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Influence of Clethodim Application Timing on Control of Volunteer Corn in Soybean

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Herbicide options for management of volunteer corn in soybean include a variety of acetyl CoA carboxylase-inhibiting herbicides, yet often, applications of acetyl CoA carboxylase herbicides are delayed until the weed is visible above the soybean canopy. Volunteer corn growing above the soybean canopy is a highly competitive weed, and herbicides applied at this point can kill the weed, yet soybean yield loss is still a concern. Our objective was to compare the effect of controlling various densities of volunteer corn growing in soybean EARLY ($\leq$ 30 cm) versus LATE ($\approx$ 90 cm) on percent control and soybean yield. Seven volunteer corn densities (0, 0.5, 2, 4, 8, 12, and 16 plants m^{-2}) were hand planted into 19-cm row soybean. Clethodim 79 g ai ha^{-1} was tank-mixed with glyphosate at 840 g ae ha^{-1} and applied to the volunteer corn EARLY and LATE. The EARLY application provided higher and less variable control of volunteer corn 14 d after treatment (DAT) compared to LATE applications at all volunteer corn densities. There was no difference in control at 28 DAT for both the EARLY and LATE applications. Soybean yield was not affected by either application timing. Although no yield reduction was seen with the LATE treatments, later-season applications of clethodim to control volunteer corn may offer more variable control and could allow for additional Bt selection pressure on targeted insect pests.

Nomenclature: Glyphosate; clethodim; corn, *Zea mays* L.; soybean, *Glycine max* (L.) Merr.; Bt, *Bacillus thuringiensis* Berliner.

Key words: Herbicide resistance, volunteer corn, weed competition.

Las opciones de herbicidas para el manejo de maíz voluntario en soya incluyen una variedad de herbicidas inhibidores de acetyl CoA carboxilase, aunque a menudo, las aplicaciones de este tipo de herbicidas es retrasada hasta que las malezas son visibles por encima del dosel de la soya. El maíz voluntario que llega a crecer por encima del dosel de la soya es una maleza altamente competitiva, y los herbicidas que se aplican en este punto pueden matar a la maleza, pero las pérdidas de rendimiento de la soya continúan siendo una preocupación. Nuestro objetivo fue comparar el efecto de controlar varias densidades de maíz voluntario creciendo dentro de la soya, temprano ($\leq$30 cm) versus tarde ($\approx$90 cm), sobre el porcentaje de control y el rendimiento de la soya. Siete densidades de maíz voluntario (0, 0.5, 2, 4, 8, 12, y 19 plantas m^{-2}) fueron plantadas en soya sembrada en hileras espaciadas a 19 cm. Se aplicó una mezcla en tanque de clethodim a 79 g ai ha^{-1} con glyphosate a 840 g ae ha^{-1} a maíz voluntario temprano y tardío. La aplicación temprana brindó mayor control y control menos variable del maíz voluntario 14 d después del tratamiento (DAT) al compararse con las aplicaciones tardías en todas las densidades de maíz voluntario. No hubo diferencias en control a 28 DAT en ninguna de las aplicaciones temprana y tardía. El rendimiento de la soya no fue afectado por ninguno de los momentos de aplicación. Aunque no se observaron reducciones en el rendimiento de la soya producto de las aplicaciones tardías, aplicaciones tardías con clethodim al maíz voluntario durante la temporada de crecimiento podrían favorecer un control más variable y podrían permitir mayor presión de selección de resistencia a Bt en insectos plaga.

Herbicide-resistant (mainly glyphosate-resistant) volunteer corn has become an annual problematic weed in corn and soybean rotational systems. The presence of volunteer corn has been correlated to the adoption of conservation tillage practices and the increasing adoption of herbicide-resistant corn (Davis et al. 2008). Prior to the introduction of glyphosate-resistant soybean varieties, volunteer corn was an annual pest in soybean–corn rotations (Andersen 1976; Andersen and Geadelmann 1982; Beckett and Stoller 1988; Beckett et al. 1988; Newcomer 1971). Beckett and Stoller (1988) quantified the competitive effects of volunteer corn growing in soybean and found that volunteer corn at a density of 5 to 6 plants m^{-2} could reduce soybean yield by 25% if not controlled.

Since the introduction of glyphosate-resistant soybean varieties, the primary POST weed management strategy in soybean has been multiple applications of glyphosate (Johnson et al. 2009; Young 2006). This strategy has been very effective, but has selected for weed shifts and glyphosate-resistant weed biotypes (Johnson et al. 2009). Herbicide-resistant corn hybrids were introduced in 1998, but the hybrids were originally not widely adopted (U.S. Department of Agriculture National Agricultural Statistics Service [USDA-NASS] 2012). One factor that has increased adoption of herbicide-resistant hybrid corn is the industry practice of inserting multiple transgenic traits into the same hybrid corn plant (herbicide resistance traits and Bt traits derived from *Bacillus thuringiensis* to manage corn insect pests) (Davis et al. 2008; USDA-NASS 2011). POST glyphosate applications do not control glyphosate-resistant volunteer corn, which has allowed volunteer corn to re-emerge as a problematic weed and compete with soybean. Marquardt et al. (2012a) found that glyphosate-resistant volunteer corn plants at 0.5 m^{-2}

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decrease soybean yield by 10% when not controlled in 19-cm row soybean.

Controlling volunteer corn in soybean was a challenge prior to the introduction of herbicide-resistant hybrid corn, but multiple POST chemical options were labeled for soybean with adequate efficacy, including clethodim, diclofop, quizalofop-p-ethyl, fenoxaprop-p-ethyl, sethoxydim, and fluazifop-p-ethyl (Andersen 1976; Andersen et al. 1982; Andersen and Geadelmann 1982; Beckett and Stoller 1988; Dale 1981; Young and Hart 1997). Another management strategy to control volunteer corn in soybean was to apply glyphosate in a directed spray or with rope-wick applicators prior to the introduction of glyphosate-resistant soybean varieties. After the introduction of glyphosate-resistant corn hybrids, Soltani et al. (2006) evaluated multiple rates of clethodim, quizalofop-p-ethyl, fenoxaprop-p-ethyl, sethoxydim, and fluazifop-p-butyl, each tank mixed with glyphosate to control glyphosate-resistant volunteer corn in soybean. 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 to 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 glyphosate-resistant volunteer corn (Soltani et al. 2006). There was no volunteer corn dose response when quizalofop-p-ethyl was applied (Soltani et al. 2006).

The literature clearly indicates that glyphosate-resistant volunteer corn can be effectively managed in a glyphosate-resistant soybean–corn rotational system. What is not discussed in the literature is the effect of volunteer corn density and size on herbicide efficacy. The objectives of our research were to evaluate the efficacy, soybean yield reductions, and POST application timing of clethodim tank mixed with glyphosate to control various densities of glyphosate-resistant volunteer corn growing in 19-cm row soybean.

Materials and Methods

Volunteer corn seed was hand harvested in the fall of 2009 and 2010 from DKC 61-19 corn hybrids (DKC 61-19, Dekalb® Brand, Monsanto Company, 800 North Lindbergh Blvd., St. Louis, MO 63167) for use in 2010 and 2011, respectively. This is a transgenic hybrid, expressing traits for glyphosate resistance, Lepidoptera feeding resistance (Bt protein Cry1A), and rootworm (*Diabrotica* spp.) feeding resistance (Bt protein Cry3Bb1). Field research was conducted at two locations (Throckmorton Purdue Agriculture Center [TPAC], Lafayette, IN and Pinney Purdue Agriculture Center [PPAC], Wanatah, IN) in 2010 and 2011. The soil type at TPAC was a Toronto-Milbrook silty loam (fine–silty, mixed, superactive, mesic Udollic Endoaqualfs) with a pH of 6.2 and 2.9% organic matter. The soil type at PPAC was a Pinhook loam (coarse–loamy, mixed, superactive, mesic Mollic Endoaqualfs) with a pH of 6.1 and 2% organic matter. The sites were fall chisel plowed, field cultivated in the spring, and fertilized according to Purdue University Extension recommendations (Camberato et al. 2011). P93M61 glyphosate-resistant soybean (P93M61, Pioneer Hi-Bred, P.O. Box 1000, Johnston, IA 50131) was drilled (19-cm rows) at a rate of 543,400 seeds ha^{-1} at TPAC (June 8, 2010 and May 19, 2011) and 469,300 seeds ha^{-1} at PPAC (May 20, 2010 and May 9, 2011). The drilled soybean area was divided into plots (3 m by 9 m), and the targeted volunteer corn densities (a small percentage of seeds did not emerge) were hand planted with the use of a spike planter (Hand Jab Planter, Almaco, 99 M Avenue, Nevada, IA 50201) in a randomized complete-block design with a factorial arrangement of treatments with four replications on the day of soybean planting. The main factors were volunteer corn density (0, 0.5, 2, 4, 8, 12, 16 seeds m^{-2}) and application timing—EARLY ($\leq$ 30 cm volunteer corn) or LATE ($\approx$ 90 cm volunteer corn). Clethodim (79 g ai ha^{-1}) (Select Max®, Valent U.S.A. Corporation, 1600 Riviera Avenue, Suite 200, Walnut Creek, CA 94596) was tank mixed with glyphosate (840 g ae ha^{-1}) (Roundup® PowerMAX, Monsanto Company). The herbicides were applied with a CO_2-pressurized backpack sprayer at an application volume of 142 L ha^{-1} with the use of TeeJet® XR11002 spray tips (XR11002, TeeJet Technologies, 1801 Business Park Drive, Springfield, IL 62703). Prior to mixing the herbicide, ammonium sulfate (N-Pak Liquid AMS®, Land O'Lakes, Inc., 4001 Lexington Avenue North, Arden Hills, MN 55126) was added to the water at a rate of 2% v/v.

Control ratings on the volunteer corn plants were collected 14 and 28 d after treatment (DAT) for both the EARLY and LATE application timings. Control was rated on a 0 (no control) to 100 (plant death) scale. At soybean maturity, the plots were harvested with a plot combine to calculate the total soybean yield per plot. One-liter subsamples were collected from each plot to calculate actual soybean yield (without harvest contaminants). The subsamples were taken by collecting the harvested material per plot as the plot combine weigh buckets cycled. Then 100 g of harvested material was separated from the subsamples. The soybean was separated from the harvest contaminants (e.g., volunteer corn, soil, plant debris) and weighed to calculate the percentage of soybean weight in each plot. This percentage was multiplied by the total harvested material to determine the actual soybean yield in each plot (Marquardt et al. 2012a).

Data Analysis. The data were checked for normality and transformed when necessary as suggested by the Box-Cox procedure in SAS (SAS software, Version 9.2, 2002–2008, SAS Institute Inc., Cary, NC 27513). The visual control ratings were separated by application timing and analyzed as a mixed model with the use of the PROC MIXED procedure in SAS with site and year as random variables. The yield data were separated by application timing with site and year as random variables and analyzed with the use of single-degree-of-freedom linear contrast statements with the PROC MIXED procedure in SAS.

Results and Discussion

During the 2 yr of this research, it was interesting to find that our primary hypothesis that EARLY applications of clethodim tank mixed with glyphosate would protect the yield of soybean better than LATE applications of clethodim tank mixed with glyphosate was not supported. There was no difference in the percent control at 28 DAT between herbicide applications made EARLY in the season compared to LATE in the season at any of the six densities of volunteer corn tested (Table 1). Yet, as expected, the variability of control was increased at 14 DAT when the tank mix was applied LATE. Also, as the density of volunteer corn plants increased from 0.5 to 16 plants m^{-2}, the variability of control increased for the LATE timing (Table 1). Previous research has shown that as volunteer corn density in a plot increases the individual volunteer corn leaf area also increases, but the rate of the increase is reduced as the volunteer corn density is increased (Marquardt et al. 2012a). This is likely due to intraspecific competition between volunteer corn plants at increased densities. The increase in population density and corresponding increase in leaf area could account for the decreased control that was observed in the LATE applications of clethodim, potentially because of less coverage of the herbicide. Yet, because clethodim is translocated to the growing point of the plant, the LATE control ratings at 28 DAT indicate that although some of the volunteer plants may not have received a significant amount of herbicide (as seen at 14 DAT), the amount of clethodim that was applied (79 g ai ha^{-1}) was enough to eventually kill the volunteer plants. When the tank mix was applied EARLY, we did not see decreased control issues at 14 DAT (Table 1). This is most likely an attribute of the size of the volunteer corn plants, which allowed for better herbicide coverage compared to the LATE application at 14 DAT.

The yield results illustrated that there was no difference between the EARLY or LATE applications of clethodim at any of the volunteer corn densities (Table 2). These results are consistent with the 28 DAT control ratings for both of the application timings, yet the yield results do not support our hypothesis that the LATE application would cause a decrease in soybean yield. There was no volunteer corn density effect within application timing when each density was compared to the 0 plants m^{-2} treatment (control). As long as volunteer corn plants are treated with clethodim ($\geq$ 79 g ai ha^{-1}) at or before the corn plants reach 90 cm, soybean yield loss did not occur. We expected the high-density volunteer corn treatments to decrease soybean yield if clethodim was applied LATE. The LATE timing was used to correspond to when the second application of glyphosate (in a typical two-pass POST glyphosate weed management strategy) would be applied. Although tank mixing a graminicide with glyphosate at this POST timing would kill the grass species present, volunteer corn stalks (even when dead) would be above the soybean canopy, competing with the soybean plants for light. This apparent competition did not have an effect on soybean yield. It is possible that the maturity group of the soybean we chose for our experiment could have had a larger role in the lack of the observed soybean yield reductions. The variety was a maturity group III, which may have compensated for the competitive effects of the volunteer corn plants even after the LATE application timing. An earlier-maturing soybean variety may have been further along in the vegetative growth stages at the time of the LATE application, which could have potentially given the soybean plants less time to respond and compensate for the competitive effects of the volunteer corn plants.

Although we did not support our hypothesis that controlling volunteer corn plants growing in soybean early in the season rather than later would protect soybean yield, an early application is recommended from an insect resistance management standpoint if the herbicide-resistant volunteer corn plants also express transgenic Bt traits. Volunteer corn plants that express Bt toxins apply additional Bt selection pressure on targeted insect pests (Krupke et al. 2009;

Table 2. Soybean yield comparing the effect of application timing (EARLY vs. LATE) and volunteer corn (VC) density. The data are analyzed with single-degree-of-freedom linear contrast statements. Means ± standard error (SEM) with $P < 0.05$ are different within rows.

	EARLY		LATE		
VC treatment	Yield	SEM	Yield	SEM	P value
Plants m^{-2}	kg ha^{-1}	± kg ha^{-1}	kg ha^{-1}	± kg ha^{-1}	
0	3,584	235	3,592	209	0.8683
0.5	3,551	200	3,748	205	0.3896
2	3,919	208	3,828	135	0.8172
4	3,325	252	3,399	195	0.4790
8	3,811	189	3,362	235	0.0647
12	3,582	163	3,641	201	0.7709
16	3,434	219	3,256	189	0.3196

Table 1. Mean percent control (0–100 scale) of volunteer corn (VC) with the clethodim (79 g ai ha^{-1}) plus glyphosate (840 g ae ha^{-1}) tank mix 14 and 28 d after treatment (DAT) for the EARLY and LATE application timings. The data are analyzed as a full factorial and means ± standard error (SEM) with different letters are different at $P = 0.05$.

	EARLY ($\leq$ 30 cm VC)				LATE ($\approx$ 90 cm VC)			
VC Treatment	14 DAT	± SEM[a]	28 DAT	± SEM[a]	14 DAT	± SEM[a]	28 DAT	± SEM[a]
plants m^{-2}	%							
0	–	–	–	–	–	–	–	–
0.5	98 a	0.63	99 a	–	89 c	3.09	99 a	1.03
2	98 a	0.63	99 a	–	75 de	2.54	92 abc	1.92
4	98 a	0.72	99 a	–	78 d	3.27	94 abc	1.65
8	98 a	1.00	99 a	–	78 d	3.39	93 abc	1.77
12	96 a	2.00	98 a	1.66	73 e	2.58	96 ab	1.20
16	97 a	1.43	99 a	–	74 de	3.30	95 ab	1.80

[a] Treatment means and standard errors represent backtransformed data.

Marquardt et al. 2012a,b). The additional selection pressure could speed up the evolution of resistance to the Bt toxins in targeted insect pest populations, which could threaten the continued efficacy of Bt traits in hybrid corn. At this time, further research would be beneficial to determine how different soybean maturity groups respond to LATE applications of clethodim. The research would allow for a better understanding of the system and help create robust management recommendations for control of transgenic volunteer corn in soybean.

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