Chapter 9
Herbicide Resistance

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9.1 Introduction

Herbicide resistance is not a topic or concern specifically focused upon the relatively recent introduction and adoption of genetically modified crops. In fact, the first case of herbicide resistance in weeds was reported in the scientific literature in 1970, but the occurrence of evolved resistance to herbicides in plants was suggested in 1956 (Harper 1956; Ryan 1970). Since the original report, over 300 herbicide-resistant weed biotypes in more than 180 different plant species have been reported (Heap 2009). Generally, the recurrent use of an herbicide or herbicide mechanism of action imparts significant selection pressure on the weed population and provides an ecological advantage to those rare individuals within the population that have the heritable mutation conferring herbicide resistance (Owen and Zelaya 2005). The relatively recent introduction of crop cultivars with genetic modifications for herbicide resistance served to narrow the spectrum of herbicides used for weed control thus focusing on single herbicides (i.e. glyphosate) and increasing the potential for evolved herbicide resistance in weeds (Young 2006). It should be noted, however, that the genetically modified trait(s) typically does not impart selection pressure on the weed population, but rather the grower decision to utilize the herbicide causes the selection for resistance (Owen 2008a, b). However, despite claims that (due to a number of physicochemical characteristics related to glyphosate) glyphosate-resistant weeds would never evolve, the broad-scale adoption of genetically modified glyphosate-resistant crops globally has resulted in the evolution of glyphosate resistance in 16 weeds species, to date, and the rate of resistance evolution appears to be increasing at an increasing rate (Bradshaw et al. 1997; Heap 2009). This chapter provides a perspective of genetically modified herbicide-

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resistant crops, the implications of grower adoption of the genetically modified herbicide-resistant crops and the impact of this adoption on weed communities.

9.1.1 Overview of Adoption

Since the commercial introduction of genetically modified crops in 1996 (for methods, see Chaps. 1, 2), the area planted to these cultivars has increased globally at an increasing rate (Anonymous 2006). In 2006, approximately 100 million hectares of genetically modified herbicide-resistant crops were planted worldwide and an estimated 80% had the genetically modified trait conferring glyphosate resistance (Service 2007). The use of these cultivars increased an estimated 12% in 2007 and represented 114.3 million hectares and included 23 countries (Anonymous 2006). The primary countries that plant genetically modified herbicide-resistant crops are the United States (US), Argentina, Brazil, and Canada. North America represents 57% of the genetically modified herbicide-resistant crops planted globally while Central and South America contribute 33% of the total hectares. It is estimated that approximately 90% of the genetically modified herbicide-resistant crops grown globally are glyphosate-resistant crop cultivars and are represented primarily by soybean, cotton and maize (Duke and Powles 2008). Genetically modified herbicide-resistant canola dominates the cultivars grown in Canada and the US, representing >80% of total crop grown (Beckie and Owen 2007). Recently there has been a significant adoption of glyphosate-resistant genetically modified maize in the US, in part attributable to maize-based ethanol production. Overall, the revolution of adoption of genetically modified crops likely represents the largest man-caused biological experiment in history. This will cause enormous selection pressure that the wide-spread application of glyphosate on millions of hectares will impose on weed communities and inevitably result in significant changes by selecting for weeds that do not respond to the prevalent control tactics. Recently genetically modified herbicide-resistant (glyphosate) sugarbeets were commercially introduced in the US, which will add more selection pressure on weed communities (Duke 2005; Gianessi 2005).

9.1.2 Types of Herbicide Resistance

Herbicide resistance has evolved in weeds in several general forms. The most common type of herbicide resistance in weeds is the modification of the herbicide target site (Zelaya and Owen 2004). Target site resistance can be either monogenic or polygenic; the latter is often referred to as “creeping resistance” and may result from recurrent applications of low herbicide rates (Gressel 1995). In the case of monogenic herbicide resistance, typically resistance is accrued when there is a single-nucleotide point mutation of one amino acid, representing a substitution in the sensitive weed population, resulting in a resistant biotype (Gressel and Levy 2006). However, recent studies suggest that weeds can also evolve monogenic herbicide resistance by "losing" an amino acid in the target protein (Patzoldt et al. 2006). A partial list of target site resistance demonstrated in weed populations includes resistant weed biotypes for acetolactate synthase (ALS) inhibiting herbicides, protoporphyrinogen oxidase (PPO) inhibiting herbicides, triazine herbicides and glyphosate (Ryan 1970; Baerson et al. 2002; Ng et al. 2003; Zelaya and Owen 2004; Patzoldt et al. 2006). Herbicide resistance in weeds also is the result of differential translocation of the herbicide to the target site (Feng et al. 2004). Weeds are also able to evolve herbicide resistance by rapidly and efficiently metabolizing the herbicide prior to the accumulation of a toxic concentration of the herbicide at the target site (Yuan et al. 2006). This is also known as non-target site resistance and is typically mediated by cytochrome P450 monooxygenases, glutathione *S*-transferases or glycosyltransferases, depending on the herbicide. Herbicide resistance can also be a function of ABC transporters which serve to facilitate compartmentalization of the herbicide, again protecting the target site of the herbicide (Lu et al. 1997). Finally, weeds have demonstrated other novel forms of herbicide resistance, such as morphological adaptations (i.e. leaf pubescence) and phenological changes (i.e. avoidance attributable to delayed germination) in weed populations (Owen 2001). Interestingly, weeds have demonstrated the ability to evolve multiple resistances to several herbicide modes of action (Patzoldt et al. 2005; Legleiter and Bradley 2008). Herbicide resistance in crops has been established using altered target site, the most common strategy used (i.e. glyphosate-resistant crops), enhanced metabolism (i.e. glufosinate-resistant crops) and cultivars with multiple resistances to herbicides have been developed (Green 2007; Green et al. 2008; Green et al. 2009).

9.1.3 Modes of Herbicide Action in Herbicide-Resistant Crops

Most of the current herbicide-resistant crop cultivars are represented by cultivars created by transgenic modifications. (Duke 2005) These herbicide modes of action include inhibition of photosystem II (bromoxynil), inhibition of glutamine synthetase (glufosinate) and inhibition of EPSPS (glyphosate). They are facilitated by the insertion of five transgenes to confer resistance to the respective herbicides: CP4, GOX or a mutated EPSPS for glyphosate resistance, a nitrilase gene for bromoxynil resistance and the *bar* gene for glufosinate resistance. Historically, there are non-transgenic herbicide resistance traits for cyclohexanedione herbicides, imidazolinone herbicide, sulfonylurea herbicides and triazine herbicides; however the dominant herbicide-resistant trait on the market is for transgenic glyphosate resistance (Duke 2005; Duke and Powles 2008). Recently, two novel transgenes, *gat4621* and *hra*, were introduced that confer high levels of resistance to glyphosate- and ALS-inhibiting herbicides, respectively (Castle et al. 2004; Green et al. 2008; Green et al. 2009).

A gene that codes for dicamba monooxygenase (*DMO*), a Rieske non-heme monooxygenase that metabolizes dicamba, has been discovered in the soil bacteria *Pseudomonas maltophilia* and can be biotechnologically inserted into the nuclear and chloroplast genome of soybean, thus conferring these transgenic plants resistance to dicamba (Behrens et al. 2007). These cultivars are anticipated to be commercially released in several years. Furthermore, transgenes that code for resistance to 2,4-D and ACCase inhibitor herbicides are also anticipated to be inserted into the various crops in the near future. Thus, the number of herbicide modes of action with transgenic resistant crop cultivars appears to be increasing and it is anticipated that these new transgenes will improve weed management options for growers and help resolve current and future problems with the evolution of herbicide-resistant weed biotypes. However, whether or not the mitigation of current and future herbicide-resistant weed problems actually occurs depends entirely on how growers utilize the technologies and whether or not they establish appropriate integrated weed management strategies.

9.1.4 Implications of Genetically Modified Herbicide-Resistant Crops

The wide-spread adoption of genetically modified herbicide-resistant crops has made a number of significant impacts on agricultural systems. Notably, the level of weed control and consistency of efficacy has increased compared to “traditional” soil-applied herbicides (Duke 2005). Furthermore, given that genetically modified herbicide-resistant crops are represented largely by resistance to glyphosate and to a lesser amount glufosinate, and given that these herbicides are used post-emergence to the weeds and have generally favorable edaphic and toxicological characteristics, there are likely significant positive environmental benefits. Another important environmental benefit attributable to these crops is the adoption of conservation tillage practices including no tillage production systems which result in important reductions of soil erosion, thus improving water quality and lessening the degradation of soil (Young 2006). The benefits that growers attribute to genetically modified herbicide-resistant crops reflect the perceived simplicity and convenience of weed control (Owen 2008a, b). However, an objective review of the implications of genetically modified herbicide-resistant would suggest that there are important risks that must also be considered.

9.1.4.1 Selection Pressure Indirectly Attributable to Genetically Modified Herbicide-Resistant Crops

The consistent and widespread use of one herbicide has considerable implications on the weed community (Owen 2008a, b). Differential response of weed species to the herbicide results in some weeds that are ecologically favored in the system.

The recurrent use of a specific herbicide with a high level of efficacy on the sensitive weeds results in weeds that are favored by the system and thus become the dominant members of the weed community (Scursoni et al. 2006; Scursoni et al. 2007). For example, Asiatic dayflower (*Commelina cumminus*) is known to be tolerant to glyphosate and has become an increasing problem in genetically modified glyphosate-resistant crops (Ulloa and Owen 2009). The other aspect of selection pressure is the shift in a weed species that is predominantly sensitive to the herbicide to a biotype that has a mutation conferring resistance to the herbicide (Owen 2008a, b). Regardless of the ultimate type of weed shift, the greater the selection pressure that the herbicide imparts upon the agroecosystem, the more pervasive the change in the weed community; it should be recognized that it is not a matter of "if" the change in the weed community occurs but rather "when" the change is identified. Selection pressure from herbicides used in agriculture will inevitably result in changes in weed communities (Owen and Zelaya 2005).

9.1.4.2 Evolved Herbicide Resistance

The evolution of herbicide resistance predates the adoption of genetically modified herbicide-resistant crops by almost four decades (Ryan 1970; Duke 2005). Resistance to 19 herbicide mechanisms of action has been documented globally, with evolved resistance to ALS inhibitors, triazines, ACCase inhibitors, synthetic auxins, bypyridiliums, ureas and amides, glycines and dinitroaniline herbicides being the most prevalent. Interestingly, some weeds demonstrate the ability to evolve resistance to multiple mechanisms of herbicide action (Preston et al. 1996; Patzoldt et al. 2005). Rigid ryegrass (*Lolium rigidum*) biotypes have been documented to resist as many as seven mechanisms of herbicide action (Heap 2009). Furthermore, a number of weed species have demonstrated the ability to evolve cross-resistance to different herbicide families with similar mechanisms of action (Hinz and Owen 1997). Despite the fact that the mutations that confer resistance to herbicides typically occur at extremely low frequencies within non-selected weed populations, resistance to any and all herbicides can evolve given the current management of weeds in most crop production systems and the strategies of resistance that weeds have demonstrated (Gressel 1996; Gressel and Levy 2006).

9.1.4.3 Changes in Herbicide Use

One of the pervasive questions surrounding the adoption of genetically modified herbicide-resistant crops is the impact on herbicide use. It is well documented that, initially, the number of active herbicide ingredients used in genetically modified herbicide-resistant crops declined dramatically (Young 2006; Bonny 2007). However, whether or not the herbicide load on the environment was lessened in genetically modified herbicide-resistant crops depends on the measurement metric. It is argued that, with the genetically modified herbicide-resistant crops, fewer applications of herbicides are required and thus less herbicide is used. However, given that the herbicides used on genetically modified herbicide-resistant crops are used at amounts that are many-folds higher than the herbicides that were replaced, it is argued that more herbicide is used compared to conventional crops (Benbrook 2001). Furthermore, the number of herbicide applications in genetically modified herbicide-resistant crops has increased steadily since the introduction of these crops (Young 2006).

9.1.4.4 Lack of Integrated Weed Management

The primary benefits of the genetically modified herbicide-resistant crops, as stated by growers, is the convenience and simplicity of weed control (Bonny 2007; Owen 2008a, b). This has contributed to the dramatic decline in alternative tactics used to manage weeds and thus a loss of integrated weed management in genetically modified herbicide-resistant crops. The loss of integrated weed management then results in weed shifts in the genetically modified crops which negatively impacts crop production economics and has important long-term implications on the sustainability of cropping systems based on genetically modified herbicide-resistant crops (Owen and Boerboom 2004; Sammons et al. 2007; Owen 2008a, b).

9.2 Specific Crops with Herbicide Resistance

Currently there are six crops that have genetically modified herbicide-resistant cultivars. The genetically modified herbicide-resistant crops that are most widely planted include canola, cotton, maize and soybean (see also Chaps. 21, 15, 18, 24). Genetically modified herbicide-resistant sugarbeets were commercially released in 2008 and the adoption rate was reported to be exceptionally high. Genetically modified glyphosate-resistant alfalfa is also available but further commercial use is currently under review. Other important crops such as wheat, rice and turf do not have genetically modified herbicide-resistant cultivars. A short summary of the genetically modified herbicide-resistant crops follows.

9.2.1 Maize

Corn cultivars with resistance to herbicides include genetically modified transgenic (glyphosate and glufosinate) and non-transgenic (sethoxydim and imidazolinone) hybrids. Imidazolinone-resistant hybrids were introduced in 1993, sethoxydim-resistant hybrids in 1996, transgenic glyphosate-resistant hybrids in 1997 and transgenic glufosinate-resistant hybrids in 1998 (Dill 2005). Genetically modified glyphosate resistance in maize is the result of either the *cp4* transgene that codes for an altered EPSPS that does not allow binding of glyphosate, or *N*-acetylation of glyphosate resulting in the non-herbicidal metabolite *N*-acetyl glyphosate (Padgette et al. 1995; Castle et al. 2004). Recently, maize cultivars with an *hra* transgene that confers 1000-fold cross-resistance to ALS-inhibiting herbicides was introduced (Green et al. 2009). The adoption of transgenic herbicide-resistant corn hybrids appears to be ever increasing (Owen and Zelaya 2005; Dill et al. 2008).

9.2.2 Soybean

Genetically modified herbicide-resistant soybean became commercially available in the US in 1996. The cultivars utilize the *cp4* transgene from *Agrobacterium* sp. that codes for a glyphosate-resistant form of EPSPS. Soybean cultivars with glyphosate resistance represent more than 90% of soybean planted in the US (Duke and Powles 2008). Soybean cultivars possessing the *bar trans*gene from *Streptomyces hygroscopicus* thus conferring resistance to glufosinate have been developed and are now commercially available (Green 2009). A newly-reported mechanism, *N*-acetylation of glyphosate, provides considerable resistance to glyphosate and is currently under development in soybean (Siehl et al. 2005).

9.2.3 Cotton

Cotton resistance to glyphosate was originally due to the *cp4 epsps* transgene and grower adoption of the genetically modified glyphosate-resistant cultivars has been rapid since their introduction in 1997 (Cerdeira and Duke 2006). However, there were problems with the transgene expression in reproductive structures which resulted in the development of cultivars with two *cp4 epsps* transgenes and various promoters to provide better expression of resistance later in the development of the plants (CaJacob et al. 2007; Dill et al. 2008). Cotton with transgenic resistance to bromoxynil was introduced in the US in 1994, and glufosinate-resistant cultivars were introduced in 2003 (Duke 2005).

9.2.4 Canola

Genetically modified herbicide-resistant canola was introduced commercially in Canada in 1995 and approximately 80% of the herbicide-resistant canola is transgenic, primarily to glyphosate, which is much higher than the global percentage (ca. 20%; James 2008). Transgenic glyphosate-resistant canola contains the transgene that code for the mutant *cp4 epsps* but also has a transgene that codes for glyphosate oxidoreductase (GOX; Duke 2005). The other transgenic herbicide-resistant canola is resistant to glufosinate and contains the *bar* transgene that facilitates the acylation of glufosinate to herbicidally inactive metabolites (Lydon and Duke 1999).

9.2.5 Sugarbeets

While there has been regulatory approval for transgenic glyphosate-resistant sugarbeets since 1998, cultivars were only recently commercially introduced. The transgenic resistance to glyphosate in sugarbeet is attributable to the mutant *cp4 epsps* transgene. It should be noted that sugarbeet weed management practices historically have been more intensive than with many other crops. Thus, given the expected intensity of herbicide selection pressure that would result from the adoption of genetically modified glyphosate-resistant sugarbeet cultivars, it is likely that weed population shifts and evolved glyphosate resistance in weed populations will rapidly ensue (Owen and Zelaya 2005).

9.2.6 Turf

Genetically modified glyphosate-resistant creeping bentgrass was developed (event ASR368) and field trials were established in Jefferson County, Oregon, in 2003 under a permit granted by USDA-APHIS (Anonymous 2002). Independent studies demonstrated pollen-mediated transgene flow, resulting in wild plant populations expressing the transgenic glyphosate-resistant trait (Reichman et al. 2006; Mallory-Smith and Zapiola 2008). Consequently, further production of genetically modified glyphosate-resistant creeping bentgrass was stopped (Charles 2007).

9.2.7 Alfalfa

Genetically modified glyphosate-resistant alfalfa cultivars were deregulated and subsequently commercialized in 2005 in the US. However, alfalfa is an open-pollinated crop and pollination is accomplished by bees which can travel considerable distances with viable pollen. Thus, contamination in non-transgenic alfalfa seed was expected. In 2007, a preliminary injunction order was issued indicating that USDA-APHIS had erred when the GLY-HR alfalfa was deregulated (US District Court for the Northern District of California, No. C 06-01075 CRB), halting seed sales and planting after 30 March 2007 (Fisher 2007; Harriman 2007).

9.2.8 Rice

Genetically modified glufosinate-resistant rice was initially developed to manage weedy red rice (*Oryza sativa* L.; Gealy and Dilday 1997). However, given marketing issues, no genetically modified herbicide-resistant rice cultivars have been commercially released (rice is also covered in Chap. 22).

9.2.9 Wheat

There are no genetically modified herbicide-resistant wheat cultivars (see also Chap. 16). The program to develop transgenic glyphosate-resistant wheat cultivars was terminated in May 2004 (Dill 2005).

9.3 Implications of Genetically Modified Herbicide Resistance on Cropping Systems

Given the unprecedented global adoption of transgenic herbicide-resistant crops, it is important to consider the undeniable impact that these crops have on the respective cropping systems, pesticide use, biodiversity and ultimately the environment. Given the scope of this chapter, an in-depth review of these topics is not possible; however this should not minimize the importance of this global revolution and the impacts that have occurred. Consider that the range of topics includes the potential movement of transgenic traits to non-transgenic crops or near-relative plants, the potential for genetically modified herbicide-resistant crops to affect the soil biota and selection of best adapted species (Ammann 2005; Cattaneo, Yafuso et al. 2006; Gressel and Levy 2006; Abud et al. 2007; Pineyro-Nelson et al. 2009; Powell et al. 2009). An excellent overall review of genetically modified herbicide-resistant crop impact on the environment was published by Cerdeira and Duke (2006) and should be considered if detailed information is required. The topics addressed below include the implications of genetically modified herbicide-resistant crops on tillage, the diversity of weed management tactics and the timeliness of the implementation of these tactics.

9.3.1 Tillage

The cost of petrochemicals has reinforced the desirability of fewer tillage trips in the production of crops as well as the benefits attributable to improved time management. Based on these perceived and real benefits, crop production in no tillage and other conservation tillage systems increased dramatically because of genetically modified herbicide-resistant crops (Cerdeira and Duke 2006; Service 2007; Dill et al. 2008). No tillage or strip tillage cotton production increased almost threefold between 1997 and 2002 (Anonymous 2004). However, more recent data suggest that conventional tillage has returned as the dominant tillage practice in genetically modified glyphosate-resistant cotton because of important changes in weed populations (Mueller et al. 2005; Dill et al. 2008). Dramatic increases in no tillage and conservation tillage systems for maize and soybean production systems are also noted and largely attributable to genetically modified herbicide-resistant crop cultivars (Duke 2005; Gianessi 2005; Young 2006; Dill et al. 2008). The reductions in tillage result in significant economic and time savings for growers, as well as reductions in equipment expenses (Gianessi 2005; Gianessi and Reigner 2007).

An important consideration of greater percentages of genetically modified herbicide-resistant crops produced under conservation tillage was the environmental savings from reduced soil erosion (Fawcett and Towery 2004; Gianessi 2005). Wind erosion of soil was reduced 31% and water soil erosion was reduced 30% in 1997 compared to 1982 because of the conservation tillage practices adopted in the production of transgenic herbicide-resistant crop cultivars (Fawcett and Towery 2004).

9.3.2 Diversity of Weed Management Tactics

There has been a significant decline in the use of alternative herbicides and this trend is largely attributable to the global adoption of genetically modified herbicide-resistant crops (Shaner 2000; Young 2006). Historically important herbicides have been replaced by the predominant use of glyphosate, often as the sole herbicide and weed management tactic; the lack of herbicide diversity has created an environment where changes in weed communities are inevitable. Furthermore, the size of farm has increased and the use of glyphosate for weed control provides the perception of better time utilization (Owen and Zelaya 2005). Thus the perception of simple and convenient weed management have dramatic impacts on the continued utility of glyphosate as weed populations adapt to the pervasive selection pressure imposed by the weed management system. While the lack of diversity of weed management tactics may not necessarily eliminate the use of glyphosate, it does provide a strong impetus for the development of improved weed management tactics and the adoption of a greater diversity of tactics (Green 2007).

Consider that crop rotation, while historically a strong weed management tactic, has become significantly less important given the typical crop rotations that include crops that are genetically modified and resistant to the same herbicide (Owen 2009). Furthermore, mechanical weed management has lessened in importance because of conservation tillage systems that are typically used for genetically modified herbicide-resistant crops.

Importantly, the development of new herbicide products and specifically research for new sites of herbicide action has slowed significantly (Green 2007; Green et al. 2008). It is possible that a higher glyphosate price could result in the use of alternative (older) herbicides and a greater diversity of weed management tactics. However, the desirability of weed management based on the perception of a simple and convenient weed management tactic will likely continue to slow growers from adopting a more diverse weed management system.

9.3.3 Timelines of Weed Management Tactics

The development of genetically modified herbicide-resistant crops, particularly those cultivars that are resistant to glyphosate has resulted in major changes in herbicide application timing (Young 2006). While historically soil-applied herbicides that provided residual control of weeds were the foundation of weed control, glyphosate applied post-emergence to weeds and crops has largely replaced the use of other herbicides. Glyphosate controls a large number of weeds, almost irrespective of weed size and environmental conditions (Sammons et al. 2007). Furthermore, growers perceive that genetically modified glyphosate-resistant crops and glyphosate provide an effective, consistent, simple and low-risk “system” for crop production with less tillage (Carpenter and Gianessi 1999; Service 2007). Thus, growers apply glyphosate almost without regard to timing (weed or crop stage of development) and presume that if the weeds have died, the tactic was successful (Owen 2007). Unfortunately, this perception of simplicity and convenience is misleading and results in significant losses of potential yield due to weed interference with the crop (Owen 2008a, b; Owen et al. 2009). Glyphosate is frequently sprayed after weeds have effectively competed with the genetically modified glyphosate-resistant crops and significant yield has been lost despite the effective “killing” of the weeds.

9.4 Herbicide-Resistant Weeds

Globally, new herbicide-resistant populations continue to evolve at an increasing rate. This situation has become more apparent with the evolution of weeds that are resistant to glyphosate (Powles 2008). It is difficult if not impossible to gain an accurate view of the current status of herbicide-resistant weeds. The most widely utilized and consistent source of information about the global status describing herbicide-resistant weeds is the *International Survey of Herbicide-resistant Weeds* (www.weedscience.org; Heap 2009). The current tally of herbicide-resistant weeds includes 332 resistant biotypes represented by 189 species of which 113 are dicots and 76 are monocots. These weeds are reported on over 300 000 fields. However, this website requires that reports of new herbicide-resistant weed populations are frequent and accurate. Unfortunately, weed scientists must volunteer these reports and often only individual fields are reported, which may not accurately represent the extent of the herbicide-resistant weed infestations. Regardless, it is clear that weeds are capable of evolving resistance to all herbicides, although there are several classes of herbicides for which resistant weed populations have yet to be discovered. Currently 102 weed species are resistant to ALS inhibitor herbicides, followed by 68 weed species that are resistant to PS II herbicides and 36 weeds species that have evolved resistance to ACCase inhibitor herbicides (Heap 2009). Synthetic auxin herbicides have 28 resistant weed species, 24 weed species are resistant to the bypyridiliums herbicides, 21 species are resistant to the urea herbicides, 16 weed species have evolved resistance to glyphosate and 10 species are resistant to DNA herbicides.

As long as herbicides remain the primary if not sole tactic for weed control, weed populations will receive sufficient selection pressure to force the evolution of herbicide-resistant weed biotypes. Specifically with regard to genetically modified-herbicide resistant crops, the industry originally denied the possibility of evolved resistance to glyphosate, despite suggestions that resistance was inevitable (Gressel 1996; Bradshaw et al. 1997; Owen 2000; Zelaya and Owen 2000). Regardless of how the situation surrounding glyphosate and weed resistance was debated, there can now be no question that changes in weed populations are occurring more rapidly and are widely distributed across a number of crop production systems, despite apparent knowledge that growers have about the situation (Johnson et al. 2009; Kruger et al. 2009). Currently there are 16 weeds reported and confirmed to have evolved resistance to glyphosate (Heap 2009). In the US, nine species have been confirmed glyphosate-resistant and generally the resistance has evolved in conjunction with genetically modified glyphosate-resistant crops. Currently seven new species of glyphosate-resistant weeds have been confirmed in the US since 2004 and it is clear that the evolution of glyphosate-resistant weed species in genetically modified glyphosate-resistant crops is increasing at an increasing rate (Owen 2008a, b). Weeds in the Compositae family are represented by four species that have confirmed evolution to glyphosate and the Amaranthaceae has two species. Populations of *Xanthium strumarium*, *Chenopodium album* and *Kochia scoparia* are currently suspected to have resistance to glyphosate but have not yet been confirmed (Boerboom 2008).

9.4.1 Weedy Near-Relatives to Genetically Modified Herbicide-Resistant Crops – Gene Flow

There is considerable concern about the potential of gene flow from crops to weeds now that there are genetically modified traits included in many globally important food crops. One issue is the fear of the general public about transgenes and also the potential of increasing the prevalence of pernicious and highly invasive new weed species. Another consideration is the potential impact that transgenes may have on the genetic diversity of food crops such as maize in Mexico and soybean in China, particularly land races and wild progenitors (Gepts and Papa 2003; Lu 2004; Raven 2005). Importantly, for gene flow between crops and weeds to occur, a near-relative wild plant must co-exist spatially and temporally with the genetically modified herbicide-resistant crop. The requirement of weedy near-relatives to be available to receive the transgenic pollen makes some crops less of a risk than others. For example, soybean and maize do not have weedy near-relatives within the major production regions, while sunflower and wheat should be considered higher risk when genetically modified cultivars are available. Obviously, crops that do not have genetically modified cultivars present no risk for transgene introgression into near-relative weeds.

Genetically modified herbicide-resistant traits generally do not affect the relative fitness of compatible weed populations and thus have little influence unless the herbicide is present. The best example of transgene movement between genetically modified herbicide-resistant crops and weedy near-relatives is genetically modified canola and the weedy Brassicaceae. Reports indicate that the transgene moves from the genetically modified crop and weedy near-relatives, but there is little effect on fitness (Hauser et al. 2003; Legere 2005). However as new genetically modified herbicide-resistant crops are released that have weedy near-relatives (e.g. *Beta vulgaris*), the lack of direct effect on weeds from transgene movement may change.

9.4.2 Implications of Herbicide Resistance – Persistence in the Agroecosystem

The persistence of herbicide resistance in weed populations reflects the longevity of the seedbank and the relative percentage of the seedbank that contains the trait for resistance. It should be noted that seeds from genetically modified herbicide-resistant crops can also contribute to the seed bank and thus the herbicide resistance problem. However, with few exceptions (e.g. canola) the persistence of volunteer genetically modified herbicide-resistant crops is minimal, given that crop seeds generally do not last very long in the seedbank. Thus herbicide resistance attributable to volunteer genetically modified herbicide-resistant crops has a minimal effect on the seedbank. Canola, however, has demonstrated the capability to persistence in the soil seedbank and may be a factor for several years (Legere 2005).

Generally, herbicide resistance attributable to a weed population shift such that the dominant biotype is resistant will require a number of years to increase in the seedbank (Maxwell and Jasieniuk 2000). However, once established, the herbicide-resistant biotype will persist for many years, depending on the environmental conditions, the weed species and effectiveness of management tactics imposed upon the weed population. If marginal weed management (i.e. attributable to utilization of recurrent single herbicide tactics) is imparted on the weed population, the soil seedbank increases rapidly (Bauer and Mortensen 1992). If the weed species has seeds that are long-lived in the soil (e.g. *Abutilon theophrasti*) and herbicide resistance has evolved, the problem is likely to persist indefinitely regardless of the effectiveness of subsequent management tactics. If the weed species has seeds that are less persistent in the seedbank (e.g. *Amaranthus rudis*), effective management tactics can reduce the herbicide-resistant weed population relatively quickly (Steckel et al. 2007). However, it is important to consider that other production practices can also impact the seedbank and hence the persistence of herbicide resistance in the agroecosystem. For example, tillage can increase the longevity of the weed seedbank by burying seeds and placing them in a position where they remain viable for a number of years. Thus, unless extraordinary weed management tactics are used subsequent to the establishment of a herbicide-resistant weed seedbank, it is likely that herbicide resistance will persist in the agroecosystem.

9.5 Conclusions

There is no question that the adoption of genetically modified herbicide-resistant crops represents the most important global revolution in agriculture. In 2007, genetically modified herbicide-resistant cultivars were planted on an estimated 114.3 million hectares and included 23 countries (Anonymous 2006). The trend of basing crop-production systems on genetically modified herbicide-resistant crops continues to escalate, in particular with maize. Fortunately, there is little evidence that many of the current genetically modified herbicide-resistant crops have impacted weed communities directly. This is attributable to the fact that there are no weedy near-relatives of the transgenic crops in the areas of major production. The exception to that is genetically modified herbicide-resistant canola (Legere 2005). However with the introduction of new genetically modified herbicide-resistant crops, there could be more exceptions in the future (e.g. sugarbeets).

While there is no direct impact of genetically modified herbicide-resistant crops on weed communities, there is a significant indirect impact; the recurrent use of the herbicide (i.e. glyphosate) for which transgenic resistance exists imposes significant selection pressure on weed populations and evolved resistance to glyphosate is increasing at an increasing rate. Please recognize that this selection process is no different than with any other herbicide and reflects the weed management strategy utilized by growers. Interestingly, as more resistance in weed populations to the herbicides used in transgenic crops develops, growers will be forced to return to older herbicides for which resistant weed populations have previously evolved (Owen 2008a, b).

While target site resistance has historically been the primary type of herbicide resistance that has evolved in weed populations, the weed populations that have evolved resistance to glyphosate often have less well understood mechanisms of resistance. In fact, it appears that there are multiple mechanisms of resistance to glyphosate and these mechanisms are subtle and difficult to identify (Gressel 1996; Feng et al. 2004). It is also concerning that many of the weeds that have evolved herbicide resistance demonstrate the ability to evolve resistance to other herbicide mechanisms of action, thus further complicating management tactics.

Perhaps the greatest concerns with regard to genetically modified herbicide-resistant crops and evolved herbicide resistance in weeds are the grower attitudes about the importance of herbicide resistance and diverse management strategies (Johnson et al. 2009; Kruger et al. 2009). It is clear that, while growers recognize the risk of evolved herbicide resistance in weed populations, they choose not to implement proactive management tactics and then strive for remediation after the problem(s) develop. Succinctly, genetically modified herbicide-resistant crops have facilitated an attitude in adopters to neglect the appropriate use of integrated weed management tactics and thus will exacerbate future problems with herbicide resistant weeds (Boerboom et al. 2009; Owen et al. 2009).

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