Chapter 12
Herbicide Resistant Weeds

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Contents

Abstract The International Survey of Herbicide-Resistant Weeds (www.weedscience.org) reports 388 unique cases (species x site of action) of herbicide-resistant weeds globally, with 210 species. Weeds have evolved resistance to 21 of the 25 known herbicide sites of action and to 152 different herbicides. The ALS inhibitors (126 resistant species) are most prone to resistance, followed by the triazines (69 species), and the ACCase inhibitors (42 species). Herbicide-resistant weeds first

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became problematic in the USA and Europe in the 1970s and early 1980s due to the repeated applications of atrazine and simazine in maize crops. Growers turned to the ALS and ACCase inhibitor herbicides in the 1980s and 1990s to control triazine-resistant weeds and then to glyphosate-resistant crops in the mid 1990s in part to control ALS inhibitor, ACCase inhibitor, and triazine-resistant weeds. The massive area treated with glyphosate alone in glyphosate-resistant crops has led to a rapid increase in the evolution of glyphosate-resistant weeds. Glyphosate-resistant weeds are found in 23 species and 18 countries and they now dominate herbicide-resistance research, but have not yet surpassed the economic damage caused by ALS inhibitor and ACCase inhibitor resistant weeds. *Lolium rigidum* remains the world's worst herbicide-resistant weed (12 countries, 11 sites of action, 9 cropping regimes, over 2 million hectares) followed by *Amaranthus palmeri, Conyza canadensis, Avena fatua, Amaranthus tuberculatus,* and *Echinochloa crus-galli*. In the years ahead multiple-resistance in weeds combined with the decline in the discovery of novel herbicide modes of action present the greatest threat to sustained weed control in agronomic crops. The discovery of new herbicide sites of action and new herbicide-resistant crop traits will play a major role in weed control in the future however growers must make the transition to integrated weed management that utilizes all economically available weed control techniques.

Keywords Herbicide-resistance · Resistant weeds · Resistance management · ALS inhibitors · ACCase inhibitors · Glyphosate · Survey · Integrated weed management, Herbicide tolerant crops · Herbicides

12.1 Introduction

Weeds impact crop production through direct competition for nutrients, moisture and light, and if left uncontrolled weeds can cause over 80 % crop yield loss (Oerke, 2002). Prior to the introduction of modern herbicides man relied upon hand weeding, hoeing, tillage, crop rotations, cover crops, crop management (crop competition, seeding rates and times, row spacing, nutrition etc.), biological controls and burning as the primary methods of weed control. The first modern herbicides, the synthetic auxins (2,4-D, MCPA), were developed during world war II and first marketed in 1944 for broadleaf weed control in cereals. Their success spawned a new era in weed control and herbicide discovery. In the last 65 years agricultural chemical companies have brought more than 300 herbicide active ingredients to the market. Herbicides became the most reliable and least expensive weed control method in crop production and they are a major contributor to the dramatic increases in crop yields achieved over the last 65 years. Although highly successful, herbicides also face challenges to do with their safety to humans and the environment but their biggest challenge is that of weeds evolving resistance to them. Scientists foresaw the potential of herbicide-resistant weeds (Harper 1956) however it took until 1970 before the first well documented report of a herbicide-resistant weed. Until recently growers have been fortunate enough to have a steady supply of new herbicides to deal with the inevitable appearance of herbicide-resistant weeds. In the last few decades this steady supply of new herbicides has ceased, and growers are now faced with the harsh reality that herbicide-resistance can no longer be dealt with as it has in the past. Modern crop production is dependent on effective herbicides and now, more than ever, the sustained use of herbicides is threatened by herbicide-resistant weeds. This chapter aims to introduce herbicide-resistance, report its current status, and provide practical management strategies that will help stave off resistance until new herbicides and weed control practices arrive.

12.2 Evolution of Resistance

Weed resistance is the evolved capacity of a previously herbicide-susceptible weed population to survive a herbicide and complete its life cycle when the herbicide is used at its normal rate in an agricultural situation. Herbicide-resistance is a normal and predictable outcome of natural selection. Rare mutations that confer herbicide resistance exist in weed populations prior to any herbicide exposure and they increase in proportion over time after each herbicide application until they predominate at which time the population is called resistant. There are many factors that influence how long it takes for a weed population to evolve resistance to herbicide applications. The initial frequency of herbicide resistant mutations found in a weed population is dependent on the weed species and the herbicide mechanism of action. Some weed species, such as *Lolium rigidum* and *Amaranthus tuberculatus*, have a great propensity to evolve resistance partly due to their innate genetic variability. Herbicides also vary dramatically in their risk level for resistance. For some herbicides, like the ALS inhibitors and ACCase inhibitors, there are numerous mutations that can confer target site resistance, making these herbicides very prone to resistance. For other herbicides, like the synthetic auxins, or glyphosate, there are few target site mutations that confer resistance, making them relatively low risk herbicides for resistance. Resistance can also occur through the quantitative selection of multiple low level resistance genes (polygenic resistance) resulting in a progressive shift towards resistance in the population as a whole. These low level resistance genes may confer enhanced metabolism, decreased translocation, sequestration, and gene amplification and they are the cause of many of the cases of glyphosate resistance. Other key factors that influence the rate of evolution of resistance are the selection pressure (frequency and efficacy of herbicide use), the residual activity of the herbicide, the genetic basis of resistance (degree of dominance of the resistance trait and the breeding system of the weed), how prolific the weed is at producing seed, seed longevity in the soil, and the fitness of the resistance trait. Of these factors it is the selection pressure (in particular the frequency of herbicide use) that we can influence the most, and decreasing the selection pressure is the basis of herbicide resistance management strategies.

12.3 Mechanisms of Resistance

There are five primary mechanisms of herbicide resistance.

1. **Target site resistance** is the result of a modification of the herbicide binding site (usually an enzyme), which precludes a herbicide from effectively 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 of the site of action of the herbicide.
2. **Enhanced metabolism** occurs when the plant has the ability to degrade the herbicide before it can seriously affect the plant.
3. **Decreased absorption and/or translocation** can cause resistance because herbicide movement is restricted and the herbicide does not reach its site of action in sufficient concentration to cause death.
4. **Sequestration** of a herbicide into vacuoles or onto cell walls can keep the herbicide from the site of action resulting in resistance.
5. **Gene amplification/over-expression** is the most recently identified herbicide resistance mechanism, and causes resistance by increasing the production of the target enzyme, effectively diluting the herbicide in relation to the target site.

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 herbicides. The most common type of cross-resistance is target site cross resistance, where an altered target site (enzyme) confers resistance to many or all of the herbicides that inhibit the same enzyme.

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. A diagnosis of multiple resistance requires knowledge of the resistance mechanisms (Heap and LeBarron 2001).

12.4 The Occurrence of Herbicide Resistant Weeds

The data used in the tables and figures of this chapter come from the International Survey of Herbicide-Resistant Weeds website which is located at www.weedscience.com (Heap 2012). As of August 2012 the survey recorded 388 unique cases of resistant weeds. A unique case refers to the first instance of a weed species evolving resistance to one or more herbicides in a herbicide group (herbicides that act on the same site of action). There are 210 weed species (123 dicots and 87 monocots) that have evolved resistance to one or more herbicides. The rate of discovery of new types of herbicide resistant weeds is remarkably consistent at about 11 new cases per year (Fig. 12.1). Weeds have evolved resistance to 21 herbicide groups (Table 12.1) in

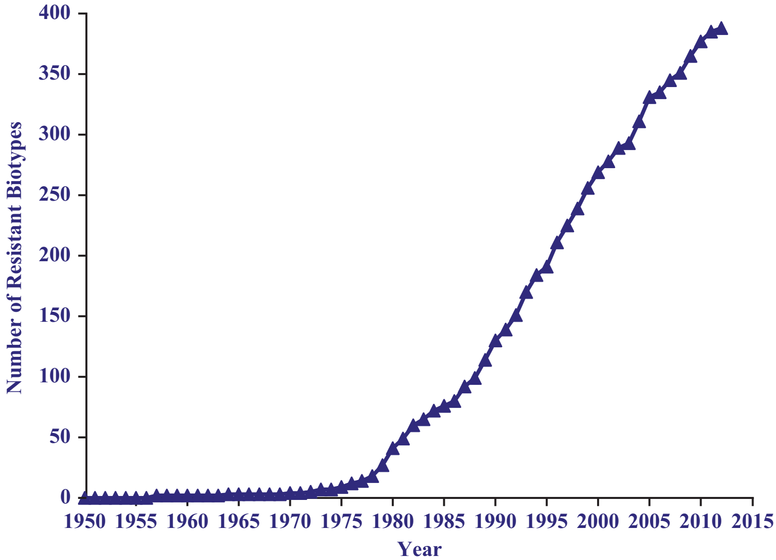

Fig. 12.1 The chronological increase in the number of herbicide-resistant weeds worldwide. Data accessed from the www.weedscience.com website on August 10, 2012. (Heap 2012)

61 countries (Table 12.2) and 152 herbicide active ingredients. Fig. 12.2 shows the clear difference in the propensity of weeds to evolve resistance to different herbicide groups.

12.4.1 ALS Inhibitor (B/2) Resistant Weeds

ALS inhibitor herbicides prevent the biosynthesis of the branched-chain amino acids (valine, leucine, and isoleucine) by inhibiting the acetolactate synthase enzyme in plants (Ray 1984). The ALS inhibitor herbicides are the highest risk herbicide group for the development of resistance (Fig. 12.2), with the first cases of resistance being identified only four years after their introduction. The first reported case of ALS inhibitor resistance was metabolic resistance to chlorsulfuron in *Lolium rigidum* in Australia (Heap and Knight 1982, 1986), followed by target site resistance in 1987 in *Lactuca serriola* (Mallory-Smith et al. 1990) in the USA. There are now 126 weed species that have evolved resistance to the ALS inhibitors (Table 12.1). There are a number of reasons why ALS inhibitors have selected more resistant weeds than any other herbicide group. One major factor is that there are more ALS inhibitor herbicides (over 55 actives in 5 chemical classes, twice as many as any other herbicide group) and they are used on a greater area annually than any other herbicide group. Another is that ALS inhibitors exert a strong selection pressure because they have very high activity on sensitive biotypes and they also have soil residual activity. However these factors alone do not account for the nearly 5 new weed species identified with ALS inhibitor resistance each year (Fig. 12.2). The

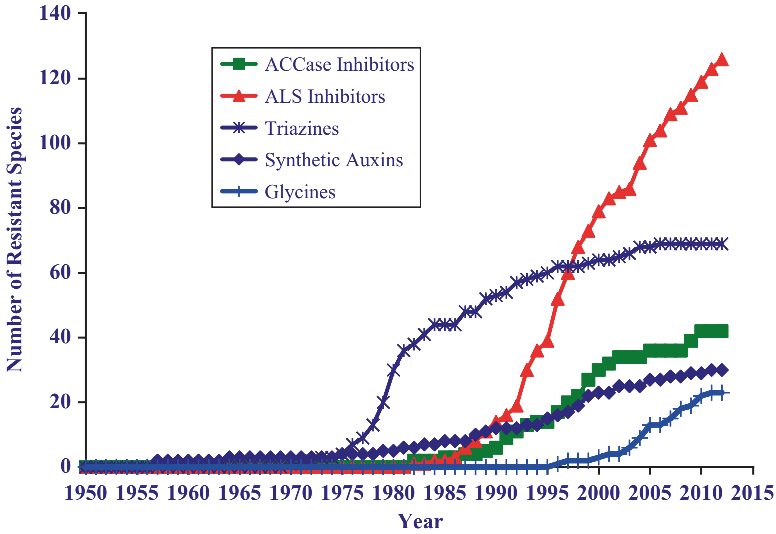

Fig. 12.2 The chronological increase in the number of herbicide-resistant weeds for several herbicide classes. Data accessed from the www.weedscience.com website on August 10, 2012. (Heap 2012)

Achilles heel of the ALS inhibitors is the ability of the target enzyme (acetolactate synthase) to undergo many mutations but still remain functional, and most cases of ALS inhibitor resistance are due to an alteration in this enzyme. At present there are eight amino acids (Ala 122, Pro 197, Ala 205, A sp 376, Arg 377, Trp 574, Ser 653, and Gly 654) on the ALS gene that resistance-conferring substitutions have been identified (www.weedscience.com ALS inhibitor mutation table Heap, 2012). There are many substitutions that can occur for each of these amino acids, in fact for Pro 197 there 9 different substitutions (Ala, Arg, Asn, Gln, His, Ile, Leu, Ser, and Thr) shown to cause resistance, and there are 24 substitutions in total that cause resistance. It is because there are so many variations in the ALS gene that confer resistance to the ALS enzyme that the ALS inhibitor herbicides are so prone to resistance. There are 5 different classes of ALS inhibitor herbicides and there are different patterns of cross-resistance to these classes depending on the particular mutation. This presents a problem to the grower, as without identifying the mutation that they are dealing with they do not know which classes of ALS inhibitor herbicides may still be effective on their particular resistant population.

12.4.2 Triazine (C1/5) Resistant Weeds

The triazines (PSII inhibitors) became heavily used in corn production in the USA and Europe in the 1960s and 1970s. Twenty six PSII inhibitor herbicides have been commercialized belonging to 6 chemical classes. Triazine herbicides inhibit

Table 12.1 The occurrence of herbicide-resistant weed species to herbicide groups

#	Herbicide group	HRAC/ WSSA	Example herbicide	Dicots	Monocots	Total
1	ALS inhibitors	B/2	Chlorsulfuron	77	49	126
2	Photosystem II inhibitors	C1/5	Atrazine	47	22	69
3	ACCase inhibitors	A/1	Diclofop-methyl	0	42	42
4	Synthetic Auxins	O/4	2,4-D	23	7	30
5	Bipyridiliums	D/22	Paraquat	17	9	26
6	Glycines	G/9	Glyphosate	10	13	23
7	Ureas and amides	C2/7	Chlorotoluron	8	14	22
8	Dinitroanilines and others	K1/3	Trifluralin	2	9	11
9	Thiocarbamates and others	N/8	Triallate	0	8	8
10	PPO inhibitors	E/14	Oxyfluorfen	5	0	5
11	Triazoles, ureas, isoxazolidiones	F3/11	Amitrole	1	4	5
12	Nitriles and others	C3/6	Bromoxynil	3	1	4
13	Chloroacetamides and others	K3/15	Butachlor	0	4	4
14	Carotenoid biosynthesis inhibitors	F1/12	Flurtamone	2	1	3
15	Glutamine synthase inhibitors	H/10	Glufosinate-ammonium	0	2	2
16	Arylaminopropionic acids	Z/25	Flamprop-methyl	0	2	2
17	Unknown	Z/27	(chloro)—flurenol	0	2	2
18	4-HPPD inhibitors	F2/27	Isoxaflutole	1	0	1
19	Mitosis inhibitors	K2/23	Propham	0	1	1
20	Cellulose inhibitors	L/27	Dichlobenil	0	1	1
21	Organoarsenicals	Z/17	MSMA	1	0	1

HRAC Group—Herbicide grouping system developed by the Herbicide Resistance Action Committee

WSSA Group—Herbicide grouping system developed by the Weed Science Society of America

Data accessed from the www.weedscience.com website on August 10, 2012. (Heap 2012)

photosynthesis by competing with plastoquinone at its binding site which is located on the D1 protein in the photosystem two complex in chloroplasts (Gronwald 1994). The first well documented case of herbicide resistance was that of triazine-resistant *Senecio vulgaris* that appeared as a result of repeated use of simazine in a plant nursery in Washington State and was reported by Ryan (1970). The case itself was of little economic significance however it did alert weed researchers working in corn to the potential of triazine-resistant weeds and shortly thereafter in the mid 1970s there was an explosion of research documenting triazine-resistant weeds in corn production in both the United States and in Europe. There are some cases of triazine resistance due to enhanced metabolism (Gronwald 1997) however the majority of triazine resistance cases are due to a mutation ($Ser_2$64 to Gly) in the psbAgene, which codes for the Dl protein and reduces the binding of triazine herbicides to the thylakoid membrane in chloroplasts. There are currently 69 documented cases of triazine resistance and the majority of them were identified prior to 1995 despite the continued widespread use of herbicides like atrazine, simazine, and metribuzin today. *Amaranthus, Chenopodium* and *Solanum sp.* are particularly prone to evolve triazine resistance and infest large areas in corn producing regions of the USA and Europe.

Table 12.2 The occurrence of herbicide-resistant weeds in countries

Rank	Country	# Resistant Weeds	Rank	Country	# Resistant Weeds
1	USA	140	32	Costa Rica	5
2	Australia	61	33	Mexico	5
3	Canada	58	34	Norway	5
4	France	33	35	Thailand	5
5	Spain	33	36	Bulgaria	4
6	China	30	37	India	3
7	Italy	29	38	Philippines	3
8	Brazil	27	39	Portugal	3
9	Israel	27	40	Austria	2
10	Germany	26	41	Paraguay	2
11	United Kingdom	24	42	Sri Lanka	2
12	Belgium	18	43	Sweden	2
13	Japan	18	44	Cyprus	1
14	Malaysia	17	45	Ecuador	1
15	Czech Republic	16	46	Egypt	1
16	Chile	15	47	El Salvador	1
17	Turkey	15	48	Ethiopia	1
18	Poland	14	49	Fiji	1
19	South Africa	14	50	Guatemala	1
20	Switzerland	14	51	Honduras	1
21	South Korea	12	52	Hungary	1
22	Iran	11	53	Indonesia	1
23	New Zealand	10	54	Ireland	1
24	Argentina	9	55	Kenya	1
25	Venezuela	9	56	Nicaragua	1
26	Denmark	8	57	Panama	1
27	Bolivia	7	58	Saudi Arabia	1
28	Greece	7	59	Slovenia	1
29	The Netherlands	7	60	Taiwan	1
30	Colombia	6	61	Tunisia	1
31	Yugoslavia	6			

Data accessed from the www.weedscience.com website on August 10, 2012. (Heap 2012)

12.4.3 ACCase Inhibitor (A/1) Resistant Weeds

ACCase inhibitor herbicides target the enzyme acetyl co-enzyme A carboxylase which catalyzes the first step in fatty acid biosynthesisin grasses (Buchanan et al. 2000). ACCase inhibitor herbicides came into widespread use in the 1980s in both broadleaf and cereal crops and there are now 20 active ingredients in 3 chemical classes. Although cases of enhanced metabolism and over expression of the ACCase enzyme have been identified, the overwhelming cause of resistance to this herbicide group is due to an altered, insensitive form of the ACCase enzyme (Brown et al., 2002). There are now 42 monocot weed species with resistance to the ACCase inhibitors (Table 12.1). ACCase inhibitors are prone to resistance for the same reason that the ALS inhibitors are prone to resistance, there are many mutations that prevent ACCase inhibitors from binding to the ACCase enzyme (De´lye et al., 2005, Liu et al., 2007, Hochberg et al., 2009). Even though there are more triazine resistant species than ACCase inhibitor resistant species the economic impact of ACCase inhibitor resistant weeds is far greater than that of triazine-resistant weeds. ACCase inhibitor resistant weeds are widespread wherever cereal crops (wheat, barley, etc.) are grown and continue to increase in area and severity. ACCase inhibitor resistant *Avena, Lolium, Phalaris, Setaria* and *Alopecurus sp*. infest over 20 million hectares globally and contribute significantly to reductions in crop yields. These grass species are particularly problematic because they have not only evolved resistance to ACCase inhibitors but to most of the effective grass herbicides available to wheat producers, leaving growers with dwindling options to manage them.

12.4.4 Synthetic Auxins (O/4)

Synthetic auxins (22 commercialized actives in 5 chemical classes) were the first herbicides to be used on a massive scale and continue to be among the most widely used herbicides today. Synthetic auxins mimic the natural plant hormone indole-3-acetic acid (IAA) and affect several aspects of plant growth, including cell division, elongation, and differentiation, resulting in physiological and morphological abnormalities, including severe epinasty, hypertrophy, faciation of the crown and leaf petioles, and premature abscission of leaves (Sterling and Hall 1997). Despite being used for longer and over a greater area than any other herbicide group there are only 30 weed species that have evolved resistance to the synthetic auxins, and of these 30 only a handful are more than scientific curiosities. We have not seen widespread resistance to the synthetic auxins the way we have with triazine, ACCase inhibitor, ALS inhibitor or even glyphosate-resistant weeds. Four of the 30 cases are not classic synthetic auxin resistance, they are grasses that have become resistant to quinclorac (an unusual synthetic auxin that acts on grasses through a novel mechanism), and in those cases we do see widespread resistance. Of the other 26 cases, only dicamba resistant *Kochia scoparia* in the USA and 2,4-D resistant *Raphanus raphanistrum* in Australia infest more than 1,000 hectares. This is intriguing and points to the synthetic auxins as being one of the least prone to resistance of any of the widely used herbicide groups. The agricultural chemical industry was fortunate to initially discover a herbicide group that has a very low risk for resistance.

12.4.5 Glyphosate (G/9) Resistant Weeds

Glyphosate is the most widely used herbicide in the world, has been in commercial use since 1974 and is an extremely valuable resource (Baylis 2000, Woodburn 2000). Glyphosate inhibits the chloroplast enzyme 5-enolpyruvylshikimate-3-phosphate synthase (EPSPS) which disrupts the shikimate pathway resulting in the inhibition of aromatic amino acid production. Weeds have evolved resistance to glyphosate through decreased translocation/sequestration (Feng et al. 2004), target site mutations (Kaundun et al. 2008), and gene amplification (Gaines et al. 2010). The first case of glyphosate resistance was that of *Lolium rigidum* from an apple orchard in Australia in 1996, coincidentally the same year that the first Roundup Ready crop was commercialized. There are now 23 glyphosate resistant weeds found in 18 countries (Table 12.3) with half of them evolving resistance in Roundup Ready cropping systems and the other half from orchards and non-crop situations. This statistic belies the extent of the problem of glyphosate-resistant weeds in Roundup Ready crops vs the other cases of glyphosate-resistant weeds. On an area basis the survey reports that the 11 glyphosate-resistant weeds in Roundup Ready crops account for 98% of the area infested with glyphosate-resistant weeds globally. Whilst glyphosate-resistant *Conyza canadensis* is the most widespread glyphosate-resistant weed it is easily managed with synthetic auxins and other herbicides. It is the *Amaranthus* species (*Amaranthus palmeri* and *Amaranthus tuberculatus*) that present the greatest economic threat of any of the glyphosate-resistant weeds. Glyphosate-resistant *Amaranthus palmeri* was first identified in cotton in Georgia in 2005 and now infests 12 states primarily in cotton and soybean in the southern cropping belt of the USA. Similarly glyphosate-resistant *Amaranthus tuberculatus* was first identified in 2005 in Missouri and now infests 11 states, primarily in corn and soybean in the mid-west corn/soybean cropping belt in the USA. Other economically important glyphosate-resistant weeds in the USA include *Ambrosia sp.*, *Kochia scoparia*, and *Sorghum halepense. Kochia scoparia* threatens to increase rapidly because of its efficient method of seed dispersal (tumbleweed), a key reason that helped it rapidly spread ALS inhibitor resistance in western states of the USA in the 1990s. In South America the most serious cases of glyphosate resistance are *Sorghum halepense* (Argentina) and *Digitaria insularis* (Paraguay and Brazil) in Roundup Ready soybeans. Glyphosate-resistant *Conyza sp.* are also prevalent in Brazilian soybean crops (Table 12.3). It is important to note that even though many weeds have evolved resistance to glyphosate, and there will be many more to come, Roundup Ready crops and glyphosate will continue to be used extensively for at least another decade because glyphosate provides economic broad spectrum weed control. Growers will add supplemental herbicide groups to control glyphosate-resistant weeds just as they did with the continued use of atrazine after the appearance of triazine-resistant weeds. An important strategy in the management of glyphosate-resistant weeds is the use of other herbicides and the PPO inhibitors and HPPD inhibitors are of major utility when used in rotation/sequence with glyphosate in the mid-west USA. Unfortunately we have already seen the appearance of 5 weed species with resistance to PPO inhibitors, two of them in corn/soybean rotations in the USA (*Amaranthus tuberculatus*, and *Ambrosia artemissiifolia*), as well as HPPD inhibitor resistant *Amaranthus tuberculatus*.

12.4.6 Weed Resistance to Other Herbicides

Other groups with significant resistant weed problems are the bipyridiliums (26 species), phenylureas and phenylamides (22 species), and the dinitroanalines (11 species). Although these groups are still used they are not as prominent as they once were, and few new cases of resistance to them have been identified in the last 10 years.

Table 12.3 The occurrence of glyphosate-resistant weeds worldwide

#	Species	First Year	Country and Year (states are in order of first recorded case)
1	*Amaranthus palmeri*	2005	USA (2005—GA, NC, AR, NM, AL, MS, MO, TN, IL, LA, MI, VA)
2	*Amaranthus tuberculatus*	2005	USA (2005—MO, IL, KS, MN, IN, IA, MS, ND, SD, OK, TN)
3	*Ambrosia artemisiifolia*	2004	USA (2004—AR, MO, OH, IN, KS, ND, SD, MN)
4	*Ambrosia trifida*	2004	USA (2004—OH, AR, IN, KS, MN, TN, IA, MO, MS, NE, WI), Canada (2008—ON)
5	*Bromus diandrus*	2011	Australia (2011—SA)
6	*Chloris truncata*	2010	Australia (2010—NSW, QLD, SA)
7	*Conyza bonariensis*	2003	South Africa (2003), Spain (2004), Brazil (2005), Israel (2005), Columbia (2006), USA (2007—CA), Greece (2010), Portugal (2010)
8	*Conyza canadensis*	2000	USA (2000—DE, KY, TN, IN, MD, MO, NJ, OH, AR, MS, NC, PA, CA, IL, KS, VA, NE, MI, OK, SD, IA), Brazil (2005), China (2006), Spain (2006), Czech Republic (2007), Canada (2010—ON), Poland (2010), Italy (2011)
9	*Conyza sumatrensis*	2009	Spain (2009), Brazil (2010)
10	*Cynodon hirsutus*	2008	Argentina (2008)
11	*Digitaria insularis*	2005	Paraguay (2005), Brazil (2008)
12	*Echinochloa colona*	2007	Australia (2007—NSW, QLD, WA), USA (2008—CA), Argentina (2009)
13	*Eleusine indica*	1997	Malaysia (1997), Colombia (2006), China (2010), USA (2010—MS, TN)
14	*Kochia scoparia*	2007	USA (2007—KS, SD, NE), Canada (2012—AB)
15	*Leptochloa virgata*	2010	Mexico (2010)
16	*Lolium multiflorum*	2001	Chile (2001), Brazil (2003), USA (2004—OR, MI, AR), Spain (2006), Argentina (2007)
17	*Lolium perenne*	2008	Argentina (2008)
18	*Lolium rigidum*	1996	Australia (1996—VIC, NSW, SA, WA) USA (1998—CA), South Africa (2001), France (2005), Spain (2006), Israel (2007), Italy (2007)
19	*Parthenium hysterophorus*	2004	Colombia (2004)
20	*Plantago lanceolata*	2003	South Africa (2003)
21	*Poa annua*	2010	USA (2010—MO, TN)
22	*Sorghum halepense*	2005	Argentina (2005), USA (2007—AR, MS, LA)
23	*Urochloa panicoides*	2008	Australia (2008—NSW)

Data accessed from the www.weedscience.com website on August 10, 2012. (Heap 2012)

12.5 Worst Herbicide Resistant Weeds

The International Survey of Herbicide-Resistant Weeds database can be useful in identifying which weeds have the greatest propensity to evolve resistance. Table 12.4 presents a list of the 20 worst herbicide-resistant weeds based on the countries they infest, the number of sites of action that they have become resistant to, the number of sites and area of infestation and the number of cropping regimes that the weed has become resistant in. These same criterion were used in 1996 to identify the 20 worst weeds with the aim of predicting which would become resistant to glyphosate. This was successful, with the analysis predicting the very first glyphosate-resistant weed (*Lolium rigidum*), and also predicting 12 of the current list of 23 glyphosate-resistant weeds. The current list (Table 12.4) is not much changed from the 1996 list however the order of the worst resistant weeds has changed to some degree. Species in bold have evolved resistance to glyphosate. There are 8 species on this list that have not evolved resistance to glyphosate. Six of them (*Avena fatua*, *Echinochloa crus-galli*, *Setaria viridis*, *Alopecurus myosuroides*, *Phalaris minor*, and *Raphanus raphanistrum*) are not common weeds in Roundup Ready crops and thus do not receive a high selection pressure by glyphosate. This leaves *Chenopodium album* and *Amaranthus retroflexus*, both prime candidates for evolving glyphosate-resistance and should be managed accordingly. When weeds evolve resistance to a herbicide group it is often not a major problem for growers to use alternative herbicide groups to control them. The real issue is when weeds evolve multiple-resistance, leaving growers few or no herbicidal options for weed control. Multiple resistance in weeds is increasing rapidly and will be the major source of crop failure and economic problems caused by herbicide-resistant weeds.

Table 12.5 presents the number and percentage of herbicide resistant species by family and the most notable aspect of this table is that five weed families, Poaceae, Asteraceae, Brassicaceae, Amaranthaceae, and Chenopodiaceae account for about 70% of all cases of herbicide resistance even though they represent only 50% of the world's principal weeds. It is apparent that the grasses (Poaceae) and crucifers (Brassicaceae) are very prone to the development of herbicide resistance compared to other families and their prevalence as weeds in general(Table 12.5).

12.6 Herbicide Resistant Weeds in Major Crops

Herbicide-resistant weeds occur in all major cropping systems wherever herbicides are used. Table 12.6 presents the occurrence of herbicide-resistant weeds in various cropping systems.

12.6.1 Wheat

Sixty-four weed species have evolved herbicide resistance in wheat, 38 are broadleaf species and 26 are grass species (Table 12.6). Nineteen grasses have evolved resistance to ACCase inhibitors in wheat. The most troublesome weeds of wheat are grasses that have evolved multiple-resistance, in particular *Lolium rigidum* (11 sites of action), *Alopecurus myosuroides* (9 sites of action),and *Avena fatua* (5 sites of action). Throughout large areas of the wheat producing regions of the world these three species have evolved target site resistance to the ACCase inhibitor and ALS inhibitor herbicides. In addition metabolism based resistance is common in both *Lolium rigidum* and *Alopecurus myosuroides* (and to a lesser extent *Avena fatua*)

Table 12.4 The top 20 worst herbicide-resistant weeds globally—weighted by propensities in countries, MOA's, sites, hectares, and cropping systems

#	Species	Common Name	Countries	SOA	Sites	Hectares	Regimes
1	**Lolium rigidum**	**Rigid Ryegrass**	12	11	25,000	2,174,000	8
2	**Conyza canadensis**	**Horseweed**	14	5	11,000	2,383,000	9
3	Avena fatua	Wild Oat	13	5	48,000	4,902,000	5
4	**Amaranthus tuberculatus**	**Common Waterhemp**	2	6	69,000	4,741,000	7
5	Chenopodium album	Lambsquarters	18	4	28,000	593,000	9
6	Echinochloa crus-galli	Barnyardgrass	17	9	7,000	624,000	5
7	**Amaranthus palmeri**	**Palmer Amaranth**	1	4	201,000	4,093,000	7
8	Amaranthus retroflexus	Redroot Pigweed	14	4	7,000	156,000	11
9	**Eleusine indica**	**Goosegrass**	7	7	3,000	52,000	11
10	**Echinochloa colona**	**Junglerice**	13	6	2,000	64,000	8
11	**Lolium multiflorum**	**Italian Ryegrass**	9	6	4,000	113,000	11
12	**Kochia scoparia**	**Kochia**	3	4	23,000	1,574,000	7
13	Alopecurus myosuroides	Blackgrass	12	6	2,000	15,000	4
14	**Poa annua**	**Annual Bluegrass**	10	9	1,000	6,000	4
15	Setaria viridis	Green Foxtail	5	4	8,000	1,082,000	7
16	Phalaris minor	Little Seed Canary	6	3	61,000	654,000	3
17	**Conyza bonariensis**	**Hairy Fleabane**	11	4	1,000	6,000	9
18	**Ambrosia artemisiifolia**	**Common Ragweed**	2	5	1,000	52,000	5
19	**Sorghum halepense**	**Johnsongrass**	7	4	1,000	70,000	5
20	Raphanus raphanistrum	Wild Radish	2	4	6,000	45,000	4

Species in bold have evolved resistance to glyphosate. These 20 weeds were chosen by cycling through the International Survey of Herbicide Resistant Weeds database 5 times summing the ranks for each of the 210 weed species. The weeds were then sorted and ranked separately by the number of countries, SOA's, etc. for each of the categories. The cumulative rank for each species for each of the five categories was determined and the 20 with the highest ranks are shown. The rest may be seen on www.weedscience.com

Data accessed from the www.weedscience.com website on August 10, 2012. (Heap 2012) which has provided them the ability to survive all of the major wheat herbicides available for their control. *Avena fatua* is the most widespread resistant weed globally, estimated to infest around 5 million hectares (Table 12.4). It should be noted that the area estimates provided by scientists are often out of date and inaccurate, resulting in an underestimate of the true area infested by herbicide-resistant weeds. Eighteen grass species and 37 broadleaf species have evolved resistance to the ALS inhibitors in wheat. As mentioned above, the grasses present the most serious economic and practical problems because there is enough diversity in herbicide mechanisms to control the ALS inhibitor resistant broadleaf resistant weeds.

12.6.2 Corn

Fifty-eight weed species have evolved resistance to herbicides in corn, 41 are broadleaf species and 17 are grass species (Table 12.6). The widespread adoption of atrazine for weed control in corn in the 1960s and 1970s resulted in widespread triazine-resistant weeds in corn between 1975 and 1985. Today there are 35 broadleaf weeds and 10 grasses that have evolved resistance to triazine herbicides in corn, primarily in the USA and Europe. In the 1990s ALS inhibitor resistant weeds proliferated in corn (22 cases in total) and from 2000 onwards we saw 12 species evolve glyphosate-resistance in corn. The ALS inhibitor and glyphosate-resistant weeds in corn mainly occurred in the USA and not in Europe, because the Europeans did not use ALS inhibitors extensively and they did not grow Roundup Ready corn. *Amaranthus tuberculatus* is the most serious herbicide-resistant weed of corn, and it has evolved multiple resistance to ALS inhibitors, PSII inhibitors, PPO inhibitors, 4-HPPD inhibitors, glyphosate, and the synthetic auxins. Corn growers are fortunate in that they have many herbicide sites of action available to them to control resistant weeds once they appear.

12.6.3 Soybean

Forty-five weed species have evolved resistance to herbicides in soybean, 25 are broadleaf species and 20 are grass species (Table 12.6). While 6 species had evolved triazine-resistance in soybean the majority of herbicide-resistant weeds in soybean are to ALS inhibitors, ACCase inhibitors, and more recently glyphosate. Fourteen grasses have evolved resistance to the ACCase inhibitors with *Sorghum halapense, Setaria sp., Digitaria sp.*, and *Echinochloa sp.* presenting the biggest problems. In the 1990s the soybean growers in the USA were reliant on ALS inhibitors, such as imazethapyr, for weed control and 27 weed species evolved resistance to ALS inibitors in soybean. The rapid adoption of Roundup Ready Soybean, first introduced in 1996, resulted in a reduction in the identification of new ALS inhibitor resistant weeds in soybean. The reliance on glyphosate as the primary weed control in Roundup Ready Soybean resulted in fifteen weed species evolving resistance to

Table 12.5 The number and percentage of herbicide-resistant species by family, and the percentage of species considered principal weeds by Holm et al. (1991, 1997) for each of these families

Family	Number of resistant species in family	Resistant Species (% of total)	Weed species (% of world's principal weeds)*
Poaceae	71	34	25
Asteraceae	36	17	16
Brassicaceae	17	8	4
Amaranthaceae	10	5	3
Chenopodiaceae	8	4	2
Polygonaceae	7	3	5
Scrophulariaceae	7	3	1
Cyperaceae	6	3	5
Caryophyllaceae	5	2	1
Alismataceae	5	2	1
Solanaceae	4	2	2
Lythraceae	4	2	1
23 other families pooled	30	14	18
Total	210	99	84

Data accessed from the www.weedscience.com website on August 10^{th} , 2012 (Heap 2012)

Table 12.6 The occurrence of herbicide-resistant weeds in various cropping situations

Category	Crop	# Resistant Biotypes
Field Crops	Wheat	64
	Corn	58
	Soybean	45
	Rice	39
	Pulses	17
	Canola	13
	Cotton	11
	Sugarbeet	8
	Sugarcane	3
	Other Crops	73
Vegetables	Vegetables (carrot, lettuce, potato, etc.)	21
Perennial Crops	Orchard (apple, pear, peach,…including vineyard)	38
	Pasture (clover, alfalfa, pasture seed, etc.)	26
	Forestry	6
	Other Perennial (tea, coffee, rubber, mint, etc.)	12
Non Crop	Non Crop—(roadside, railway, industrial site)	35

Data accessed from the www.weedscience.com website on August 10, 2012 (Heap 2012)

glyphosate in soybean, eight of them are broadleaves and 7 of them grasses. *Amaranthus sp., Conyza sp.*, and *Ambrosia sp.*, are the most troublesome glyphosate-resistant broadleaf weeds in soybean in the USA. *Digitaria insularis* and *Sorghum halepense* in South America present the worst cases of glyphosate-resistant grasses in soybean. Multiple resistance in *Amaranthus palmeri* in the south and *Amaranthus tuberculatus* in the mid-west are the greatest threat to soybean production in the USA.

12.6.4 Rice

Thirty-nine weed species have evolved resistance to herbicides in rice, 26 are broadleaf species and 13 are grass species (Table 12.6). The majority of herbicide-resistance cases (31 species) in rice are to the ALS inhibitors. Twenty broadleaf species and 11 grasses have evolved resistance to ALS inhibitors in rice, with the worst cases being *Echinochloa sp., Lindernia sp., Sagittaria sp., Scripus sp., Monochoria sp., Ammania sp.,* and *Limnophila sp*. Eight grasses have evolved resistance to ACCase inhibitors in rice, the worst being *Echinochloa sp., Leptochloa sp., Ischaemum rugosum* and *Eleusine indica*. The Echinochloa sp. (*Echinochloa colona, Echinochloa crus-galli, Echinochloa oryzoides*, and *Echinochloa phyllopogon*) are an intractable problem in rice because they have evolved multiple resistance to most of the available rice herbicides, including ACCase inhibitors (Group A—fenoxaprop+many), ALS inhibitors (Group B—bensulfuron+many), Ureas and Amides (Group C2–propanil), Isoxazolidinones (Group F3–clomazone), Chloracetamides (Group K3–butachlor), Thiocarbamates (Group N—thiobencarb & molinate), and Synthetic auxins (Group O—quinclorac). It is estimated that there are over 2 million hectares infested with target site cross-resistance to butachlor and thiobencarb in *Echinochloa crus-galli* in China (Huang and Gressel, 1997).

12.6.5 Perennial Crops

Thirty-eight weed species have evolved resistance in orchards, 26 in pastures, 6 in forestry and 12 in other perennial crops like tea, coffee, rubber and mint. Orchards are particularly prone to resistance because growers often attempt to keep the ground bare through several (3–10) applications of herbicides annually. Common herbicides used in orchards are the triazines (atrazine, simazine, and metribuzin), the bipyridiliums (paraquat and diquat), glyphosate, and glufosinate in orchards. Eighteen weed species have evolved resistance to the triazines, 5 to the bipyridiliyums, 11 to glyphosate, and 2 to glufosinate. It is interesting to note that glyphosate and glufosinate are considered very low risk herbicides for selecting resistance and the 11 glyphosate resistance cases in orchards constitute half of all known cases of glyphosate resistance. Glufosinate resistance in *Eleusine indica* and *Lolium multiflorum* in orchards are the only known cases of glufosinate resistance worldwide and has implications for the use of glufosinate in glufosinate resistant corn and soybean in the USA.

12.6.6 Non-Crop

Herbicides are often used to keep ground bare in non-crop situations, particularly on roadsides, railways, and industrial sites. Thirty five weed species have evolved resistance in these situations, 20 of them broadleaves and 15 of them are grasses. These situations often require repeated applications annually of the same herbicide and often the use of herbicides with a high level of residual, which has led to significant problems with herbicide-resistant weeds. Herbicide-resistant weeds selected on roadsides and railways are often not confirmed until they move into farmers' fields and present an economic problem. Triazine and ALS inhibitor resistance in *Kochia scoparia* and *Conyza canadensis* became widespread along roadsides and railways in the USA through many years use of these inexpensive herbicides and both species have extremely efficient dispersal systems allowing them to spread quickly into farmers' fields.

12.7 Herbicide Resistant Crops

Herbicide resistant crops are both the cause and solution to many herbicide resistant weed problems. Roundup-Ready crops (crops genetically engineered to survive high rates of the herbicide glyphosate) have dominated the herbicide resistant crop market since the introduction of Roundup-Ready soybeans in 1996. At that time soybean growers were facing serious resistance problems with ALS inhibitor and ACCase inhibitor resistant weeds and they saw Roundup Ready soybeans as the solution to those problems. Indeed Roundup Ready crops did rescue many growers from crop failure due to herbicide resistant weeds. Roundup Ready crops were adopted at a greater rate than nearly any other agricultural technology and their utility in managing weeds with resistance to other herbicide groups is one of the reasons for this rapid adoption rate. In addition to soybeans, Roundup Ready alfalfa, canola, cotton, corn, and sugarbeet have been commercially used and Roundup Ready rice, wheat, and bentgrass are under development (Dill 2005; Dill et al. 2008). The very success of Roundup Ready crops has resulted in the biggest threat to their sustainability, that of glyphosate-resistant weeds. Glyphosate is a low risk herbicide for the development of herbicide resistant weeds, however the massive adoption of Roundup Ready crops, and the over reliance on glyphosate alone for weed control by many growers has made the rapid increase in glyphosate resistant weeds the biggest herbicide resistance problem that we face today. Roundup Ready crops made farmers lives much easier at first, they no longer needed to know what weeds were growing in their fields (as glyphosate controlled most species), and they no longer needed to worry as much about the timing of herbicide applications as glyphosate controls weeds at all growth stages. In reality the growers should be very worried about controlling weeds at an early stage because of the negative impact on yield if weeds are left to compete with crops even when the weeds are relatively small. One negative aspect of the success of Roundup Ready crops is that we now have a whole generation of growers that know little about weed control. Another negative aspect is that glyphosate itself is so inexpensive that it made the discovery and development of new herbicide modes of action uneconomical because new products would not be able to compete with glyphosate in the major herbicide markets (corn, soybean, cotton etc.). Certainly there were other factors at play, including the increasing regulations and costs associated with bringing new products to the market and the availability of cheap generic products other than glyphosate. Because of these factors discovery programs have been decimated over the past 15 years. All this would be fine if it were not for the appearance of glyphosate-resistant weeds. Now that companies can see that glyphosate is not sustainable on its own their discovery programs are being reignited. But there is always a lag phase of 7 to 15 years to identify, test, and register products, so growers are faced with the dilemma of dealing with resistance using existing herbicides.

This is where herbicide resistant crops can, to some extent, come to the rescue again. Given that we will not have new herbicide modes of action to deal with herbicide-resistant weeds for some time then the next best thing is to be able to use the existing herbicides in new ways. Glufosinate, dicamba, 2,4-D, HPPD inhibitor and PPO inhibitor resistant crops offer great promise to use these modes of action in new ways and will certainly be one part of the puzzle to combat herbicide-resistant weeds. There are other herbicide resistant crop traits such as the ALS inhibitor (primarily imidazolinone and sulfonylurea) resistant crops and ACCase inhibitor resistant crops but they suffer the problem that there are already many weeds that have become resistant to these herbicide groups, and they are prone to select resistance very quickly.

12.8 Integrated Weed Management is Herbicide Resistance Management

Integrated weed management (IWM) includes strategies for weed control that consider the use of all economically available weed control techniques, including: preventative measures, monitoring, crop rotations, tillage, crop competition, herbicide site of action rotation, herbicide resistant crops, biological controls, crop competition, nutrition, burning etc. Herbicide resistance is a very predictable outcome of evolution. In fact any weed control practice will be subject to the forces of evolution and no matter what practice, if done consistently and long enough, weeds will evolve to survive the practice. The best way to foil the forces of evolution is to challenge it with diversity such that any one practice is not used consistently enough to select resistance and avoidance mechanisms.

Integrated weed management requires a holistic look at all aspects of crop production. It begins with preventing the spread of weeds by cleaning farm machinery between fields, tarping grain trucks, using certified seed, controlling weed seed nurseries along fence lines, farm roads, irrigation ditches, and stockyards, and ensuring that hay and livestock is weed free before bringing them onto the property. Growers need to inventory their weed problems in order to craft effective IWM programs. The aim of IWM is to destabilize and disrupt weed populations so they don't become serious problems. Available cultural practices for weed control include crop rotations, crop management (use of vigorous seed, competitive varieties, stale seed beds, reduced row spacing, early seeding, high seeding rates, shallow seeding, good "on row" seed packing, good crop nutrition and soil conditions, intercropping, and cover crops), tillage (harrowing, spring and fall tillage, inter-row tillage, strip tillage, rotary hoeing and conventional tillage), mowing, burning, allelopathy, and biological controls. While these cultural controls are valuable, herbicides are often the backbone of an IWM program because they are the most cost effective and efficacious method of weed control in the IWM toolbox. It is very important to rotate herbicide sites of action to avoid the selection of herbicide-resistant weeds and/or herbicide weed shifts. Herbicide mixtures and sequences are also an effective resistance management strategy. In fact there is a growing body of evidence that herbicide mixtures may be more effective than herbicide rotations at delaying resistance (Beckie and Reboud 2009). Ideally each component of the herbicide mixture should be active at different target sites, have a high level of efficacy, and both herbicides should have efficacy on key problem weeds. The use of pre-plant and pre-emergence herbicides will continue to increase as a way to rotate herbicide sites of action in the cropping system. Herbicide resistant crops will also play a larger role in IWM programs in future because they facilitate the goal of rotating herbicide sites of action. To avoid the selection of polygenic low level resistance it is also important to use the full recommended herbicide rate and proper application timing for the hardest to control weed species present in the field.

12.9 Summary

Herbicides have provided farmers with unprecedented success in controlling weeds over the last 65 years. Without herbicides the world would face a major reduction in crop yields resulting in high food costs and food shortages. Herbicide-resistant weeds have been a fact of life for growers for over 40 years and they have been successful in overcoming resistance problems primarily because the agricultural chemical industry was able to provide a steady supply of new herbicide sites of action to combat resistant weeds. This is no longer the case, no new herbicide sites of action have been delivered to the market in over 20 years (Duke 2011) and there does not appear to be any on the near horizon. Many growers are reliant on using glyphosate in Roundup Ready crops for weed control and this is now known to be unsustainable. Until new herbicide sites of action are brought to the market the best strategy to manage herbicide resistant weeds is to implement integrated weed management practices that will include the use of different herbicide sites of action in rotation, sequence, and mixtures. Herbicide-resistant crops will enable growers to achieve more sustainable herbicide site of action rotations and move away from relying upon glyphosate as their primary weed control solution. The biggest problem that we face in the future is multiple resistance in weeds resulting in no herbicidal options for weed control in some crops. *Amaranthus, Conyza, Echniochloa*, and *Lolium* species are the most worrisome because of their ability to rapidly evolve resistance to a wide range of herbicide sites of action in addition to them being primary weeds in many cropping systems. It is clear from history that any consistent practice to control weeds year after year will result in directed evolution towards their survival. The solution is to vary weed control practices and destabilize evolution.

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