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Article

The Impact of Volunteer Corn on Crop Yields and Insect Resistance Management Strategies

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Abstract: Volunteer corn (VC) has reemerged as a problematic weed in corn/soybean rotational cropping systems. This reemergence and increasing prevalence of volunteer corn has been correlated to an increased adoption of herbicide-resistant (HR) corn hybrids and the adoption of conservation tillage. Since the introduction of HR crops, control options, weed/crop competition, and other concerns (*i.e.*, insect resistance management of Bt traits) have increased the amount of attention that volunteer corn is receiving. The objective of this review is to discuss what is known about VC prior to and after the introduction of HR crops, and to discuss new information about this important weed.

Keywords: competition; volunteer corn; resistance management; Bt; *Cry3Bb1*

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1. Introduction

The introduction of herbicide-resistant (HR) crops has been correlated to the reemergence of volunteer corn as a serious problem weed in corn/soybean rotations [1]. Volunteer corn is a weed produced by leftover corn grain that is spilled, or not harvested, from the field [2]. The grain germinates in the field and grows as a weedy pest. Volunteer corn seed often overwinters in northern latitude fields and germinates the following spring after tillage or planting operations. While in warmer climate fields, volunteer corn can germinate soon after corn harvest and can serve as a year-round host to corn pests such as the corn leaf hopper, *Dalbulus maidis* [3].

Volunteer corn first emerged in the literature as a problem weed with the introduction of conservation tillage and no-till practices in the late 1960s and 1970s. Prior to the adoption of conservation tillage, corn grain that was not harvested, or was spilled, was often buried deep enough with full tillage practices (moldboard plowing) as to inhibit seed germination. Volunteer corn is often documented in the literature as a weed in soybean or other rotated crops (*i.e.*, sugar beets) with corn [4], but volunteer corn may also have a competitive effect in continuous corn production. In either case, volunteer corn can lower crop yields through direct and indirect competition [5].

HR corn hybrids have made controlling volunteer corn a more complex problem. Corn hybrids of this type include both genetically modified plants (glyphosate and glufosinate-resistant hybrids) and HR plants that have been selected for through traditional breeding (sethoxydim and imidazolinone-resistant hybrids). Previous research has indicated that greater than 85% of the grain produced by HR corn hybrids carry an HR trait [6]. Krupke *et al.* [6] specifically studied the glyphosate-resistant (GR) trait, which represents the majority of HR corn in production [7]. Herbicide-resistant volunteer corn carries the same high tolerance to herbicide applications (*i.e.*, glyphosate) as hybrid corn, and in a greenhouse experiment, HR volunteer corn survived postemergence applications of glyphosate at rates up to 26.88 kg ae ha^{-1} (unpublished data). Currently, a majority of United States producers use glyphosate as the main postemergence herbicide in both corn and soybean [8]. Therefore, most HR volunteer corn is not controlled by this herbicide.

Another pressing issue of volunteer corn concerns the insect resistance management of the Bt traits, which are used to help control corn insect pests such as the western corn rootworm (*Diabrotica virgifera virgifera* LeConte) (WCR). Many of these traits are currently being stacked with HR traits to create corn hybrids with resistance to both herbicide and insect feeding pressure. Researchers worry that HR volunteer corn, with the Bt trait, may express the Bt toxin at less than optimal doses, potentially exposing large numbers of insects to sub-lethal doses of Bt [6]. HR volunteer corn expressing low levels of Bt toxin could accelerate the evolution of resistance to Bt in insect pests such as WCR.

The goal of this review is to discuss what is known about volunteer corn both prior to and after the introduction of HR crops, and to highlight the gaps in our knowledge about this important weed.

2. Competition of Volunteer Corn

Volunteer corn competition has been studied in soybean (a common rotational crop with corn) prior to the introduction of HR crops, yet there is little written in the literature about the competitive effects of volunteer corn in other crops prior to HR crop adoption. Beckett and Stoller [5] found that volunteer corn reduced soybean yield up to 25% at densities of 5 to 6 plants m^{-2} in soybean planted in 0.76 m rows. This reduction in yield was most often due to direct competition for nutrients or resources. In addition, Beckett and Stoller [5] found that increasing densities of volunteer corn significantly and inversely affected soybean growth and yield components (leaf area index, nodes per plant, plant dry weight, pods, and seeds). The effect was caused by the area of influence of clumped volunteer corn plants, which was determined to be economically important within a 40 cm area around a volunteer corn clump of 10 plants per clump [5]. Clumped volunteer corn is common when entire ears are not harvested in the field and grain on the ear germinates in the field. Failure to harvest full corn ears is often a result of corn that was harvested late and/or incurred structural injury (*i.e.*, stalk damage causing plants to fall on the ground prior to mechanical harvest). In a similar study, Alms *et al.* [9] found that volunteer corn densities ranging from 0 to 4.4 plants m^{-2} could lower soybean yield from 0% to 58%. Marquardt *et al.* [10] found that volunteer corn growing in soybean at densities of 0.5 plants m^{-2} lowered yields by 12%, and when volunteer corn densities reached 16 plant m^{-2}, yield reduction was as high as 41% in soybean planted in 0.20 m rows. Greater than 50% of the soybean currently planted in the upper-Midwest is grown in row spacing smaller than 0.76 m, usually ranging from 0.19 m to 0.38 m rows [11]. In Indiana, 87% of soybean planted in 2006 was planted in rows 0.51 m or smaller [12]. Volunteer corn that emerged after soybean emergence did not affect soybean yield in 0.20 m row spacing [10].

In the future, corn demand will increase due to a United States government mandate that requires increased biofuel production, and due to an increasing global population. As a result, experts estimate that by 2016 approximately 38 million corn hectares will be planted with continuous corn comprising 30% of the total hectares in production [13]. A consequence of continuous corn production is the increased occurrence of volunteer corn in the succeeding corn crop.

Volunteer corn creates competition and interference in corn fields planted with hybrid plants. Uneven emergence of corn stands, and replanting corn into existing corn stands, have been shown to reduce grain yield due to competition between corn plants [14–16]. Nafziger *et al.* [15] reported yield losses of 6% to 8% when 25% of the corn stand emerged 1.5 weeks late. In the same study, a three-week delay in planting 25%, 50%, or 75% of the plants resulted in yield losses of 10%, 20%, and 22%, respectively. Uneven emergence results in a variation in corn heights, which reduces yield significantly. Liu *et al.* [14] found one out of six plants with a two-leaf stage delay in emergence, reduced yield by 4%, and one out of six plants with a four-leaf stage delay reduced yield by 8%. When the initial corn stand was left uncontrolled in a corn replant situation, yield of the untreated check was approximately 1000 kg ha^{-1} lower than the highest yielding treatments [16]. This yield loss, from an uncontrolled initial stand in a corn replant situation, was consistent with the 8% yield loss reported from uneven emergence by Nafziger *et al.* [15] and Liu *et al.* [14]. Volunteer corn may not be as competitive as hybrid corn in replanted corn or an uneven corn emergence situation, but the data from the latter have provided researchers with valuable information that can be used to help assess the possible impacts of volunteer corn in corn.

Multiple studies have addressed the direct competition between volunteer corn and hybrid corn, and have been presented at regional meetings and in university extension publications. Volunteer corn densities of 8.5 plants m^{-2} caused a 40% yield loss in hybrid corn [9]. Stahl *et al.* [17] found that 2 volunteer corn plants m^{-2} was the lowest density causing yield loss. Yield losses of 14% to 19% were observed with volunteer corn densities of 5 plants m^{-2}. Hybrid corn leaf area and dry weight were reduced by competition with volunteer corn plants in comparison to the volunteer corn-free treatments when samples were collected at the VT corn growth stage [18]. Hybrid corn yield was reduced by volunteer corn competition, but when volunteer corn yield was combined with hybrid yield there was no yield difference between treatments with and without volunteer corn [18]. Therefore, if volunteer corn can be harvested, the negative effects on the yield of hybrid corn will be offset by the yield of the volunteer corn.

While volunteer corn can directly interfere with crops, it can also indirectly affect crop yields, especially in more arid environments. In areas of the Great Plains of the United States, corn is commonly rotated with wheat in a three-year rotation of corn-fallow-winter wheat. During the fallow rotation, infestations of volunteer corn have been shown to reduce available soil water by 2.54 cm for every 0.62 volunteer corn plants m^{-2} [19]. This reduction in the available soil water can reduce winter wheat tillering and ultimately wheat yield, which can be reduced by 62.74 kg ha^{-1} for every 0.12 volunteer corn plants m^{-2} [19].

3. Control Options for Volunteer Corn

Controlling volunteer corn in soybean has been a challenge both prior to, and after the introduction of HR hybrid corn, yet multiple chemical options are available with adequate efficacy, including clethodim, diclofop, quizalofop-*p*-ethyl, fenoxaprop-*p*-ethyl, sethoxydim, and fluazifop-*p*-ethyl [5,20–23]. Soltani *et al.* evaluated multiple rates of clethodim (15, 22.5, and 30 g ai ha^{-1}), quizalofop-*p*-ethyl (18, 27, and 36 g ai ha^{-1}), fenoxaprop-*p*-ethyl (27, 40.5, and 54 g ai ha^{-1}), sethoxydim (75, 112, and 150 g ai ha^{-1}), and fluazifop-*p*-butyl (37.5, 56.2, and 75 g ai ha^{-1}) each tank mixed with glyphosate to control glyphosate-resistant (GR) volunteer corn in soybean [22]. Control of volunteer corn was dose dependent, with the lowest doses of clethodim, fenoxaprop-*p*-ethyl, and fluazifop-*p*-butyl resulting in inadequate control of volunteer corn (less than 80% control on a 0%–100% control scale). Control with sethoxydim was also found to be dose-dependent, but was inadequate (80%) even at the highest dose of 150 g ai ha^{-1}. Sethoxydim is not recommended as an efficacious control option for GR volunteer corn [22]. There was no volunteer corn dose-response when quizalofop-*p*-ethyl was applied [22]. Prior to the release of GR corn and soybean, volunteer corn could be controlled using postemergence applications of previously mentioned graminicides, or applications of glyphosate using wiper or “rope-wick” technologies [5,20,23–26]. Marquardt and Johnson showed that volunteer corn densities (0, 0.5, 2, 4, 8, 12, and 16 plants m^{-2}) and size (30 or 90 cm) did affect the efficacy of clethodim applied at 79 g ai ha^{-1} [27]. The consistency of control at 14 days after treatment with clethodim was reduced when the volunteer corn density was increased, and the herbicide applied after the volunteer corn plants were 90 cm or greater in size. However, control of greater than 90% was observed at 28 days after treatment, even at the highest density of volunteer corn, when clethodim was applied to volunteer corn plants 90 cm in size. Overall, the soybean yield in this study was not reduced as long as the herbicide was applied to the volunteer corn plants.

From 2000 to 2005, GR soybean adoption increased from 54% to 87%, while GR corn increased from 7% to 26% [28]. During the time when GR soybean adoption was greater than GR corn adoption, control of volunteer corn with glyphosate was an effective management option; but as GR corn adoption increased, late-season presence of volunteer corn in soybean increased dramatically [1]. In the United States, from 1995 (the year before the commercialization of GR soybean) to 2005, graminicide use on soybean went from 34% to 7% of the total soybean hectares [8]. The graminicides were used less during this time period due to glyphosate’s ability to effectively control grassy weeds, including non-GR volunteer corn. With increased occurrences of GR volunteer corn in soybean, the inclusion of a graminicide, tank-mixed with glyphosate, would be advantageous. The graminicide would control HR volunteer corn, while the glyphosate would control the rest of the weeds present in the soybean field.

Managing GR volunteer corn in GR corn can be problematic. One option for controlling GR corn in corn is to rotate corn hybrids with different herbicide-resistant traits (*i.e.*, plant glufosinate-resistant corn hybrids) and control GR volunteer corn with glufosinate [16]. The problem with this method is two-fold. First, many of the popular hybrids stacked with glufosinate resistance are also GR. The second issue is that glufosinate efficacy, in respect to controlling volunteer corn, is highly variable, especially early in the growing season [29]. Cool temperatures reduce glufosinate activity [30] because of decreased translocation to the meristemetic regions [31]. Row cultivation is the only viable volunteer corn control option when HR hybrid corn genetics have not been rotated and volunteer corn is growing in existing stands of hybrid corn.

For corn replant situations, limited research has been published on herbicide options for controlling GR corn, which have increased in likelihood due to corn planting occurring earlier in the calendar year [16,32]. Steckel *et al.* reported that clethodim at 0.05 kg ai ha^{-1}, paraquat at 0.84 kg ai ha^{-1}, or paraquat at 0.70 kg ai ha^{-1} plus simazine at 0.56 kg ai ha^{-1} resulted in at least 75% control of initial corn stands; and controlled corn in populations of less than 2 plants m^{-2} in a corn replant situation [16]. It was also reported that paraquat at 0.56 and 0.70 kg ha^{-1}, paraquat at 0.56 kg ha^{-1} tank-mixed with simazine at 0.56 kg ha^{-1}, and glufosinate at 0.59 kg ai ha^{-1} resulted in poor control [16].

Plant nutrient content, particularly nitrogen, can influence herbicide efficacy. Tame oats (*Avena sativa* L.) were more tolerant to fluazifop and glyphosate when grown under low nitrogen (1.0 mol m^{-3}) compared to high nitrogen (10 mol m^{-3}). Additionally, fluazifop translocation was nearly three times greater under high nitrogen *versus* low nitrogen [33]. Cathcart *et al.* reported that a 50% growth reduction (GrR_{50}) of green foxtail required 5.15 g ai ha^{-1} of glufosinate under low nitrogen (0.7 mM) as compared to 0.90 g ha^{-1} under high nitrogen (7.0 mM) [34]. Redroot pigweed (*Amaranthus retroflexus* L.) has also been shown to be more susceptible to herbicides under high nitrogen fertility. Terry *et al.* reported that both glufosinate and clethodim efficacy on GR corn was reduced by nearly 50% when treated corn plants had low nitrogen plant concentrations (2%), compared to high plant nitrogen concentrations (3%) [35]. This further highlights the importance of using full herbicide rates when spraying volunteer corn in soybean fields because volunteer corn plants are likely nitrogen deficient.

4. Volunteer Corn and Insect Resistance Management

The introduction of transgenic Bt hybrids to manage WCR, and the subsequent addition of glyphosate resistance to these hybrids has dramatically increased adoption of HR corn [7]. Increased adoption of corn hybrids stacked with HR and Bt traits, in addition to the use of glyphosate as the primary postemergence herbicide for weed control in soybean, may result in increased occurrences of volunteer corn expressing some or all of the same Bt toxins as the corn hybrid planted in the field the previous year. Krupke *et al.* hypothesized that volunteer corn with Bt expressed the Bt protein at a lower concentration than hybrid corn, and noted that there was no difference in WCR feeding damage between Bt-negative and Bt-positive volunteer corn roots [6]. Exposure of target insects to decreased

Bt expression (*i.e.*, sub-lethal exposure) is a concern for insect resistance management. Variant WCR females (a biotype that lays eggs in crops other than corn, reducing the utility of crop rotation as a WCR management tool) add an additional concern when managing volunteer corn in soybean due to the additional presence of WCR even in soybean fields.

Research efforts directed towards quantifying the efficacy of Bt corn hybrids, including analyses of beetle emergence data and their effects upon estimates of resistance evolution [36–38]. However, the models do not take into account the effect of Bt-positive volunteer corn and its impact on resistance evolution. Increased prevalence of volunteer corn could alter estimates of the time for evolution of resistance to Bt, due to large numbers of WCR larvae potentially being exposed to sub-lethal levels of Bt toxins expressed by volunteer corn.

The in-plant expression and production of Bt endotoxins have been shown to be sensitive to soil nitrogen fertility levels [39,40]. Bruns and Abel [39], and Coviella *et al.* [41] describe the effect of nitrogen fertility on the production of the Bt corn event MON810 (*Cry1Ac)* (which targets lepidopteran insect pests) and discovered a direct and positive correlation between increasing levels of available soil nitrogen and Bt protein concentration. Krupke *et al.* [6] stated that transgenic volunteer corn plants that emerge in soybean fields and express Bt proteins may produce toxin levels that are lower than Bt-expressing hybrid corn plants. One key difference between soybean and corn fields in soybean/corn rotational systems is the additional input of nitrogen (N) to corn fields. This additional N could have an effect, not only on the expression of Bt proteins in volunteer corn, but also in hybrid corn plants. Marquardt *et al.* [27] identified N fertility effects on the production of *Cry3Bb1*, the Bt protein that targets below ground Coleopteran pests, specifically the WCR. A greenhouse study found that as the %N in the roots of transgenic volunteer corn plant increased, the Bt protein concentration also increased. While a similar effect was not shown in a companion field study, N does have a clear role in the production of *Cry3Bb1* in transgenic volunteer corn plants. Bt protein expression is correlated to soil N availability, and while the effect of this finding on WCR transgenic corn resistance management strategies is yet to be determined, control of HR/Bt expressing volunteer corn in soybean may become an integral part of WCR resistance management.

5. Conclusions

As the adoption of HR corn hybrids continues to increase, instances of HR volunteer corn will become a more important weed management issue in the future. Additional concerns, including insect resistance management, may help increase awareness of the importance of controlling volunteer corn to protect yields and the efficacy of Bt insect control. While many herbicide options exist to control volunteer corn (both HR volunteer corn and conventional volunteer corn) in soybean and fallow areas, controlling volunteer corn in existing corn stands will remain limited to rotation of hybrid genetics and row-cultivation. At this time, it is clear that volunteer corn can decrease hybrid corn yields, but the addition of volunteer corn yield to hybrid corn yield could negate any yield loss, if it can be mechanically harvested. However, control of volunteer corn in soybean has been shown to be important to protect soybean yields. Overall management decisions by growers will help determine the impact of volunteer corn on insect resistance management and volunteer corn as a weed.

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