In: Weed and Pest Control
Editors: I. S. Travlos, D. Bilalis and D. Chachalis
ISBN: 978-1-63484-100-9

Chapter 5

GLYPHOSATE-RESISTANT VOLUNTEER MAIZE (*ZEA MAYS* L.): IMPACT AND MANAGEMENT

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ABSTRACT

The United States is the largest producer of maize in the world. Maize-soybean is the most prominent crop rotation in the Midwestern United States. Glyphosate-resistant volunteer maize is a problem weed not only in soybean, but also in continuous maize or sugarbeet rotations. Storm damage, harvesting problems, poor stalk quality, and insect damage, among other factors, can lead to kernel and ear losses that result in volunteer maize the following year. Volunteer maize results from the overwintering of the hybrid maize used the previous year or from failed maize stand in maize replant situation. Increased adoption of glyphosate-resistant maize resulted in increasing issues of volunteer maize. Volunteer maize also plays a role in the survival and dispersal of corn rootworm and gray leaf spot disease; therefore, it limits the benefits of maize-soybean rotation and creates challenges for insect-resistance management. Management of glyphosate-resistant volunteer maize in soybean is complicated because growers are primarily relying on glyphosate for weed control. The acetyl-coenzyme A carboxylase (ACCase) inhibiting-herbicides, also known as graminicides, are often used to control volunteer maize in soybean. Several pre-emergence herbicides exist for residual grass weed control in soybean; however, none of them provides acceptable control of volunteer

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maize. Glufosinate is an alternate herbicide that can be applied alone or in combination with ACCase inhibitors for control of glyphosate-resistant volunteer maize in glufosinate-resistant soybean. The commercialization of multiple herbicide-resistant maize hybrids may pose new challenges for management of volunteer maize.

Keywords: corn rootworm, crop rotation, integrated weed management, volunteer maize control

INTRODUCTION

Maize (*Zea mays* L.) is an annual, monoecious plant belonging to the grass family Poaceae, with each plant exhibiting both male and female reproductive parts (Kiesselbach, 1999). It has a C_4 pathway of photosynthesis; therefore, uses water and carbon dioxide more efficiently. Maize is among the most important cereals after wheat (*Triticum aestivum* L.) and rice (*Oryza sativa* L.), and is raised in several countries across the globe. Maize is commonly used for human consumption, as fuel, and as livestock feed (Farnham et al. 2003; Windham and Edwards, 1999). In addition, maize also has wide industrial applications. For example, maize oil is used in margarine, maize syrup solids are used in instant non-dairy coffee creamer, and maize syrup sweeteners are used in marmalade. As of 2015, the USA is the largest producer of maize in the world followed by China, Brazil, India, Mexico, and Argentina. In addition, the USA is the world's largest exporter of maize with approximately 20% of its harvest exported to several countries (USDA, 2014). The area of maize planted in the USA has increased from approximately 29.7 million hectares in 1990 to 36.4 million hectares in 2014 (USDA, 2014) (Figure 1). Though herbicide-resistant (HR) maize hybrids were commercialized in the USA in 1998, they were not rapidly adopted by growers (USDA-NASS, 2014). The widescale adoption of HR maize hybrids occurred with the industrial practice of inserting the *Bacillus thuringiensis* (*Bt*) trait to manage insect pests along with herbicide-resistant (HR) traits in the same hybrid (Marquardt and Johnson, 2013). The adoption of maize varieties with stacked trait has accelerated in the last few years and in 2014, 76% of the maize planted in the USA was stacked resistant (USDA, 2014).

VOLUNTEER MAIZE

Volunteer maize results from the leftover seeds or ears of hybrid maize planted and harvested the previous year (Figure 3), or from a failed maize stand during a maize replant situation (Steckel et al. 2009; Shauck and Smeda, 2012). Many factors including storm damage, harvesting problems, poor stalk quality, and insect damage can lead to kernel and ear losses, resulting in volunteer maize the following year. Most volunteer maize seeds in northern latitudes overwinter and germinate the following spring; while in warmer climates, seeds germinate soon after maize harvest.

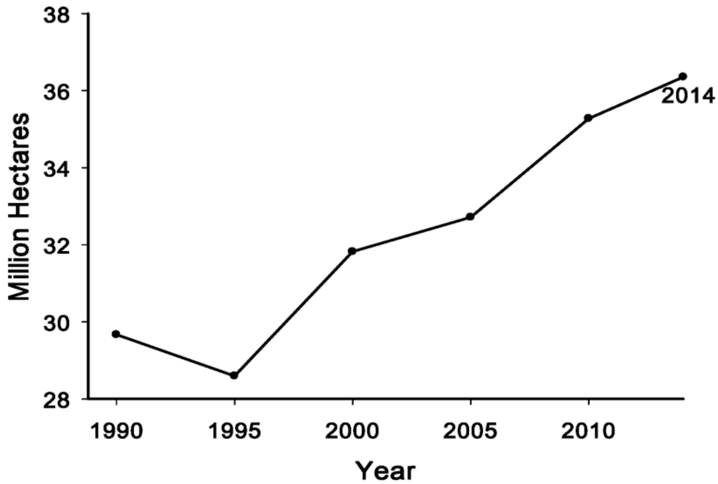

Figure 1. Total maize acreage planted (million hectares) in the USA, 1990-2014.

The use of glyphosate in rope-wick applicators for volunteer maize control in soybean was documented even before the commercialization of glyphosate-resistant crops (Andersen et al. 1982; Beckett and Stroller, 1988; Dale, 1981). However, the commercialization and wide adoption of glyphosate-resistant maize hybrids has raised issues of glyphosate-resistant volunteer maize interference in glyphosate-resistant soybean grown in rotation (Marquardt et al. 2013). The volunteer maize hybrids being glyphosate resistant cannot be controlled with glyphosate, the most commonly used herbicide in glyphosate-resistant soybean (Krupke et al. 2009). In addition, no-till and conservation tillage practices have gained popularity as growers can maintain profitable crop production while reducing labor and fuel inputs as well as soil erosion (Brown et al. 1989; Griffith et al. 1986; Hairston et al. 1984). However, weed control under no-till production systems primarily depends on herbicides (Buhler, 1988; Coffman and Frank, 1991; Koskinen and McWhorter, 1986). The adoption of no-till maize-soybean systems has favored the survival of volunteer maize as maize seeds are left on the soil surface or at shallow depths, unlike in a conventional tillage system where seeds are buried at deeper depths (Steckel et al. 2009).

IMPACT OF VOLUNTEER MAIZE ON CORN ROOTWORMS

Shaw et al. (1978) documented that volunteer maize in soybean has the potential to attract adult western (*Diabrotica virgifera virgifera* LeConte) and northern corn rootworms (*Diabrotica barberi* Smith and Lawrence) that feed and lay eggs near volunteer maize plants in soybean, particularly if the maize survives to the reproductive stages, when it is most attractive to adult rootworms (Meinke et al. 2009). Volunteer maize populations of less than 12,500 plants ha^{-1} did not result in economic damage from rootworms in maize planted the following year, but one field with over 32,500 volunteer maize plants ha^{-1} had significant economic damage from rootworms in the following year (Shaw et al. 1978). Many extension entomologists (e.g., Univ. of Illinois IPM Program 1998) have used a nominal threshold of 12,500 volunteer maize plants ha^{-1} alive in August (presumably then in the reproductive stages) as a threshold that might result economic damage from rootworm egg-laying if maize is planted the following year. To our knowledge, there is no published research that would allow the estimation of an economic rootworm injury level due to volunteer maize presence in soybeans, assuming that maize will be planted in the same field the following year.

With the commercialization of *Bt* maize hybrids with one or more Cry proteins against corn rootworm larvae (*Bt* rootworm maize), an additional concern arises from the presence of volunteer maize. Krupke et al. (2009) documented that volunteer maize resulting from a *Bt* rootworm maize hybrid planted the previous year had detectable levels of the Cry 3Bb1 *Bt* toxin, responsible for rootworm control in the MON88017 event from Monsanto. Additionally, Krupke et al. (2009) observed significant feeding damage to the volunteer maize, suggesting that the volunteer maize is expressing a reduced level of *Bt* protein compared to its MON88017 hybrid parent. This implies that volunteer maize may select for resistance to rootworm larvae that are capable of surviving on a lower sub-lethal *Bt* toxin level.

IMPACT OF VOLUNTEER MAIZE ON DISEASES

Volunteer maize growing in other crops is vulnerable to the same pathogens that infect cultivated maize during other years in those fields. Most of those plant pathogens are either soilborne or survive in the infected crop debris from the previous season(s) and could be perpetuated by volunteer maize. Volunteer maize could potentially increase the pathogen inoculum and disease potential in subsequent maize crops. Unfortunately, little to no research results are available to help us better understand the disease risks caused by volunteer maize, as scientists are only now beginning to speculate on its potential importance. Most plant pathogens fall into one of four major kingdoms of organisms: fungi, bacteria, nematodes, and viruses. The overwinter survival and location of these organisms (or their vectors) could be impacted by volunteer maize and could exacerbate disease in future maize crops if volunteer maize plants become infected.

Some of the most economically important diseases of maize are caused by fungi and bacteria that overwinter between growing seasons in the infected residue from previous crops. Volunteer maize has the potential to provide host plant tissue for reproduction of certain pathogens and more opportunities for them to overwinter and survive. Some of the most common examples of maize diseases caused by pathogens that overwinter in crop residue are Goss's bacterial wilt and blight (*Clavibacter michiganensis* subsp. *nebraskensis*), northern corn leaf blight (caused by the fungus, *Exserohilum turcicum*), and gray leaf spot (caused by the fungus *Cercospora zeae-maydis*), any of which and more could potentially be worsened with volunteer maize that becomes infected. Research results on diseases from other crops has implicated volunteer plants as important inoculum sources. For instance, Gent et al. (2005) reported volunteer onion plants infected with *Xanthomonas axonopodis* pv. *allii*, causal agent of *Xanthomonas* leaf blight in onions. They also showed that the volunteer onion plants were consistently a source of the pathogen for early disease development in nearby onion fields.

It has been demonstrated in other crops, such as wheat, that virus vectors can utilize volunteer plants from previous crops to travel to current crop fields and cause disease outbreaks (Seifers et al. 1997). Any of several diseases caused by viruses that occur in maize could be impacted by volunteer maize, such as maize dwarf mosaic, wheat streak mosaic, and maize chlorotic mottle. These and most other virus diseases are vectored by insect or other arthropod vectors that could take advantage of volunteer maize for survival or to acquire the virus particles for transmission to other plants (Louie, 1999).

There are many additional diseases that are caused by pathogens that are found in the soil. Many of these diseases are less conspicuous and more difficult to both diagnose and manage. The more common soilborne pathogens are fungi, nematodes, and bacteria. Although most of these pathogens are well adapted to survive in the absence of a host, such as during crop rotation with non-hosts, there has been some evidence that some of them could be exacerbated by volunteer plants. Crop rotation is used as a common management strategy for control of plant parasitic nematodes. Although the effects of volunteer maize haven't been studied for their impacts on nematodes that parasitize maize, there is evidence that volunteer corn in wheat supported nematodes. Results from the research conducted by Smiley et al. (2004) showed that root-lesion nematode (*Pratylenchus* spp.) population densities in volunteer cereal seedlings and grass weeds were similar to those in the planted cereal crops. Likewise, the volunteer wheat in winter wheat/summer fallow rotations supported root-lesion nematode (*Pratylenchus* spp.) population densities that were as high as those in the annual wheat rotation eliminating the value of the fallow in the rotation. Root-lesion nematodes are a common pathogen in maize and occur worldwide. Similar impacts of volunteer maize could be expected on them and other important nematode pathogens.

Numerous other pathogens have the potential to be impacted by volunteer maize. As the incidence of volunteer maize increases, these and other potential negative effects may become more evident and the subjects of additional research.

IMPACT OF VOLUNTEER MAIZE ON CROP YIELDS

Multiple studies have reported yield loss in crops grown in rotation with maize through direct competition with volunteer maize. For example, volunteer maize present at a density of 0.5 to 4 plants m^{-2} resulted in 1.5 to 13% maize grain yield loss (Jeschke and Doerge, 2008). Volunteer maize at a density of 1 to 1.7 plants m^{-2} caused 19% sucrose yield loss in sugarbeet (*Beta vulgaris* L) (Kniss et al. 2012). Similarly, 4 to 8% cotton (*Gossypium hirsutum* L.) lint yield loss was reported with each 500 g increase in volunteer maize biomass per meter of the crop row (Clewis et al. 2008). A volunteer maize density of 0.4 plants m^{-1} of soybean row length also caused a 14 to 49% yield reduction depending on the location and year (Andersen et al. 1982). Wilson et al. (2010) reported that a volunteer maize density of 8,750 and 17,500 plants ha^{-1} reduced soybean yields by 10 and 27%, respectively.

Clumps of volunteer maize plants cause more soybean yield loss compared to individual plants. Andersen et al. (1982) reported soybean yield reductions from 31 to 83% as volunteer maize clump density increased from 1 to 4 clumps spaced among every 2.4 m of soybean row. In addition to crop yield loss, volunteer maize plants can physically interfere during the harvesting operations of soybean or other crops. Volunteer maize seeds present in the harvested soybeans could result in rejection of the entire lot as strict quality standards are maintained to preserve the quality of food-grade soybeans (Deen et al. 2006). Volunteer maize can further affect crop yield by indirect interference. Under maize-fallow-winter wheat rotation in the west-central Great Plains of the USA, volunteer maize present in the fallow reduced available soil water by 2.54 cm for every 2,500 volunteer maize plants ha^{-1} and resulted in lower wheat yields (Holman et al. 2011).

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GERMINATION ECOLOGY OF VOLUNTEER MAIZE

Germination and emergence are critical stages in weed establishment and persistence in an agro-ecosystem (Bewley and Black, 1994). Several environmental factors, including temperature, light, pH, osmotic stress influence weed seed germination and seedling emergence (Baskin and Baskin, 1998). Similar to glyphosate-resistant hybrid maize, the F_2 generation maize seeds, lost during hybrid maize harvesting and grows as volunteer maize in other crops, germinated over a wide range of alternating day/night temperatures, with optimum germination (84 to 97%) at 15/10 ^{o}C to 42.5/30 ^{o}C (Table 2) (Chahal, 2014). Germination was influenced by hybrid or volunteer maize and the pH of the germination solution (Chahal, 2014). Glyphosate-resistant volunteer maize provided higher (86 to 88%) germination at acidic pH levels (5 to 6) compared to glyphosate-resistant hybrid maize (< 80%), whereas hybrid maize showed higher (> 80%) germination at mild alkaline pH levels (7 to 8) (Table 3).

Table 1. Application rates of acetyl-coenzyme A carboxylase (ACCase) inhibiting-herbicides and adjuvants for control of volunteer maize in soybean

Active ingredient	Volunteer maize size	Application rate (g ai ha^{-1})	Adjuvants*
Quizalofop	0-30 cm	30.6	NIS 0.25% v/v
	30-45 cm	37.0	
	45-76 cm	59.1	
Fluazifop	0-30 cm	69.6	COC 0.25% v/v
	30-60 cm	105.5	
Fluazifop + Fenoxaprop	0-30 cm	89.0	COC 0.25% v/v
	30-60 cm	135.1	NIS 0.25% v/v or COC 0.5% v/v
Sethoxydim	0-30 cm	105.5	AMS 2.8% w/w
Clethodim	0-30 cm	33.7	COC 0.25% v/v + AMS 1.8% w/w
	30-60 cm	51.2	

*AMS, ammonium sulphate; COC, crop oil concentrate; NIS, non-ionic surfactant.

Table 2. Effect of temperature on germination of glyphosate-resistant hybrid and volunteer maize[a]

Temperature (day/night)[a]	Germination[b]
°C	%
12.5/7.5	62 b
15/10	90 ab
20/12.5	92 ab
25/15	97 a
30/20	96 a
37.5/25	92 ab
42.5/30	84 ab
45/35	6 c

Abbreviation: ° C, degree Celsius.

[a]No significant difference in germination between hybrid and volunteer maize; therefore data were combined.

[b]Means within a column with same letter(s) are not significantly different at α = 0.05.

Table 3. Effect of pH on germination of glyphosate-resistant hybrid and volunteer maize at constant day/night temperature of 30/20°C[a]

pH	Germination[b]	
	F_2	Hybrid
	%	
3	47 e	2 F
4	68 cd	5 E
5	88 a	56 D
6	87 a	74 B
7	78 b	84 A
8	74 bc	85 A
9	62 d	66 C

[a]Significant difference was observed for germination between hybrid and volunteer maize; therefore data are presented separately.

[b]Means within a column with same letter (s) are not significantly different at α = 0.05.

Management of Volunteer Maize

Best management approaches to prevent volunteer maize from becoming a pest include selection of good stalk quality maize hybrids, maize hybrids resistant to stalk rots, and proper combine settings to minimize maize seed loss (Jeschke and Doerge, 2008). However, combine harvesters are not efficient enough to completely prevent hybrid maize harvest loss (Figure 3); therefore, volunteer maize will most likely remain a problematic weed in rotational crops. Agronomic practices such as early fall tillage can stimulate the germination and emergence of volunteer maize, thus exposing the emerged seedlings to winter freeze (Jeschke and Doerge, 2008). Spring tillage can be used to control emerged volunteer maize seedlings, but could delay planting of the intended crops and result in yield loss. The application of preplant burndown herbicides can control the emerged volunteer maize plants: for example, in a maize replant situation, glyphosate-resistant maize stand was controlled > 90% by the tank-mixed application of paraquat (70 g ai ha^{-1}) with a PS II inhibitor herbicide, such as atrazine, diuron, metribuzin, or linuron before replant (Steckel et al. 2009). However, late-season emergence of volunteer maize in crops grown in rotation could limit the importance of preplant herbicide applications.

Management of Volunteer Maize in Soybean

Most of the soil-applied or pre-emergence (PRE) herbicides registered in soybean are not very effective for volunteer maize control (Beckett and Stoller, 1988), and provide only partial control (< 80%) (Chahal et al. 2014). Therefore, due to the lack of a selective residual herbicide, control of volunteer maize before emergence may not be possible in soybean. Therefore, the only effective option for controlling glyphosate-resistant volunteer maize in glyphosate-resistant soybean is the post-emergence (POST) application of acetyl-coenzyme A carboxylase (ACCase) inhibiting-herbicides (Beckett and Stoller, 1988; Beckett et al. 1992; Chahal et al. 2014; Deen et al. 2006; Marquardt and Johnson, 2013; Young and Hart, 1997) (Table 1). However, repeated application of ACCase-inhibitors for the last several years has resulted in the evolution of 15 weed species resistant to this herbicide chemistry in the USA (Heap, 2014). To effectively manage in-crop volunteer maize plants in soybean and reduce the potential for the evolution of ACCase-inhibitor-resistant weeds, ACCase-inhibitors should be tank-mixed with other herbicides that can effectively control resistant weeds (Chahal and Jhala, 2015).

Overreliance on glyphosate for weed control in maize and soybean in the last 17 years has resulted in the evolution of glyphosate-resistant weeds (Owen, 2008). By 2014, 29 weed species worldwide had evolved resistance to glyphosate, including 14 species in the USA (Heap, 2014). There is a need to utilize diversified weed control programs for controlling the existing herbicide-resistant weeds (including glyphosate-resistant volunteer maize) and reducing the further evolution of glyphosate- and ACCase-resistant weeds in maize-soybean cropping systems. For example, glufosinate can effectively control glyphosate-resistant volunteer maize in glufosinate-resistant soybean (Chahal and Jhala, 2015). Glufosinate applied in single or sequential applications at different rates provided > 85% control of glyphosate-resistant volunteer maize (Chahal and Jhala, 2015) (Figure 2; Figure 4).

In addition, glufosinate applied in sequential applications can provide ≥ 97% control of large crabgrass [*Digitaria sanguinalis* (L.) Scop.], Palmer amaranth [*Amaranthus palmeri* S. Wats.], sicklepod [*Senna obtusifolia* (L.) H.S. Irwin and Barneby], and smallflower morningglory [*Jacquemontia tamnifolia* (L.) Griseb.] (Aulakh et al. 2011). A greenhouse study reported > 85% control of glyphosate-resistant common waterhemp (*Amaranthus rudis* Sauer) with glufosinate applied at 594 g ai ha^{-1} (Sarangi et al. 2014). A recent survey also reported that cultivation of glufosinate-resistant cotton is increasing in the midsouthern United States, specifically for the control of glyphosate-resistant Palmer amaranth (Aulakh et al. 2012; 2013). However, the reduced activity of glufosinate reported under cooler temperatures and low relative humidity conditions could be a limiting factor for the wide adoption of glufosinate-resistant maize and soybean (Anderson et al. 1993; Kumaratilake and Preston, 2005). Herbicide programs based on a single herbicide or herbicides with the same modes of action favor selection pressure, and if used repeatedly, result in the evolution of herbicide-resistant weeds. As of 2014, three weed species had evolved resistance to glufosinate worldwide (Heap, 2014), including Italian ryegrass (*Lolium perenne* L. ssp. *multiflorum*) in the USA (Avila-Garcia et al. 2012). Therefore, glufosinate should be tank-mixed with herbicides belonging to different modes of action in glufosinate-resistant soybean for broad-spectrum weed control, including volunteer maize, and to reduce the evolution of herbicide-resistant weeds (Johnson et al. 2014).

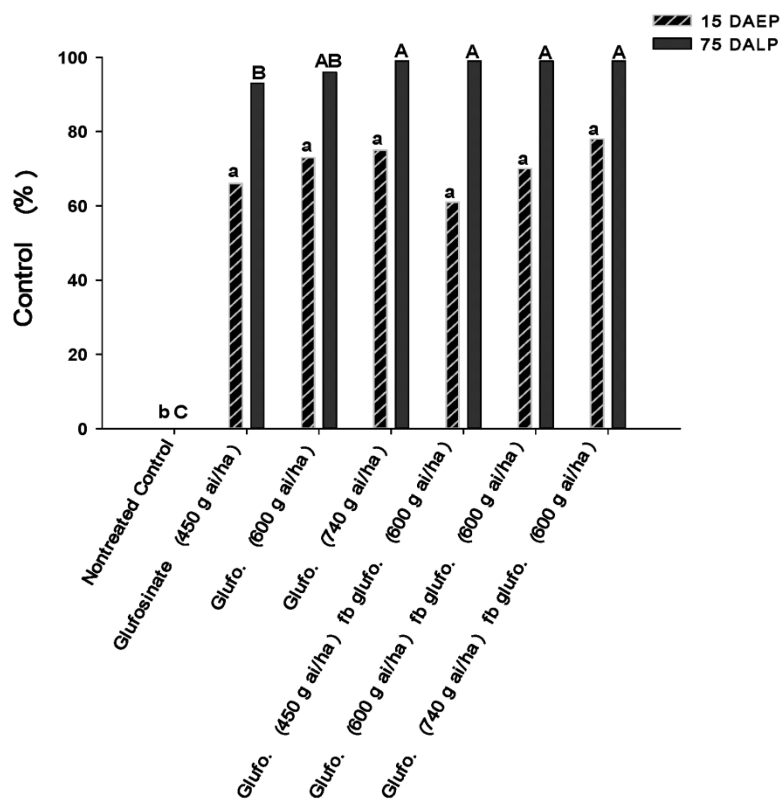

Figure 2. Control of glyphosate-resistant volunteer maize at 15 days after early POST (DAEP), and 75 days after late POST (DALP) application of glufosinate. Glufo. is glufosinate.

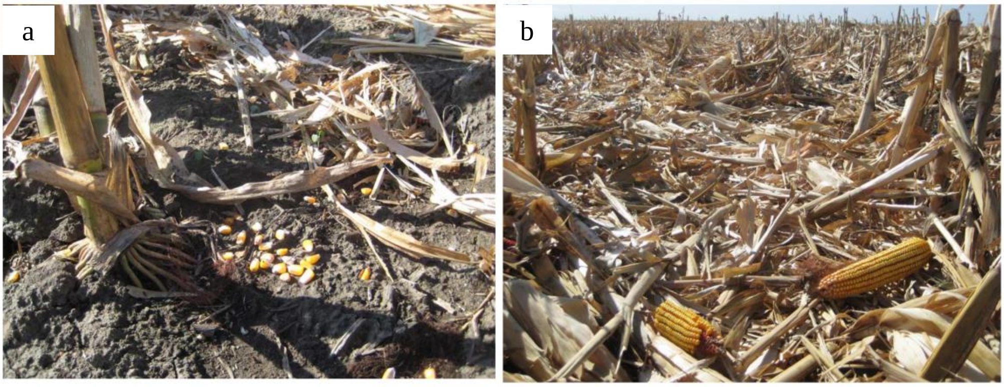

Figure 3. Improperly adjusted combine harvester leads to harvesting losses in maize as a) individual seeds (left) or b) full ears (right).

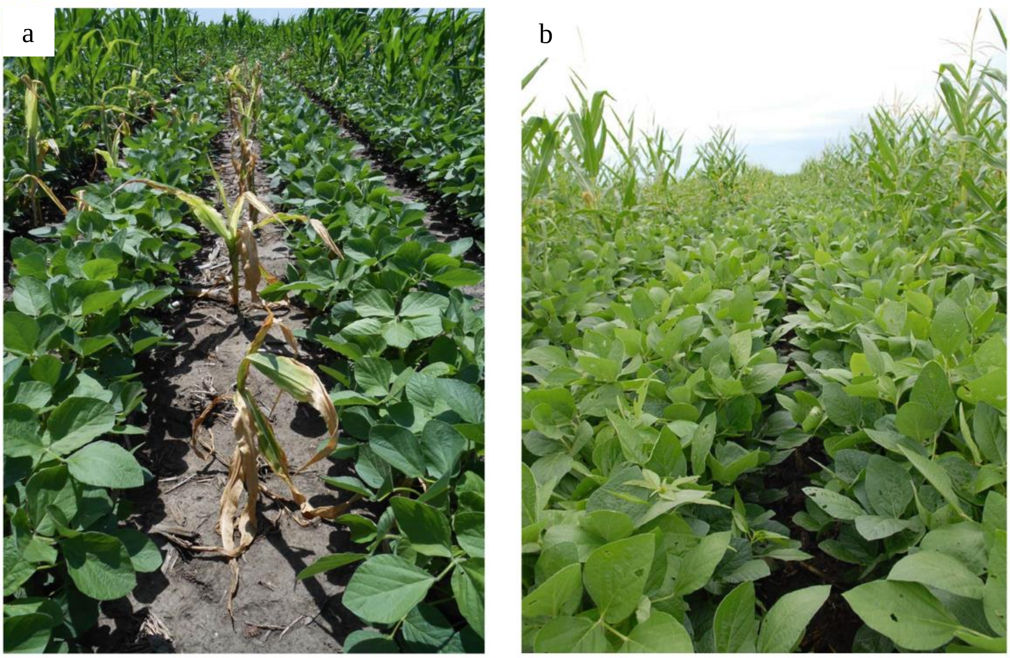

Figure 4. Control of glyphosate-resistant volunteer maize at a) 15 d after early- (left) and b) late-POST application (right) of glufosinate (450 g ai ha^{-1}).

MANAGEMENT OF VOLUNTEER MAIZE IN MAIZE

The presence of volunteer maize in a hybrid maize field is highly likely in continuous (monoculture) maize production systems. In high volunteer maize density situations, soybean could be rotated with maize as soybean has better in-crop herbicide options for volunteer maize control (Jeschke and Doerge, 2008). There are no viable herbicide options for the control of volunteer maize in a maize hybrid field. However, it is possible to control herbicide-resistant volunteer maize by rotating maize hybrids having different herbicide-resistant traits. For example, glyphosate-resistant volunteer maize can be controlled by applying glufosinate in glufosinate-resistant maize the following season (Steckel et al. 2009). The use of inter-row cultivators is another option for the control of established volunteer maize in a hybrid maize field; however, this is not possible for no-till maize growers.

MANAGEMENT OF VOLUNTEER MAIZE IN SUGARBEET

Sugarbeet is a biennial crop grown for sugar production, and has accounted for about 55% of the total sugar produced in the USA since the 1990s (USDA-ERS, 2015). It is grown in eleven states within the United States, including California, Colorado, Idaho, Michigan, Minnesota, Montana, Nebraska, North Dakota, Oregon, Washington, and Wyoming. Glyphosate-resistant sugarbeet was commercialized in 2007, and accounted for about 95% of the total sugarbeet planted in 2009/10 (USDA-ERS, 2015). In 2014, sugarbeet was harvested from about 458 thousand hectares in the United States (NASS, 2015).

In many sugarbeet growing areas, glyphosate-resistant maize is commonly grown in rotation with glyphosate-resistant sugarbeet. Volunteer maize at a density of 1 to 1.7 plants m^{-2} caused 19 to 45% reductions in sucrose yield in sugarbeet (Kniss et al. 2012). Researchers reported that sugarbeet yield reductions were partly attributed to the shading effect of volunteer maize plants that emerged before or with sugarbeet, and were taller than the sugarbeet crop during the growing season (Dotzenko and Arp, 1971; Kniss et al. 2012). In the study conducted by Kniss et al. (2012), F2 maize hybrids and clumps of volunteer maize were equally competitive to sugarbeet, and caused similar reductions in root and sucrose yield. Kniss et al. (2012) estimated that volunteer maize plants should be controlled as early as 3.5 wk after sugarbeet emergence to prevent economically significant sucrose yield reductions. Effective herbicide options for glyphosate-resistant volunteer maize control in glyphosate-resistant sugarbeet are limited. There are no PRE herbicides options available for volunteer maize control, and ACCase-inhibitors herbicides are the only POST herbicides that provide acceptable control in sugarbeet. Quizalofop and clethodim provided greater control of glyphosate-resistant volunteer maize compared to sethoxydim, and their efficacy was enhanced with the addition of an oil adjuvant (Kniss et al. 2012). When tank-mixed with glyphosate, the addition of crop oil concentrate (COC) to quizalofop or a non-ionic surfactant to clethodim can increase volunteer maize control (Deen et al. 2006). The optimal timing for controlling volunteer maize plants should be at the four to eight true-leaf stage of sugarbeet, when majority of volunteer maize plants have emerged. Furthermore, the herbicide applications to control volunteer maize plants should be targeted when volunteers are less than 25-30 cm tall to prevent shading effect on the sugarbeet plants (Kniss et al. 2012).

MULTIPLE HERBICIDE-RESISTANT MAIZE AND CHALLENGES AHEAD FOR CONTROL OF VOLUNTEER MAIZE

Seed companies are developing new multiple herbicide-resistant crops, including maize (Green et al. 2008). Maize resistant to sethoxydim, an ACCase-inhibitor herbicide, was developed with the intent to provide grass weed control in maize; however, this cultivar is no longer available in the marketplace. Volunteers resulting from sethoxydim-resistant maize are hard to control with other ACCase-inhibitor herbicides (Young & Hart, 1997). Since glyphosate plus glufosinate-resistant maize is available in the marketplace (Jhala et al. 2014), glufosinate will not be an effective option for controlling volunteer maize if the hybrid maize planted the previous year is stacked resistant.

Multiple herbicide-resistant crops, including maize with stacked resistance to 2,4-D, glyphosate, and aryloxyphenoxy propionate have recently been deregulated by the United States Department of Agriculture (USDA).While these new multiple-resistant maize and soybean cultivars have provided excellent control of certain glyphosate-resistant weeds (Craigmyle et al. 2013), volunteer maize resulting from stacked resistant hybrid maize would leave cyclohexanedione herbicides as the sole option for their management in crop (Sikkema and Soltani, 2014).

CONCLUSION

Early season control of volunteer maize in soybean and other crops is recommended because it reduces the likelihood of volunteer maize competition with crops. Limited herbicide options, primarily the post-emergence application of ACCase-inhibitors, are available for volunteer maize control in broadleaf crops including soybean and sugarbeet. By delaying the application of post-emergence grass herbicides from 15- to 30-cm maize to 30- to 60-cm maize or taller, higher herbicide rates may be required. Sole and continuous reliance on a single herbicide program results in the evolution of herbicide-resistant weeds. Therefore, to reduce the potential for the evolution of herbicide-resistant weeds, growers should adopt integrated volunteer maize management programs that include herbicides, tillage, crop rotation, and improved cultural agronomic practices.

Higher densities of volunteer maize in soybeans are capable of supporting greater adult rootworm emergence, and control of volunteer maize before the V6 stage is also likely to reduce larval rootworm survival. Additionally, the early removal of volunteer maize will reduce the attraction of rootworm adults later in the summer that might lay eggs in soybean, as well as reducing the emergence of adult rootworms, which may have been selected for survival on *Bt* toxins. Early-season management of volunteer maize requires timely field scouting, specifically in fields rotated with glyphosate-resistant maize. Multiple herbicide-resistant maize hybrids have been developed and will be commercialized in the near future that may reduce herbicide options to control volunteers; therefore, integrated management of volunteer maize will remain priority in soybean-maize cropping systems.

REFERENCES

Andersen, R.N., Ford, J.H., & Lueschen, W. E., (1982). Controlling volunteer corn (*Zea mays*) in soybeans (*Glycine max*) with diclofop and glyphosate. *Weed Science* 30, 132–136.

Anderson, D.M., Swanton, C.J.,Hall, J.C., Mersey, B.G., (1993). The influence of temperature and relative humidity on the efficacy of glufosinate-ammonium. *Weed Research*33, 139-147.

Aulakh, J.S., Price A.J., Balkcom K.S., (2011). Weed management and cotton yield under two row spacings in conventional and conservation tillage systems utilizing conventional, glufosinate-, and glyphosate-based weed management systems. *Weed Technol.* 25, 542–547.

Aulakh, J.S., Price A.J., Enloe S.F., Santen E.V., Wehtje, G., Patterson, M.G., (2012). Integrated Palmer amaranth management in glufosinate-resistant cotton: i. soil-inversion, high-residue cover crops and herbicide regimes. *Agronomy* 2, 295–311.

Aulakh, J.S., Price, A.J., Enloe, S. F., Wehtje, G., Patterson, M.G., (2013). Integrated Palmer amaranth management in glufosinate-resistant cotton: II. primary, secondary and conservation tillage. *Agronomy*3, 28–42.

Avila-Garcia, W.V., Sanchez-Olguin, E., Hulting, A.G., Mallory-Smith, C., (2012). Target-site mutation associated with glufosinate resistance in Italian ryegrass (*Lolium perenne* L. ssp. *multiflorum*). *Pest Manag. Science* 68, 1248–1254.

Baskin, C.C., Baskin, J.M., (1998). Seeds: ecology, biogeography, and evolution of dormancy and germination, 666. *Academic Press, San Diego, California, USA.*

Beckett, T.H., Stoller, E.W., (1988). Volunteer corn (*Zea mays*) interference in soybeans (*Glycine max*). *Weed Science* 36, 159–166.

Beckett, T.H., Stoller, E.W., Bode, L.E., (1992). Quizalofop and sethoxydim activity as affected by adjuvants and ammonium fertilizers. *Weed Science* 40, 12–19.

Bewley, J.D., Black, M., (1994). Seeds: Physiology of Development and Germination, 2nd Edition, pp. 273-290. *Plennum, New York, USA.*

Brown, H.J., Cruse, R.M.,Colvin, J.S., (1989). Tillage system effects on crop growth and production costs for a corn–soybean rotation. *J. Prod. Agriculture* 2, 273–279.

Buhler, D.D., (1988). Factors influencing fluorochloridone activity in no-till corn (*Zea mays*). *Weed Science* 36, 207–214.

Chahal, P.S., Jhala, A.J., (2015). Herbicide programs for control of glyphosate-resistant volunteer corn in glufosinate-resistant soybean. *Weed Technology* 29, 431–443.

Chahal, P., (2014). Herbicide programs for control of glyphosate-resistant volunteer corn in glufosinate-resistant soybean [Theses]. University of Nebraska-Lincoln, NE. Control of herbicide. Digital Commons@University of Nebraska-Lincoln, 2014.parminder.chahal @huskers.unl.edu

Chahal, P.S., Kruger, G., Blanco-Canqui, H., Jhala, A.J., (2014). Efficacy of pre-emergence and post-emergence soybean herbicides for control of glufosinate-, glyphosate-, and imidazolinone-resistant volunteer corn. *Journal of Agri. Sciences* 6, 131–140.

Clewis, S.B., Thomas, W.E., Everman, W.J., Wilcut J.W., (2008). Glufosinate-resistant corn interference in glufosinate-resistant cotton. *Weed Technology* 22, 211–216.

Coffman, C.B., Frank J.R., (1991). Weed-crop responses to weed management systems in conservation tillage corn (*Zea mays*). *Weed Technology* 5, 76–81.

Craigmyle, B.D., Ellis, J.M., Bradley, K.W., (2013). Influence of herbicide program on weed management in soybean with resistance to glufosinate and 2,4-D. *Weed Technology* 27, 78–84.

Dale, J.E., (1981). Control of johnsongrass (*Sorghum halepense*) and volunteer corn (*Zea mays*) in soybeans (*Glycine max*). *Weed Science* 40, 12–19.

Deen, W., Hamill, A., Shropshire, C., Soltani, N., Sikkema, P.H., (2006). Control of glyphosate-resistant corn (*Zea mays*) in glyphosate-resistant soybean (*Glycine max*). *Weed Technology* 20, 261–266.

Dotzenko, A.D., Arp, A.L., (1971). Yield response of sugarbeets under variouslight intensities as influenced by kochia density. *J. Am. Soc. Sugarbeet Technology* 16, 479–481.

Farnham, D.E., Benson, G.O., Pearce, R.B. Corn perspective and culture. (2003). In: P. J. White, & Johnson LA. Maize: Chemistry and Technology, 2nd Edition, pp. 1-33. St. Paul, MN: American Association of Cereal Chemists.

Gent, D.H., Lang, J.M., Bartolo, M.E., Schwartz, H.F., (2005). Inoculum sources and survival of *Xanthomonas axonopodis* pv. *allii* in Colorado. *Plant Disease* 89, 507–514.

Green, J.M., Hazel, C.B., Forney, D.R., Pugh, L.M., (2008). New multiple-herbicide crop resistance and formulation technology to augment the utility of glyphosate. *Pest Manag Science* 64, 332–339.

Griffith, D.R., Mannering, J.V., Box, J.E., (1986). Soil and moisture management with reduced tillage. In:M. A. Sprague, & G. B. Triplett (Eds.), No-Tillage and Surface Tillage Agriculture: pp. 19–58. New York: J. Wiley.

Hairston, J.E., Stanford, J.O., Hates, J.C., Reinschmiedt, L.L., (1984). Crop yield, soil erosion, and net returns from five tillage systems in the Mississippi Blackland. *Prairie J. Soil Water Conservation* 39, 391–395.

Heap, I.,(2014). Global perspective of herbicide-resistant weeds. *Pest Manag Science*70, 1306–1315.

Heap, I.M. *International survey of herbicide resistant weeds: Weeds resistant to ACCase inhibitors (A/1).* Available from: http://weedscience.org/ summary/MOA.aspx. Accessed 13 December 2014.

Heap, I. M. *International survey of herbicide resistant weeds: Weeds resistant to EPSP synthase inhibitors (G/9).* Available from: http://www.weed science.org/summary/MOA.aspx?MOAID=12. Accessed: 13 December 2014.

Heap, I.M. *International survey of herbicide resistant weeds: Weeds resistant to the herbicide glufosinate-ammonium.* Available from: http://www.weed science.org/summary/Resist ByActive.aspx. Accessed: 13 December 2014.

Holman, J.D., Schlegel, A.J., Olson, B.L., Maxwell, S.R., (2011) Volunteer glyphosate-tolerant corn reduces soil water and winter wheat yields. *Crop Management*. Online. doi:10.1094/CM-2011-0629-01-RS.

Jeschke, M., Doerge, T., (2008). Managing volunteer corn in corn fields. *Crop Insights* 18, 1–3.

Jhala, A.J., Knezevic, S.Z., Ganie, Z.A., Singh, M., (2014). Integrated weed management in corn (*Zea mays* L.). In B. Chauhan, & G. Mahajan (eds.), Recent Advances in Weed Management: pp. 177–196. New York: Springer.

Johnson, D.B., Norsworthy, J.K., Scott, R.C., (2014). Herbicide programs for controlling glyphosate-resistant johnsongrass (*Sorghum halepense*) in glufosinate-resistant soybean. *Weed Technology* 28, 10–18.

Kiesselbach, T.A., (1999). The structure and reproduction of corn: 50th Anniversary Edition. Cold Spring Harbor, NY: Cold Spring Harbor Laboratory Press.

Kniss, A.R., Sbatella, G.M., Wilson R.G., (2012). Volunteer glyphosate-resistant corn interference and control in glyphosate-resistant sugarbeet. *Weed Technology* 26, 348–355.

Koskinen, W.C., McWhorter, C.G., (1986). Weed control in conservation tillage. *J. Soil Water Conservation* 41, 365–370.

Krupke, C., Marquardt, P., Johnson, W., Weller, S., & Conley, S.P., (2009). Volunteer corn presents new challenges for insect resistance management. *Agron. Journal* 101, 797–799.

Kumaratilake, A.R., Preston, C., (2005) Low temperature reduces glufosinate activity and translocation in wild radish (*Raphanus raphanistrum*). *Weed Science*53, 10–16.

Louie, R., (1999). Diseases Caused by Viruses. In D. G. White (ed.), Compendium of Corn Diseases, 3rd Edition, pp.45–55. St. Paul, MN: The American Phytopathological Society, APS Press.

Marquardt, P.T., Johnson, W.G., (2013). Influence of clethodim application timing on control of volunteer corn in soybean. *Weed Technology* 27, 645–648.

Marquardt, P.T., Krupke, C., Johnson, W.G., (2012). Competition of transgenic volunteer corn with soybean and the effect on western corn rootworm emergence. *Weed Science* 60, 193–198.

Marquardt, P.T., Terry, R.M., Johnson, W.G., (2013). The impact of volunteer corn on crop yields and insect resistance management strategies. *Agronomy* 3, 488–496.

Meinke, L.J., Sappington, T.W., Onstad, D.W., Guillemaud, T., Miller, N.J., Komáromi, J., Levay, N., Furlan, L., Kiss, J., Toth, F., (2009). Western corn rootworm (*Diabrotica virgifera virgifera* LeConte) population dynamics. *Agricultural and Forest Entomology*11, 29–46.

USDA-NASS. United States Department of Agriculture-National Agricultural Statistics Service. 2015. National statistics for sugarbeets. Available from: http://www.nass.usda.gov/Statistics_by_Subject/index.php?sector=CROPS. Accessed: 17 February 2015.

Owen, M., (2008). Weed species shifts in glyphosate-resistant crops. *Pest manag. Science* 64, 377–387.

Sarangi, D., Sandell, L. D., Knezevic, S. Z., Aulakh, J. S., Lindquist, J. L., Irmak, S., Jhala, A. J. (2014). Confirmation and control of glyphosate-resistant common waterhemp (*Amaranthus rudis*) in Nebraska. *Weed Technol.29,* 82–92.

Shauck, T.C., Smeda, R.J., (2012). Control of glyphosate-resistant corn (*Zea mays*) with glufosinate or imazethapyr plus imazapyr in a replant situation. *Weed Technology* 26, 417–421.

Shaw, J.T., Paullus, J.H., Luckmann, W.H., (1978). Corn rootworm oviposition in soybeans. *J. Econ. Entomology* 71, 189–191.

Seifers, D.L., Harvey, T.J., Jensen, S.G., (1997). Identification of the wheat curl mite as the vector of the High Plains virus of corn and wheat. *Plant Disease* 81, 1161–1166.

Sikkema, P.H., Soltani, N.,(2014). Control of volunteer Enlist corn in soybean. Proceedings of the 69th Annual Meeting of North Central Weed Science Society, Minneapolis, Mn. pp. 69.

Smiley, R.W., Merrifield, K., Patterson, L.M., Whittaker, R.G., Gourlie, J.A., Easley, S.A., (2004). Nematodes in dryland field crops in the semiarid Pacific Northwest USA.*Journal of Nematology* 36, 54–68.

Steckel, L.E., Thompson, M.A., Hayes R.M., (2009). Herbicide options for controlling glyphosate-tolerant corn in a corn replant situation. *Weed Technology* 23, 243–246.

University of Illinois IPM Program. (1998). Corn rootworm management. Available from: URL: https://ipm.illinois.edu/fieldcrops/insects/corn_rootworm/management.html. Accessed: 10December 2014.

USDA-ERS. United States Department of Agriculture-Economic Research Service. 2014. Available from: http://www.ers.usda.gov/topics/crops/ maize.aspx. Accessed: 17 February 2015.

USDA-NASS. United States Department of Agriculture. 2014. Adoption of genetically engineered crops in the U.S. Available from: http://www.ers.usda.gov/data-products/adoption-of-genetically-engineered-crops-in-the-us.aspx. Accessed: 17 February 2015.

USDA-NASS. United States Department of Agriculture. 2015. Available from: http://www.ers.usda.gov/topics/crops/sugar-sweeteners/background.aspx#hfcs. Accessed: 17 February 2015.

Wilson, R., Sandell, L.D., Klein, R., Bernards, M., (2010). Volunteer corn control. Proceedings of 2010 Crop Production Clinics. Lincoln, NE: University of Nebraska-Lincoln Extension. pp. 212–215.

Windham, G.L., Edwards, D.I., (1999). Diseases caused by nematodes. In: D. G. White (Eds.), Compendium of corn diseases: 3rd Edition, pp. 56–62. St. Paul, MN: APS Press.

Young, B.G., Hart, S.E., (1997). Control of volunteer sethoxydim-resistant corn (*Zea mays*) in soybean (*Glycine max*). *Weed Technology* 11, 649–655.