthesis at photosystem II (3 subgroups)
	D	Photosystem-I-electron diversion
Inhibition of light processes	E	Inhibition of protoporphyrinogen oxidase (PPO)
	F1	Bleaching: Inhibition of carotenoid biosynthesis at the phytoene desaturase step (PDS)
	F2	Bleaching: Inhibition of 4-hydroxyphenyl-pyruvate-dioxygenase (4-HPPD)
	F3	Bleaching: Inhibition of carotenoid biosynthesis (unknown target)
	A	Inhibition of acetyl CoA carboxylase (ACCase)
	B	Inhibition of acetolactate synthase (ALS) or alternatively called acetohydroxyacid synthase (AHAS)
	G	Inhibition of EPSP synthase
Inhibition of cell metabolism	H	Inhibition of glutamine synthetase
	I	Inhibition of DHP (dihydropteroate) synthase
	M	Uncoupling (membrane disruption)
	N	Inhibition of lipid synthesis – not ACCase inhibition
	K1	Microtubule assembly inhibition
	K2	Inhibition of mitosis/microtubule organization
Inhibition of growth and/or cell division	K3	Inhibition of VLCFAs – very long-chain fatty acids (inhibition of cell division)
	L	Inhibition of cell wall (cellulose) synthesis
	O	Action like indole acetic acid (synthetic auxins)
	P	Inhibition of auxin transport
Unknown	Z	Unknown – please note that while the site of action of herbicides in Group Z is unknown, it is likely that they differ in site of action between themselves and from other groups.

From Menne & Köcher, 2007 and HRAC, 2010

2.6.2 Why is a mode of action important?

With the increase of resistant populations it has become much more important to understand the need for rotating modes of action in the herbicide program for a particular field. Using the same mode of action over and over in the same field will lead to the evolution of herbicide resistance (Vencill *et al.*, 2012).. Another consideration is the use of mixtures of products with different modes of action in order to reduce the selection pressure for resistance on any of the mixture partners.

3.0 The development of herbicide-resistant weeds

The correct application of herbicides following label recommendations is the most reliable and economically viable weed control practice to control weeds in broad-acre agriculture. The development of herbicide-resistant weeds is threatening the sustainability of agriculture in some areas. What, why and how this happens is described in this section.

3.1 Definitions of **resistance**

According to the WSSA (1998) herbicide resistance is defined as "… the inherited ability of a plant to survive and reproduce following exposure to a dose of herbicide normally lethal to the wild type". HRAC (2015) defines resistance as the "… naturally occurring inheritable ability of some weed biotypes within a given weed population to survive a herbicide treatment that should, under normal use conditions, effectively control that weed population". **Cross-resistance** is defined by HRAC as resistance to two or more herbicides but through only a single mode of action, and **multiple resistance** is defined as resistance to several herbicides having different modes of action.

Cross-resistance:	Resistance to two or more herbicides but through only a single mode of action
Multiple resistance:	Resistance to several herbicides having different modes of action
	HRAC, 2015

3.2 Effective **dose**

Every weed has the ability to survive an herbicide application at a particular application rate, and this may vary significantly. The application rate required for effective weed control may be much lower or much higher than the labeled rate. The rate at which a weed can survive will vary between individuals within a population and between populations, and generally follows a normal distribution curve, as shown in **Figure 10**. Since environmental conditions can affect herbicide activity (Monaco *et al.*, 2002), they can result in different levels of control in different years. A labeled rate of a herbicide is chosen during its development phase to provide excellent weed control (generally >95%) under a wide variety of environmental conditions and in a wide variety of soils over the lifetime of a product, often over 30 years. Thus the labeled rate must take into account the year-to-year variability of both changing environmental conditions and genetic diversity of weeds, and should provide excellent control in most conditions.

Efficacy range in weed populations

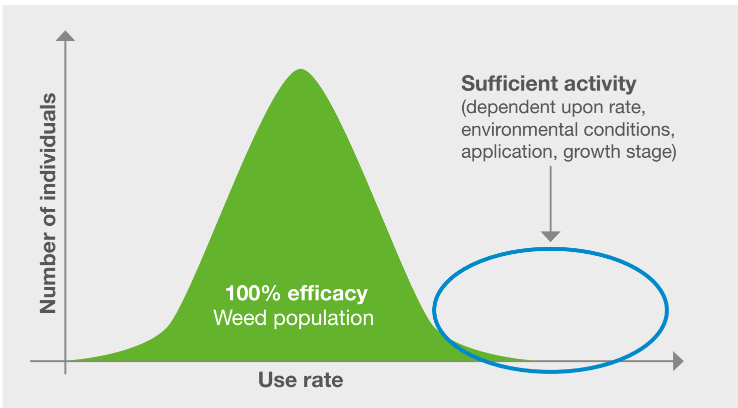


Figure 10

Source: Menne *et al.*, 2004.

3.3 Global **resistance trends**

3.3.1 Global species count

Herbicide resistance is a global problem and is being investigated and pursued globally by Bayer CropScience. Our group works with regional and local experts to help determine the extent of weed resistance problems, and helps find solutions. The resistance cases reported in The International Survey of Herbicide Resistant Weeds (Heap, 2015) are accepted only if they respect certain restrictive criteria and represent only unique cases, i.e. populations within a particular geography, for a particular species, for a particular resistance (by mode of action) or combination thereof. It takes time to follow the correct validation procedure. Since cases are often reported years after they are discovered, the current extent of herbicide resistance is not limited to the cases within the database and must be followed in the field to be properly understood. In many countries that currently show no resistance, resistances are likely to exist but just have not been validated and reported. However, the database serves to provide an accounting of key trends. The numbers of confirmed resistant biotypes keeps increasing – everywhere. The count in 2008 shows Europe leading with 146, the USA next with 45, and Australia with 28 (**Figure 11**). The 2014 count grew to 289 in Europe, to 146 in the USA, and to 70 in Australia. In just six years the change has been compelling.

Count of confirmed resistant biotypes by country (European countries represented together)

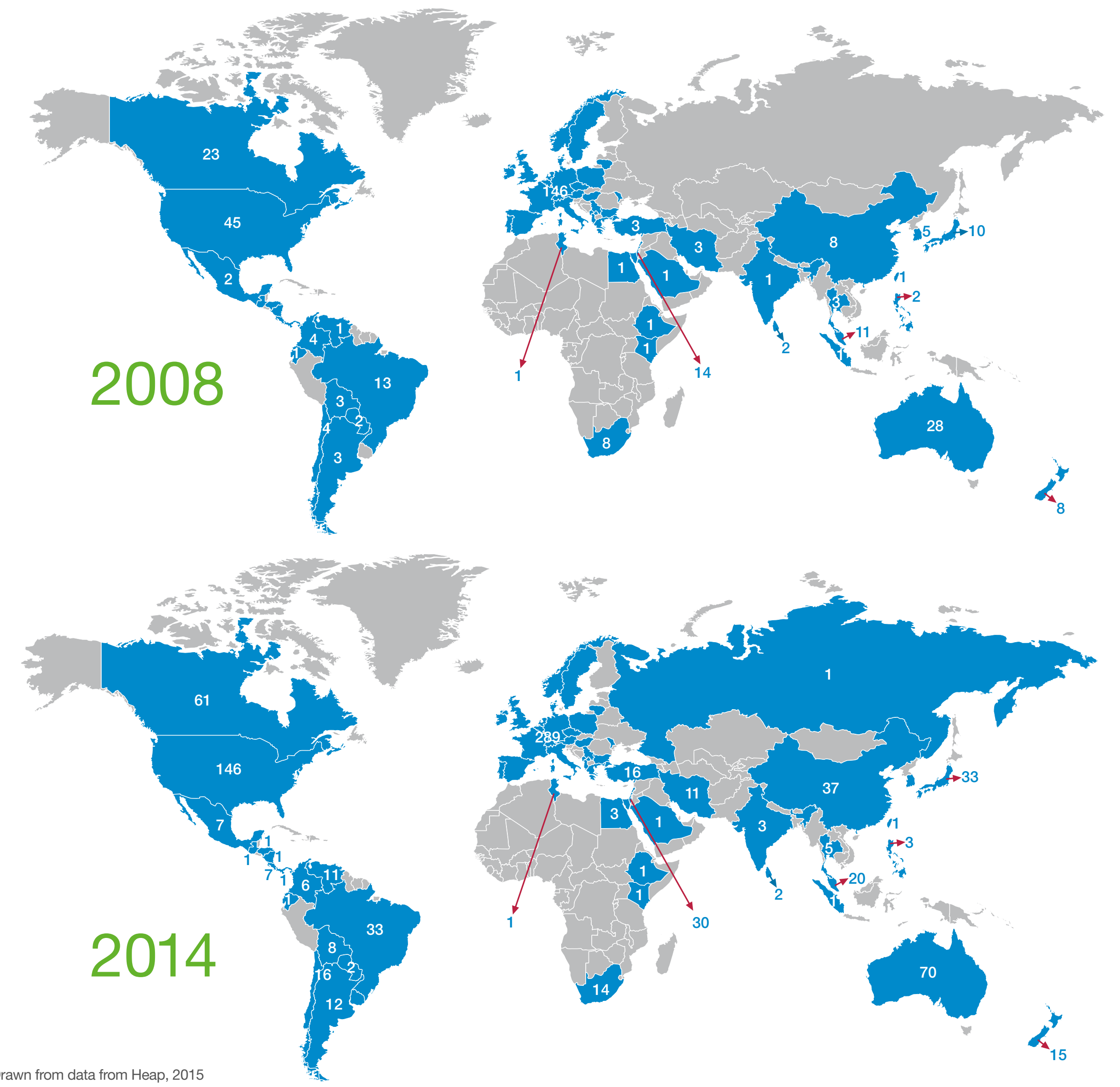


Figure 11

Drawn from data from Heap, 2015

3.3.2 Resistant species by mode of action

The results presented in **Figure 12** show the increase in resistant species for selected modes of action and are plotted beginning in the year of market introduction. For glycines (glyphosate), the year of the introduction of Roundup Ready® is used. It shows that the number of species is rising most rapidly for ALS and least rapidly for the auxins. For PSII (C1) and ACCase inhibitors, the increase in number of resistant species is somewhere in the middle, as is the case for glyphosate. Some of the increase in cases may relate to the predominance of use in single active ingredient applications or be partly an artifact of the number of investigators following a particular resistance trend. However, the **most important point** is that for all chemistries, even older classes, resistance continues to rise.

Number of resistant species for selected modes of action

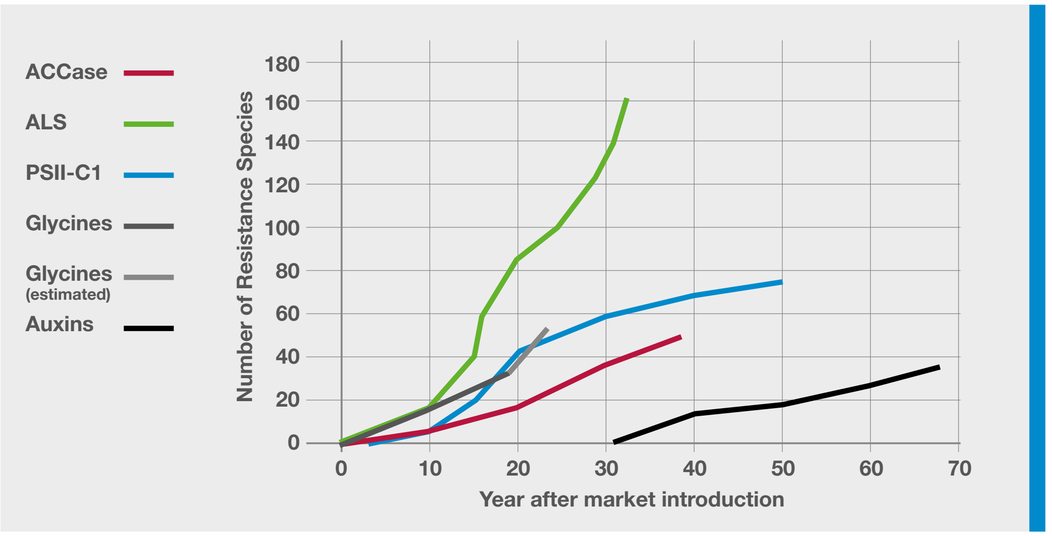


Figure 12

Drawn from data from Heap, 2015

3.4 Weed resistance is driven by evolution – a Darwinian process

3.4.1 Basic principles

Weed resistance is a global problem, and it is growing and has been over the last few years – regardless of the measure used (e.g. number of cases, resistant species, etc.). The trend of increasing resistances is constant. The number of resistant weed species, of resistant weed populations and those with multiple resistance is constantly increasing. Let's be clear about one thing; this is the result of a natural evolutionary process, as described by Charles Darwin, in which nature favors individuals that possess a competitive advantage, i.e. are more tolerant of a selection agent such as a herbicide, and pass this tolerance on to their offspring. Mutations occur naturally through cosmic and solar radiation and through DNA repair processes that suppress the negative effects of genetic errors but from time to time misfire.

3.4.2 Resistance evolution dynamics

How herbicide resistance develops can be really quite simple. If you always use the same method to control a weed, eventually it will select for individuals that can survive it. For example, using only one herbicide, or using another herbicide interchangeably but from the same mode of action group, or even repeated hand weeding in the absence of any other weed control technique can lead to resistance. If you only remove weeds by hand, eventually you will select for individuals that can survive. How? One way is by mimicry. An ingenious example comes from a population of E*chinochloa crus-galli* found in rice paddies that was able through multiple selection events and hand weeding only to adapt its phenotype (appearance) to mimic that of a rice plant. This made it impossible to visually distinguish crop from weed (Barrett, 1983). We mentioned naturally occurring mutations as the cause of genetic changes leading to survival of a particular selection agent.

The range in these genetic changes can be very large in populations. It is estimated that such mutations, e.g. a point mutation involving a single amino acid exchange conferring target-site resistance, occurs in many weeds at a frequency of 1 out of a million. For the purpose of this theoretical, let's use an even more conservative estimate of 1 out of 10 million, as shown here on this graph. Assuming that we always spray the same herbicide every year in the same crop and use no other measures to control the weed, and that each surviving individual passes this on to 10 offspring that germinate the following year, we see enrichment in the resistant individuals that looks like the progression shown in **Figure 13**.

This indicates that resistant individuals can increase to become 10% of the population in 9 years and 100% in 10 years. What is presented on the left is on a log scale. If we use a linear scale, the progression looks like **Figure 13** (right). This reflects more of what farmers can see in their fields, and indicates that resistance can only reasonably be observed in the field in the final phases, as in the last three years.

Please note that this is a **theoretical example** and that the process can happen faster, as for *Kochia scoparia* that developed a high level of resistance after five annual chlorsulfuron applications (Saari *et al.*, 1990), or it can happen much slower.
Many farmers believe that resistance only takes three years to develop, because that is what they see. Consequently, they believe that it takes only three years to get rid of the resistance once it has evolved in a field. This is not what actually happens in practice. A weed population in a field can "remember" a resistance trait (Powles SD, pers. comm. 2014), which means that it takes longer than supposed to decline. For how long will a population maintain this resistance? We don't know exactly, but we believe that in many cases it will be for decades. We personally have sampled fields that have not seen selection pressure from ACCase herbicides for at least 15 years and found that 20% or more of the population still contains resistance to this class of herbicides (Bayer CropScience, 2013). Moreover, when switching from one mode of action (MoA) to another once resistance to the former is encountered, as in the case of a *Lolium rigidum* population in southern Italy, plants appear to add resistance traits (Collavo *et al.*, 2012). It certainly takes much longer to devolve than to evolve resistance.

Theoretical case of how resistance frequency increases in a weed population

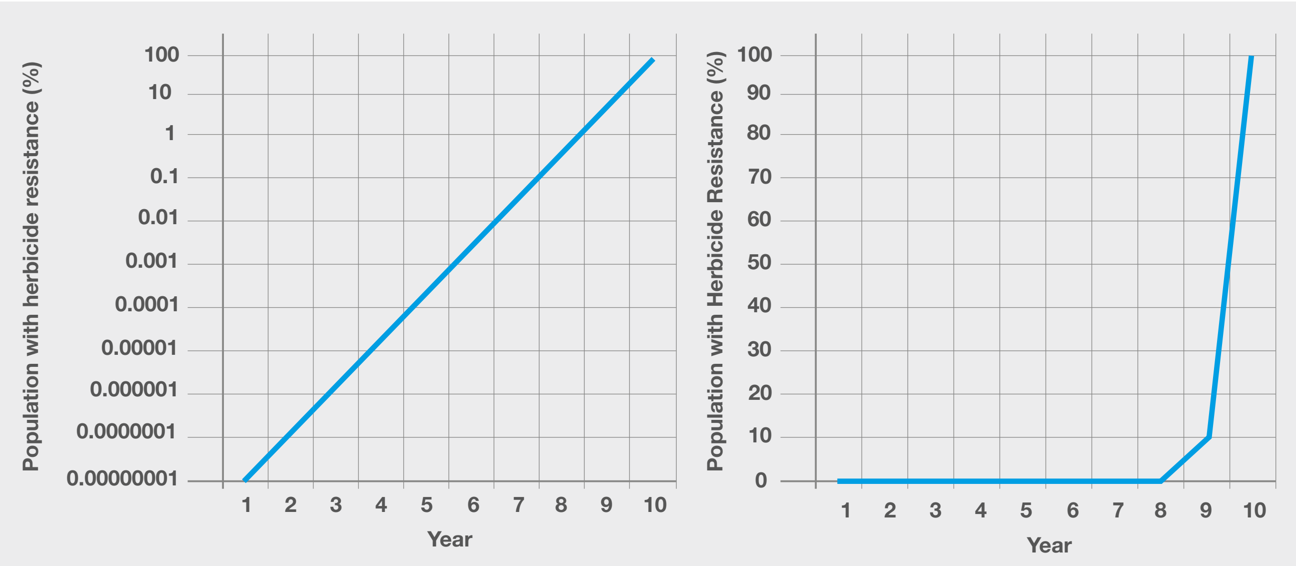
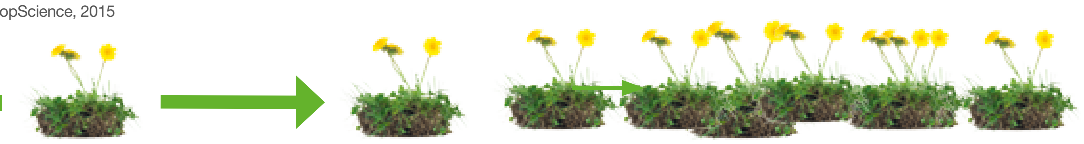


Figure 13

Source: Bayer CropScience, 2015



3.4.3 Resistance and fitness penalties

There is much evidence that resistance can result in reduced fitness, but the criteria for determining fitness have not been applied properly in most studies (Vila-Aiub *et al.*, 2009). In some cases resistance can result in no measureable fitness cost (Giacomini *et al.*, 2014) or even in a higher fitness of the resistant biotype (Wang *et al.*, 2010). Thus, the common assumption that resistance is always associated with a fitness cost is not correct.

3.5 Resistance selection pressure and risk assessment

The risk of developing resistance is increased by a combination of factors that increase the selection pressure on an herbicide. **Table 2** below gives general guidelines that help classify management options which, when combined, help to decrease or increase the risk of developing resistance in a particular field. The evolution of resistance is a "numbers game." Higher weed infestations, along with lower numbers of herbicides (and modes of action), crops, and control methods within a cropping system lead to higher risk of resistance. Weed biology also plays an important role in resistance selection pressure and the ability to develop resistance, e.g. whether a weed is self-pollinating or open pollinated, and the number of potential life cycles within a crop season, to name just a few factors.

Assessment of the risk of resistance development per target species

Management Option	Resistance Risk		
	LOW	MEDIUM	HIGH
Herbicide mix or rotation in cropping system	>2 modes of action	2 modes of action	1 mode of action
Weed control in cropping system	Cultural, mechanical and chemical	Cultural and chemical	Chemical only
Use of same mode of action in cropping season	Once	More than once	Many times
Cropping system	Full rotation	Limited rotation	No rotation
Resistance status to mode of action(s)	Unknown	Limited	Common
Weed infestation	Low	Moderate	High
Control in last three years	Good	Declining	Poor

Table 2

Source: www.hracglobal.com (2015)

3.5.1 Use of below labeled rates

Increasing evidence indicates that the use of low (below labeled) rates of herbicides can lead to the evolution of resistance, particularly through enhanced metabolism, in controlled studies (Neve *et al.*, 2005; Yu *et al.*, 2013) and in the field (Manalil *et al.*, 2011). The crossing of survivors by hand may speed up resistance selection in comparison with a field situation, but offers a standard method with which to make comparisons and get an idea of how rapidly this can occur in the field. In these studies increases in tolerance (below resistance level at full labeled use rates) appear to be incremental with each generation, resulting in a relatively slow evolution of resistance. This is attributed to the involvement of several genes and other factors in this type of resistance mechanism (Délye, 2013). Soil active herbicides are not exempt from this (Busi *et al.*, 2012). Further work (Busi *et al.*, 2014) showed that the inheritance of resistance is through a semi-dominant allele and that management options, if chosen properly, can help to reduce the selection pressure for resistance.

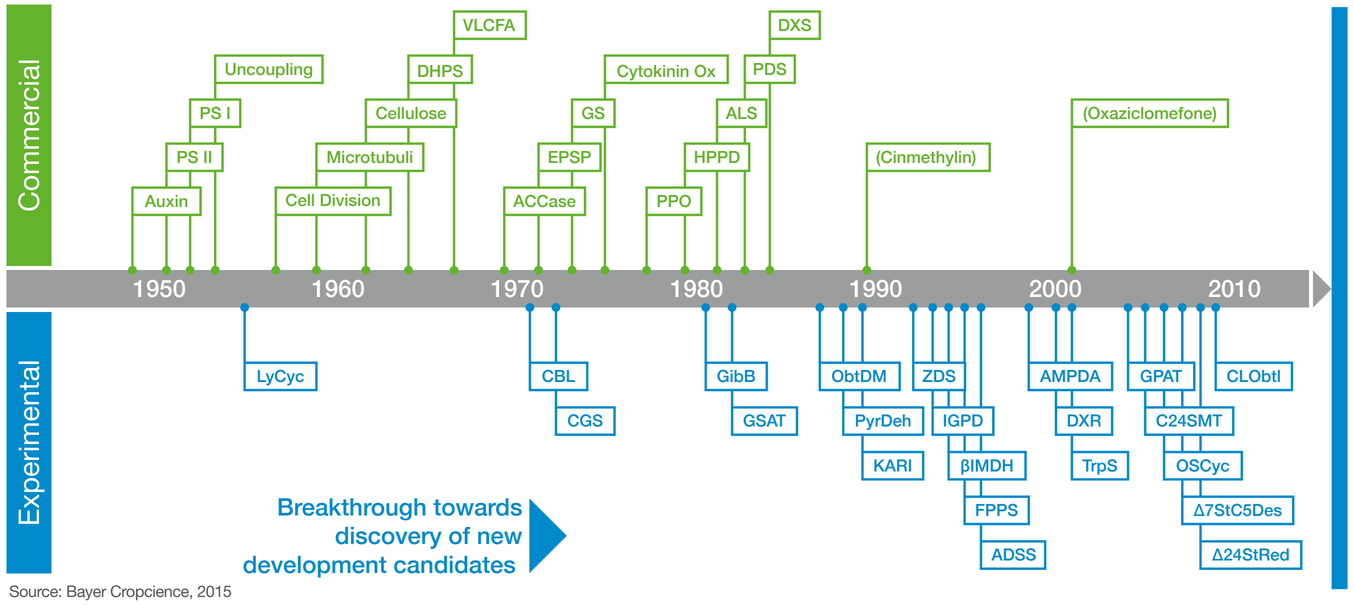
3.5.2 Help from non-chemical supplementary measures (soil tillage, cover crop, seeding density, competitive varieties, etc.)

The reality of the current situation (presented in general terms) is that we are relying mainly on herbicides to do our weed control in many areas of broad-acre agriculture and not relying much on mechanical or other cultural, non-chemical weed control practices. In order to maintain the effectiveness of herbicides, which do the heavy work in controlling weeds, we need to include more non-chemical weed control practices to take the selection pressure off resistance to the herbicides. And certainly we need to do more to protect individual modes of action and individual herbicides by using full rates, mixtures and application sequences. See Section 5 for more information on how diversifying weed management strategies can reduce weed populations and help reduce selection pressure for herbicide resistance.

3.5.3 Lack of weed control innovations

Many classes of herbicides, as determined by their mode of action, were discovered from the 1940s to the early 2000s. But since the mid-1980s no mode of action of major market significance has been discovered. Herbicides representing more than the current number of classes have been discovered but not registered (**Figure 14**). Most have failed due to toxicological, environmental or production cost issues. The increasing regulatory hurdles, along with other reasons, have made it harder to find good herbicides, and more expensive to register and develop them.

Commercially available and experimental modes of action never registered and marketed



Source: Bayer Cropcience, 2015

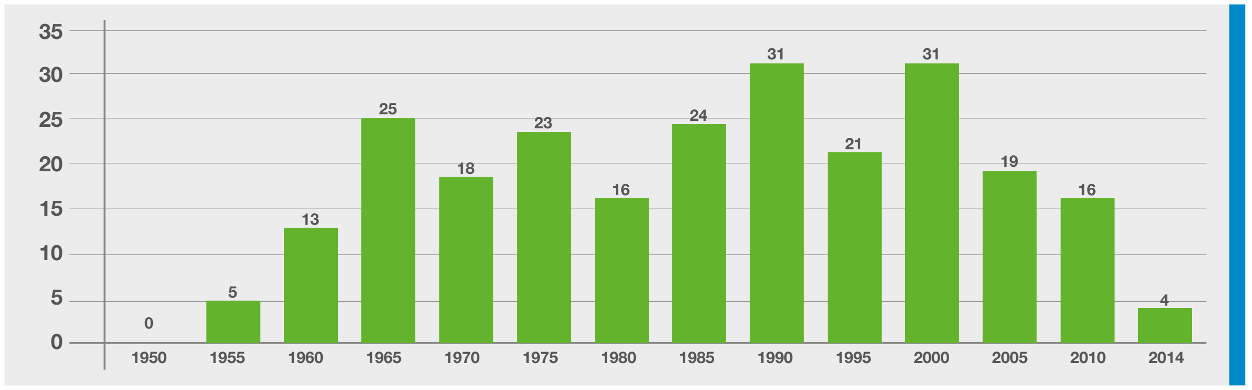
One of the most startling trends is shown in **Figure 15**, a graph of new active ingredient market launches of all modes of action, starting in 1950 and shown in 5-year intervals. It appears that we have gone full circle to the beginning of the herbicide era. The heyday was reached in the period between 1990 and 2004, showing an abrupt drop in the four-year period of 2011-2014. This truly shows the lack of herbicide innovation in the industry today. A key recommendation by the WSSA to address herbicide resistance points out the rarity of the discovery and bringing to market of new modes of action, and that existing herbicide resources are "exhaustible" (Norsworthy *et al.*, 2012).

It is sobering to think that each herbicide or mode of action lost to resistance may be lost for possibly decades in a particular field. Additionally, each herbicide lost due to a regulatory issue will completely disappear from the arsenal of available tools. We are not discovering new herbicides fast enough to replace the ones which have been lost. We must do all we can to protect each and every remaining herbicide. We do not know if an older herbicide will be the ideal complement to a brand-new herbicide with a novel mode of action that has yet to be discovered. As Stephen Powles, a renowned professor of Weed Science from Australia puts it (personal communication, 2010), "Each herbicide is a treasure that must be preserved".

It will not be easy to convince farmers that this needs to be done. Actually, it will be difficult. But there are signs that working to relieve the selection pressure on resistance will pay for itself. But as we have seen, mere facts are not enough. We need to be more persuasive. And this means we also need to communicate better.

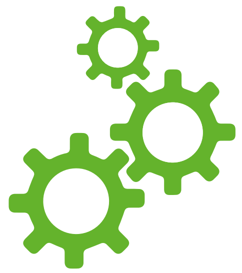
We are not discovering new herbicides fast enough to replace the ones we have lost.

Herbicide active ingredient launches 1950-2014



Source: Phillips McDougall

3.6 Resistance mechanisms



Several mechanisms can cause herbicide resistance by weeds (**Figure 16, Table 3**). Herbicides generally bind proteins whose activity is essential for the development of the weeds; this leads to the death of the plant. Mutations occur naturally through the action of environmental factors such as cosmic rays and sunlight (heat), or through natural errors of DNA repair mechanisms or other genetic errors. A target-site mutation results in a single amino acid substitution and causes a structural change in the binding pocket of the protein targeted by the herbicide, which can no longer bind tightly. Following this, the protein remains partially or fully active and the weed survives.

Enhanced metabolism results when an herbicide is structurally altered through a degradation mechanism before it can reach the target site. Plants have complex mechanisms involving multiple genes that can naturally degrade compounds produced, for example, by insects or microorganisms (fungi, bacteria, etc.). Every plant has the capacity to use these mechanisms to degrade a herbicide at a particular rate, and usually it is degraded to biologically inactive products. Thus, it is the speed of degradation that ultimately matters and influences whether the herbicide is structurally altered quickly enough so that it does not reach the target site intact.

Figure 16 illustrates a few of the more common resistance mechanisms. How herbicides work by fitting into the target site is shown conceptually. One particular resistance mechanism involves a large increase in the enzyme target too numerous to be inhibited at the cellular concentration provided by the normally effective herbicide rate.
Herbicide resistance mechanisms are even more diverse than those described above. They can be broadly classified into target-site and non-target-site resistance (**Table 3**). The list includes diverse mechanisms that utilize changes in biochemical processes within plants, changes to exterior structures or interior redirection away from the target site, or changes in germination to avoid peak soil herbicide concentrations or application windows. Target-site mutations and enhanced metabolism are by far two of the most common mechanisms encountered. It is currently believed that non-target-site resistance mechanisms involve multiple genes.

Diversity of selected herbicide resistance mechanisms

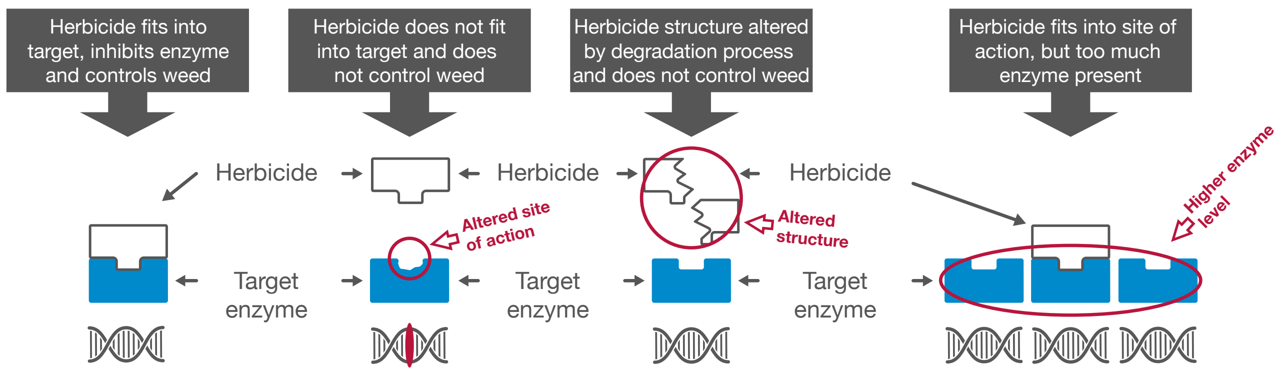
Mechanism	Resistance Class
Target-site mutation*	Target-site
Increased gene copy number*	Target-site
Enzyme overexpression	Target-site
Enhanced metabolism*	Non-target-site
Differential uptake	Non-target-site
Differential redistribution	Non-target-site
Sequestration	Non-target-site
Delayed germination	Non-target-site
Rapid necrosis/defoliation	Non-target-site

*Presented in Figure 16

Table 3

For a more thorough and detailed discussion of this aspect and resistance mechanisms, please refer to Powles & Yu (2010), Délye *et al.*, 2013; Yu & Powles, 2014; and Gaines *et al.*, 2014. Weeds constantly evolve novel mechanisms of resistance as they are confronted with new management techniques, representing a new type of stress on the population. It is thus important, in order to preserve the techniques that are currently effective on a particular weed, to change them within a through pre-planned management strategy.

Selected mechanisms of herbicide resistance



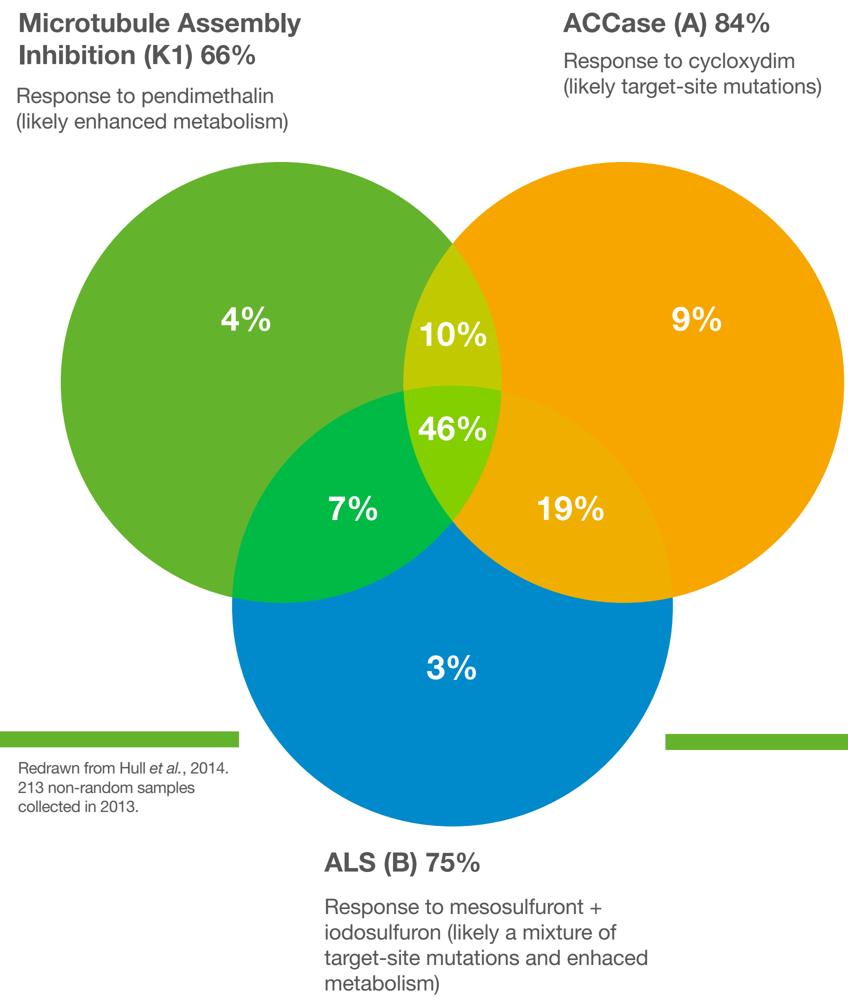
Source: Bayer Cropcience, 2015

Figure 16

3.7 Multiple resistance

Multiple resistance occurs when a weed or a population is resistant to more than one mode of action in the same plant or population. The appearance of multiple resistance in a population of weeds complicates its management. An example can be found in the UK with blackgrass (*Alopecurus myosuroides*). The proportion of *Alopecurus myosuroides* samples resistant to three herbicides representing different modes of action, alone and in combination, is almost half of the collected populations (**Figure 17**). This has led to a heavy emphasis on other pre-emergent treatments with alternative modes of action, since many of the ACCase herbicides no longer work and the efficacy of ALS herbicides is declining (Hull *et al.*, 2014). The increase in resistance to multiple modes of action has complicated weed management in other species and geographies. It is threatening the future of broad-acre agriculture (Délye *et al.*, 2013) and has resulted in a call for the discovery of novel herbicides with new modes of action (Tranel *et al.*, 2011).

Proportion of *Alopecurus myosuroides* samples resistant to three herbicides representing different MoAs, alone and in combination, in the UK



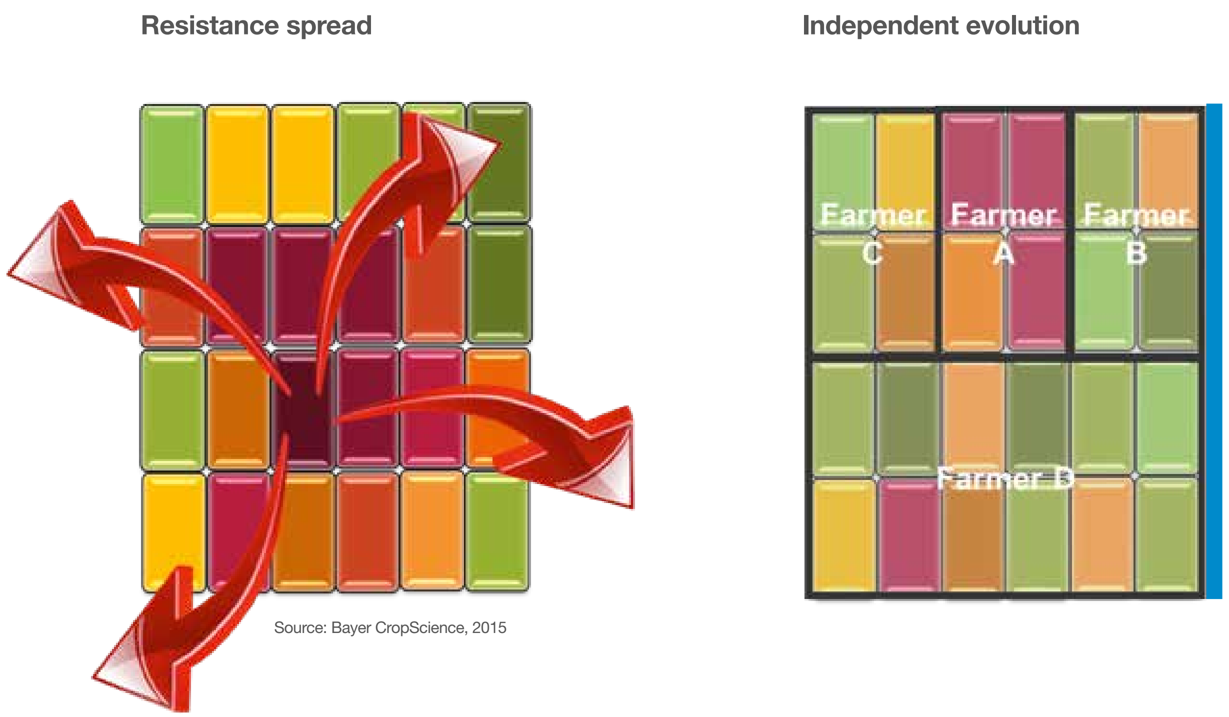
Redrawn from Hull *et al.*, 2014. 213 non-random samples collected in 2013.

Figure 17

3.8 Resistance dynamics – spread vs. independent evolution

Many farmers believe that resistance comes from their neighbors. They believe it starts in a neighbor's field and spreads eventually to their fields, as in **Figure 18** (left). Although this does indeed occur, farmers do not understand that resistance can also develop independently in their fields. One reason is that many farmers use weed control products correctly and, despite following all product recommendations for application rate and optimum conditions, still observe the development of resistance in their fields after enjoying excellent weed control for many years. They may not be paying attention to the overall picture over time. What farmers perhaps do not realize is that using one product that works well over and over again results in resistance evolution if no other complementary weed control measures are employed. It is certainly known that resistance can spread. How quickly it will spread depends on the particular species and on agronomic factors such as the use of herbicide mixtures and sequences, crop rotations, tillage, and other non-chemical weed control measures. However, resistance evolution ultimately depends on what farmers do in each field.

The in-depth resistance evolution studies we are conducting with *Alopecurus myosuroides* in small landscapes in Germany show that the spread of genes is not the main factor acting on resistance evolution, which cannot be explained exclusively through movement of pollen or seed in this particular species (Hess *et al.*, 2012; Herrmann *et al.*, 2014). The distribution of resistance can take on a checkerboard look (**Figure 18, right**), with highly resistant fields, like those in red, side-by-side with fields that have very sensitive weed populations, like those in dark green. The intensity and profile for individual fields can take on an intermediate character, as shown with the mixture of different colors. Even all one farmer's fields can look different, or similar. More and more we believe that a significant component of resistance evolution is attributable to independent evolution, based upon the weed control and agronomic practice history **in each individual field**. That means that the farmer has an opportunity to prevent, or at least significantly delay, resistance in his field based on what he does in each field. However, he must include diversity in his weed control measures. Diversity in herbicides and modes of action as well as diversity of non-chemical methods, including crop rotations, tillage and other measures, are required to manage resistant weeds and keep resistance at bay. We must do better in convincing farmers of this.



Source: Bayer CropScience, 2015

Figure 18

4.0 Resistance confirmation testing and diagnosis

The testing and confirmation of resistance is not a trivial exercise. Great care must be taken first in the sampling of the seed (or plant material) and consideration of the type of testing that should be done. Suspicion that resistance is responsible for the lack of expected efficacy is often associated with agronomic reasons that have nothing to do with resistance (e.g. application error, improper weed growth stage, environmental or soil conditions). Great care should be taken to ensure uniform conditions in testing for resistance. The selection of the susceptible population is another critical aspect of validation of resistance.

4.1 Validation testing

Several publications describe the correct steps and protocols for determination of the resistance status of a population of weeds (Beckie *et al.*, 2000; Burgos *et al.*, 2015; Heap, 2015; HRAC, 2015). For a weed biotype to be listed in the International Survey of Herbicide Resistant Weeds (**www.weedscience.org**) it must meet all of the criteria summarized in the following list (Heap, 2015):

1. *Fulfillment of the WSSA definition of resistance and the survey's definition of an herbicide-resistant weed*
2. *Data confirmation using acceptable scientific protocols*
3. *Resistance must be heritable*
4. *Demonstration of practical field impact*
5. *Identification as a problem weed to species level, not the result of deliberate/artificial selection*

4.2 Types of testing

In our studies on resistance, we use proven methods like whole pot greenhouse bioassays and innovative technologies for metabolic resistance analyses and target-site resistance analyses. In the greenhouse we use a number of compounds, many with multiple rates, to help determine what other compounds can still be used effectively, in addition to confirming resistance to a particular herbicide or herbicide class. The use of field studies is generally discouraged for validation of resistance, except as a screening tool. The difficulty of comparing a field site location suspected of resistance with a sensitive population, unless it was already growing naturally at the site, make it less precise in determining the resistance level. Metabolic resistance in weeds is determined by using analytical methods based, for example, on HPLC (high-pressure liquid chromatography); target-site resistance mutations are analyzed using molecular biology techniques based on PCR technology (polymerase chain reaction) to amplify the DNA; and the DNA sequence analyses are performed using a pyrosequencer. No other company routinely runs as many samples using the full breadth of studies as Bayer CropScience does. We are constantly evaluating new technologies to use in studying resistance.

4.3 Interpreting results and making recommendations

The purpose of testing for resistance is not only to determine the resistance status to a particular herbicide or class of herbicides. In the case of negative results, it indicates that potentially a problem occurred during the application of the product and may be responsible for the lack of expected performance. In the case of positive confirmation of such resistance, the purpose is to determine the resistance status of other available herbicide options (Beckie *et al.*, 2000). To do so, the potential options have to have been considered beforehand. Ultimately, the objective is to understand the resistance status as well as possible in order to make the best recommendation possible to a farmer for his particular field.

5.0 Integrated Weed Management

Integrated Weed Management (IWM) can be defined as "a holistic approach to weed management that integrates different methods of weed control to provide the crop with an advantage over weeds" (Harker & O'Donovan, 2013). It involves the integration of chemical, cultural and biological methods of weed control and suppression, using knowledge of the weed's weaknesses to help keep weed populations manageable, reduce selection pressure for weed resistance, and maintain sustainability of cropping systems, while reducing the environmental impact of weed management practices. This section starts with some core IWM guidelines and describes in general terms how to set up an IWM strategy. Since all weed management is on a field-by-field basis, all generalized recommendations must be put into the context of local practices.

5.1 Bayer CropScience's IWM Core Guidelines

Much has been written about IWM guidelines. The Bayer CropScience IWM Core Guidelines are an attempt to offer simple guidelines that are understandable to a large audience and applicable globally. It is true that general guidelines such as these are not specific enough for specific situations and must be adapted to local conditions. However, the aim is to ensure that a multi-faceted and well thought-out approach be undertaken to manage weeds. This includes an acknowledgement of the need to convince others to adopt the guidelines by using one of the most effective means available – demonstrating them in the field. The **core guidelines** consist of three main points: **know the weed spectrum, develop a weed management strategy, and demonstrate in practice IWM techniques.** The weed management strategy addresses several aspects that should be included to maximize effectiveness: the need to plan ahead and stick to the plan; the emphasis on adopting diversified weed management measures; the help that crops themselves can give to suppressing weed growth; the need to be aggressive in managing weeds and not to let up: the advantage of "starting clean" to help give crop establishment additional help; and the need to maximize herbicide activity to keep the surviving numbers of weeds to a minimum.

Table 4

1. Know the weed spectrum	
2. Develop a weed management strategy	
1.	Develop a plan
2.	Diversify weed management measures
3.	Enhance crop competitiveness
4.	Start clean
5.	Aggressively manage weeds
6.	Maximize herbicide activity
3. Demonstrate in practice IWM techniques	

5.1.1 Know the weed spectrum and the farming system

It is important to know what the driver weed(s) is (are). It is important to identify them correctly and to understand its (their) biology (**see Section 2**) in order to understand its (their) weaknesses and to guide the development of an effective management strategy. Scouting a field before application is important to identify the weeds present and the areas of a field that may have higher weed populations that may need special attention. One must also consider the environment, soil, farm equipment and type of system used in a particular field. The field history is important as well to avoid over-reliance on one or a few MoAs, which is particularly important for farmers who have acquired new fields about which they know relatively little. All of these factors play a role in knowing the weed spectrum.

5.1.2 Develop a weed management strategy

The goal of a management strategy is to disrupt the life cycle of the driver weeds to make their management easier by means of the chosen combination of measures. Another goal of the management strategy is that it should also be sustainable and contribute to the preservation of currently working herbicides and non-chemical weed management measures. Individual components are detailed below.

Develop a plan

The plan needs to be made for more than just one year, preferably through a full crop rotation, and take a multi-year approach to combat weeds, particularly resistant weeds. Start with the goal of the plan. For example: "I want to reduce my population of resistant weeds in field x by 99% in three years." The goal of the plan should be realistic. Once the goal of the plan has been achieved, there should be no letup in effort. The buildup of weeds can happened very quickly, so that attention needs to be paid to continuing a weed management strategy. Thus, the goal of the program should then be changed to avoiding the return of resistance and of higher weed populations. A new plan needs to be implemented, one that emphasizes diversity, or you will just be facing a return of resistance, a new kind of resistance.

Diversify weed management strategies

Diversity in weed management strategies at several levels is one of the most effective ways to keep weeds off balance and make it easier for herbicides to do their job.

The following graph (**Figure 19**) shows the potential benefit of integrating the use of several non-chemical methods with herbicides. If we start out with a theoretical blackgrass (*Alopecurus myosuroides*) population of 1,000 plants/m² and subsequently perform plowing, delayed drilling, higher crop seeding rates, and choose competitive crop varieties (with respective reductions of 69, 31, 26 and 22%), we can reduce the original blackgrass population by a total of 88% **before** we apply the herbicide (with a given efficacy of 90%), and achieve a total reduction of 99% of the initial population. Using only the herbicide, we achieve only a 90% reduction, although in extremely high weed densities it is doubtful that maximum efficacy can be achieved. The difference in control of 9 percentage points may appear to be small, but it is significant. If plowing is not desirable or possible in this situation, the switch from a winter crop to a spring crop can result in a reduction in blackgrass population by an average of 88% (Lutman *et al*., 2013). The incorporation of non-chemical weed control measures is invaluable in reducing the selection pressure for herbicide resistance.

Potential benefit of integrating the use of several non-chemical methods with herbicides

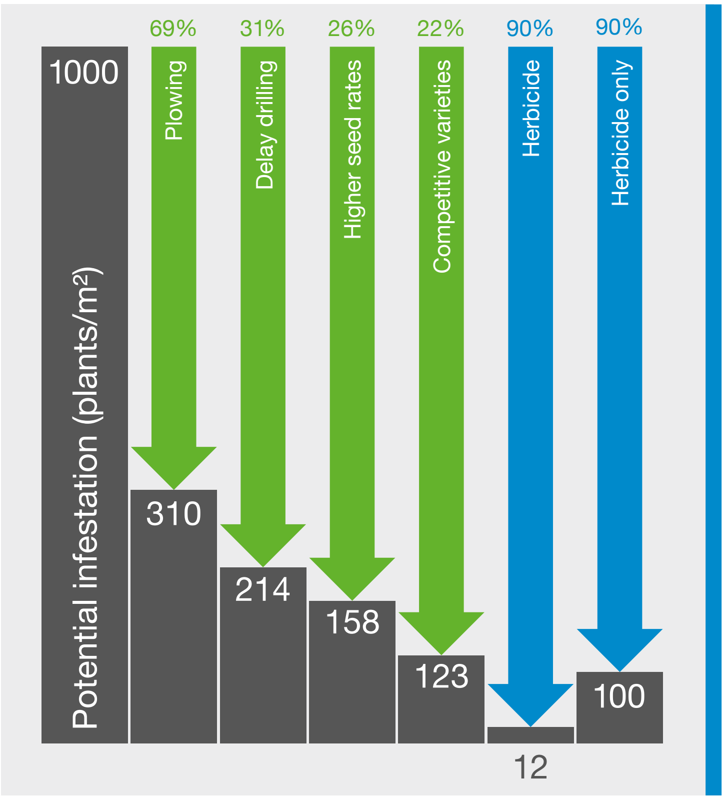


Figure 19

Redrawn from Moss & Lutman, 2013. Numbers in (or below) gray bars refer to potential infestation of blackgrass (*Alopecurus myosuroides*). Numbers above colored bars refer to the reduction in blackgrass infestation due to each measure.

Diversity also includes the management of chemical resources. As a basic principle, one should avoid repeated and continued use of the same herbicide or herbicides with the same mode of action in the same field, in the same growing season, and in the following year. Mixtures or sequential treatments of herbicides active on the driver weed but having different modes of action are an effective strategy to reduce selection pressure on a particular herbicide or herbicide group. From experience we can conclude that rotation of herbicides alone is not enough to prevent the development of resistance. To retain these valuable tools, the chemical rotation explained must be employed in association with at least some of the other weed control measures outlined. In cases where metabolic resistance is already present, the mode of action of the herbicide is not always the key criterion for the selection of products. In these cases, the mechanism of degradation can be very important and affect the utility across site of action groups and chemistries. No classification of herbicides relating to degradation is available and such examples need to be handled on a case-by-case basis. We still have much to learn about this resistance mechanism.

Enhance crop competitiveness

Enhancing crop competitiveness begins with selection of the cultivar. Farmers generally choose cultivars that are perceived to bring the highest yield when bred in a weed-free situation (Andrew *et al.*, 2015). However, if weed resistance leads to greater competition from weeds within the crop, yield losses can outpace any potential gains due to superior germplasm or breeding (Brennan *et al.*, 2001). Thus, if faced with a situation of resistant weeds in dense populations, greater attention to the competitive ability of the cultivar can bring dividends. Other cultural factors such as narrower row spacing, higher seeding rates, planting dates, irrigation management, and optimized fertilizer application and placement can result in greater ability to suppress weed growth (Norsworthy *et al.*, 2012). Rotating crops, particularly between summer and spring crops when possible, is one of the most effective strategies to enhance crop competitiveness (Lutman *et al.*, 2013).

Start clean

Planting into weed-free fields is one of the best ways to ensure early and strong crop establishment (Norsworthy *et al.*, 2012). Controlling early weed flushes with tillage or the use of non-selective herbicides before crop emergence is one way to achieve this. Using pre-emergent herbicides after tillage or in combinations with non-selective herbicides in burn-down applications (sometimes with overlapping pre-emergent herbicides) is a good strategy, and sometimes necessary, for slow-growing crops like cotton in areas with Palmer amaranth that germinates over the entire growing season (Scott & Smith, 2011).

Aggressively manage weeds

All weeds need to be managed aggressively. The best strategy is to keep weed densities low so that the contribution to the soil seed bank remains low. Studies have shown that for some species, low densities, even after successful management and reduction over several years, can quickly lead to re-establishment of high densities in a short time frame if successful management practices are abandoned (Buhler *et al.*, 2001; Norsworthy *et al.*, 2014).

Maximize herbicide activity

The key justifications for paying attention to maximizing herbicide activity are to reduce the potential number of weed escapes, thus reducing the opportunities to increase the weed population, and to derive the maximum economic benefit from the treatment. Knowing which weeds infest a field or border area is helpful to guide the correct choice of herbicides. It is essential to follow label use instructions carefully, particularly those concerning recommended use rates and application timing (weed size), and optimum application conditions (environment, adjuvants, nozzles, etc.). The scouting of weeds after herbicide applications is encouraged to determine the effectiveness of the treatment(s), and enable subsequent weed flushes to be detected. Maintaining accurate and detailed records of field history ensures that associations with certain practices become more evident and effective adjustments can be made to management strategies in subsequent years.

5.1.3 Demonstrate in practice IWM techniques

One of the most effective ways to convince farmers to adopt IWM techniques is to show them how they can work in practical field situations. This helps farmers who have not yet adopted IWM to become aware of strategies alternative to the ones they are following and the potential value of integrated weed management to them. After all, "Seeing is believing", as one farmer at a Respect the Rotation event in the USA put it.

RESPECT THE ROTATION

5.2 The need for **proactive weed control** within a field and at a **community level**

An example of a program for the management of a very competitive weed affecting an entire community comes from Arkansas. This community had recognized that simultaneous management of several aspects of infestations of *Amaranthus palmeri*, including in-field, field borders and roadsides, needs to be done not by individual farmers, but by a community working together simultaneously (Barber *et al.*, 2015). Some of their recommendations for how to institute a successful program include starting with an appropriate local leader within the agricultural community, developing a common goal and creating an identity or branding for the program, using science-based information to guide the development of practices to be adopted, and publicizing results. The adage that growers are stronger together than alone certainly applies in this case.

5.3 Other **non-chemical measures**

Cover crops can be a useful non-chemical tool to disrupt the life cycle of a weed and can lead to decrease in weed biomass, germination and seed production. However, they need to be integrated into cropping systems and adapted to the biology and germination characteristics of the target weed (Jha *et al.*, 2010; Price *et al.*, 2011; Korres & Norsworthy, 2015). Managing weed seeds at harvest and after harvest through controlled burning (where permitted), chaff collection and mechanical destruction (**Figure 20**) helps to prevent a buildup of the weed seed bank (Walsh *et al.*, 2013). Thermal weed management techniques such as flaming are not commonly adopted, and in some countries there are restrictions to avoid the potential fire risk. Other strategies are reviewed in Norsworthy *et al.*, 2012.

A Harrington Seed Destructor – post-harvest weed seed control

Figure 20

Source: http://www.producer.com/wp-content/uploads/2013/08/Harrington_Seed_Destructor.jpg

5.4 How to **measure success**

It is important to measure the success of IWM programs. This helps when setting goals because it allows progress to be assessed. The previous version of this brochure stated that the purpose of IWM is to "… reduce weed pressure and keep weeds below their economic thresholds". With the increase of weed resistance, particularly multiple resistance, and the escalation of species like Palmer amaranth that can rapidly take over fields, the economic threshold concept is being effectively superseded by less acceptance of weeds, such as a zero-tolerance concept. Thus, the previous emphasis on population density (numbers of plants per m^2) or weed biomass reduction as a measure of program effectiveness (and accepting a certain level of weeds) is becoming less relevant. A more appropriate measure for the developing situation is weed seed set and return to the soil seed bank. The emphasis on decreasing the numbers of seeds returned to the soil seed bank is more versatile and can be used, for example, to measure post-harvest weed seed control methods. It is also a measure, like weed density, which farmers can easily understand and to which they can relate.

5.5 Other **sources of information**

Please refer to our IWM website
www.iwm.bayer.com
for current sources of information.

6.0 The Bayer CropScience Weed Resistance Competence Center

Just what is the Weed Resistance Competence Center? It is the Bayer global reference center for weed resistance management, understanding resistance mechanisms and evolution in the field by weeds, testing and developing new concepts, strategies and tools to diagnose and manage resistant weeds, and communicating and sharing Bayer knowledge and solutions to farmers, advisors, distributors and officials. It has actually been conducting research and investigations on resistance in Frankfurt, Germany for almost two decades, with the official launch as the Weed Resistance Competence Center in November 2014.

6.1 Introduction

The increase in resistance in more and more species, in more and more fields, and to more and more herbicides and modes of action is complicating weed management. Farmers love simplicity. They value it. However, the future means that we will need to offer solutions that address this complexity while being as simple as possible. That is one of the challenges for us.

WEED RESISTANCE COMPETENCE CENTER

6.2 Mission and objectives

We have three objectives for the Weed Resistance Competence Center. Firstly, we strive to be leaders in weed resistance competence, understanding resistance to herbicides better than anyone, how resistance mechanisms work, how resistance evolves, and how it can be managed in each field, no matter what the current status is. Secondly, we want to take this knowledge and use it to develop and offer the best strategies and specific solutions for resistance management. We would like to tailor them to individual fields for each farmer. And thirdly, we want to effectively communicate our knowledge and solutions. We are aware that leadership will bring the responsibility to deliver effective weed control products and programs, and we are ready to meet the challenge.

6.3 Key operational tasks

Just what do we do at the Weed Resistance Competence Center? We have a multifunctional research group with an overwhelming external focus, engaging in projects in different countries and regions. We also support our Weed Control Discovery Group in the search for new weed control compounds with novel modes of action. We conduct the tried-and-true resistance diagnostics bioassays in the greenhouse with seeds harvested from weeds in the field, which is still the best way to get a clear profile of the level of resistance and find out what products still work, or not. We conduct a full range of advanced diagnostics tests in our Weed Resistance Research Laboratory using the latest biochemistry and molecular biology techniques. We develop strategies, diagnostic technologies and management tools for Integrated Weed Management programs that support our outreach activities. This includes diverse things such as models that predict resistance evolution, training modules, integrated weed management strategies, and communication platforms for delivering recommendations to farmers. We supplement our internal capabilities with external collaborations with top researchers and institutes across the globe.

Discovery Support	Diagnostic Bioassays	Resistance Mechanisms& Lab Diagnostics	IWM Strategy Development & Outreach	External Collaborations
Support search for new MoAs	Greenhouse testing	Biochemistry & molecular biology	Connecting lab results with field practices & scientific communication	Projects with universities/ institutes

Please refer to our website **www.wrcc.bayer.com** for more details about the Bayer CropScience Weed Resistance Competence Center.

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For more information about Bayer's Integrated Weed Management activities please visit our internet site: www.iwm.bayer.com

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