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Corn Yield Loss Due to Volunteer Soybean

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The widespread adoption of glyphosate-resistant corn and soybean in cropping rotations often results in volunteer plants from the previous season becoming problem weeds that require alternative herbicides for control. Corn yield losses due to season-long volunteer soybean competition at several densities in two growing seasons were used to define a hyperbolic yield loss function. The maximum corn yield loss observed at high volunteer soybean densities was about 56%, whereas, the incremental yield loss (I) at low densities was 3.2%. Corn yield loss at low volunteer soybean densities was similar to losses reported for low densities of velvetleaf and redroot pigweed, with 10% yield loss estimated to occur at 3 to 4 volunteer soybean plants m^{-2}. Several herbicides, including dicamba with or without diflufenzopyr applied at the V2 growth stage of volunteer soybean, provided > 90% control, demonstrating several economical options to control volunteer glyphosate-resistant soybean in glyphosate-resistant corn. Reevaluation of control recommendations may be needed with commercialization of other genetically modified herbicide-resistant soybean varieties.

Nomenclature: Corn, *Zea mays* L.; soybean, *Glycine max* (L.) Merr.; redroot pigweed, *Amaranthus retroflexus* L.; velvetleaf, *Abutilon theophrasti* Medik.

Key words: Competition, weed-crop interactions.

The use of genetically modified crops with similar herbicide resistance profiles in crop rotations has increased the prevalence of volunteer crops in the following year's cash crop. For example, uncontrolled volunteer glyphosate-resistant corn in glyphosate-resistant soybean resulted in greater yield loss at lower densities when compared with broadleaf and grass species that commonly infest soybean fields (Alms et al. 2016; Andersen 1976; Deen et al. 2006). There is limited research that quantifies the influence of volunteer soybean on corn yield.

The lack of yield loss information may be due to the wide array and readily available herbicides that can be used to control soybean in corn. Herbicidal control of volunteer soybean in corn has been studied and reported in extension publications (Jhala et al. 2013), conference proceedings (Knezevic et al. 2014), research reports (Zollinger and Ries 2004), extension weed control guides (Wrage et al. 2004; Zollinger et al. 2015), and popular press articles (Gunsolus 2010). Dicamba alone or mixed with diflufenzopyr, atrazine, bronate, clopyralid alone or mixed with flumetsulam, and halosulfuron applied at the V2 to V3 stage of soybean growth have been reported to result in near complete control of volunteer soybean in corn (Knezevic et al. 2014; Zollinger et al. 2015; Zollinger and Ries 2004). At later growth stages (V4 to V6), control ratings with the same herbicides and applications rates typically decrease from complete (or near complete) control to 85% or less (Gunsolus 2010; Knezevic et al. 2014; Zollinger and Ries 2004).

In the near future, volunteer soybeans may become more frequently observed in corn because of the release of several different types of genetically modified soybeans that are resistant to one or more herbicides used in corn (Scott 2014). Soybean varieties with genetic modifications for glyphosate or glufosinate resistance are the typical herbicide resistance traits present in soybeans marketed in 2016. Research is being conducted on soybeans resistant to auxin-mimic herbicides (e.g., 2.4-D and dicamba) and inhibitors of 4-hydroxyphenyl-pyruvate dioxygenase (e.g., isoxaflutole and mesotrione) with resistance to a single herbicide or "stacked" with two or more herbicide combinations. The types of herbicide-resistance genetic modification that volunteer soybean contain and the potential for corn yield loss, based on soybean density, will be considerations in deciding if and when control is warranted.

There are several contributing factors that influence volunteer soybean presence in rotational crops. Some soybean varieties are more susceptible than others to pod dehiscence (Caviness 1965; Tsuchiya 1987) and environmental factors interact with the soybean pod shattering trait. Low

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humidity, high temperature, rapid temperature changes, and alternating wetting and drying of plants influence both the amount and timing of seed loss (Tsuchiya 1987; Tukamuhabwa et al. 2002). Lodging (Weber and Fehr 1966), harvest loss due to combining delays after crop maturity (Philbrook and Oplinger 1989), missed plants, missed pods due to high cutting height, or equipment inefficiencies (e.g., plugged screens) also contribute to seed losses.

Soybean seeds lost during harvest are potential volunteer soybean plants the following season. Assuming 6,000 seeds kg^{-1}, shattering losses ranging from 57 to 175 kg ha^{-1} (Tukamuhabwa et al. 2002), and 100% germination, there would be a potential for 34 to 105 volunteer soybean plants m^{-2}. While not all seeds may germinate and seed quantity may decrease due to animal consumption, seed degradation, or other aging processes, soybean densities on a site-specific basis could be high enough to reduce the following years' cash crop yields. In addition, as soybean yield increases, the number of seed losses and hence, volunteer plant numbers, may increase. To date, we could find no readily available published information on the relationship between corn yield loss and volunteer soybean density for the northern Great Plains region of the United States. The objectives of these studies were to: (1) quantify corn yield loss due to volunteer soybean competition and (2) evaluate a variety of control options for volunteer glyphosate-resistant soybeans in glyphosate-resistant corn.

Materials and Methods

Each study was conducted during two field seasons in eastern South Dakota, an area where about 500,000 ha of corn and soybean are planted annually (U.S. Department of Agriculture–National Agricultural Statistics Service [USDA-NASS] 2013). Volunteer soybean competition and control studies were conducted in 2011 at the South Dakota State University, Brookings Agronomy Farm on a Barnes loam soil (Fine-loamy, mixed, superactive, frigid Calcic Hapludolls) and in 2012 at the Volga Research Farm on a Brandt silty clay loam (Fine-silty, mixed, superactive, frigid Calcic Hapludolls). Total precipitation was about 33 cm and 35 cm for the 2011 and 2012 growing seasons, respectively. The seasonal growing degree day totals (base 10 C from May 1 through September 30) were 1,347 for 2011 and 1,474 for 2012, which were 8 and 18% greater than the 30-yr normal of 1,240, respectively.

Treatments for both studies were established in a randomized complete block design with four replications. Fertilizer was applied to all plots on May 9, 2011, and April 23, 2012, at a rate of 167 kg N ha^{-1}. In addition, the 2011 application contained P_2O_5 and K_2O, which were at 33.5 kg ha^{-1}. Individual plots were four rows wide (76-cm row width) and 15-m long.

Soybean Density Influence on Corn Yield. Commercial Roundup Ready soybean seed (Asgrow 1230 [relative maturity 1.2] [2011] and Asgrow 1431 [relative maturity rating of 1.4] [2012]) (Monsanto, St. Louis, MO) were scattered by hand on the soil surface on May 16, 2011, and April 25, 2012, respectively. Seeding rate differed by treatment, and ranged from about about 1 g to 45 g m^{-2} ($\sim$6 seed g^{-1}), to aid in achieving a range of soybean densities (described below). After spreading, soybean seed was incorporated about 4 cm below the soil surface using a field cultivator each year. Dekalb 43-27 corn seed (relative maturity 93 d) (Monsanto, St. Louis, MO) and Dekalb 45-51 RIB corn seed (relative maturity 95 d) were planted at 76,100 seed ha^{-1} in 2011 and 2012, respectively.

After soybean emergence, manual counts were completed across each plot to quantify volunteer soybean densities. Counts were taken in three 0.7-m^2 areas per plot. Average soybean densities were 0, 1.8, 3.7, 19, 37, and 111 plants m^{-2} in 2011 and 0, 2.3, 4.2, 13, 41, and 90 plants m^{-2} in 2012. Plots were kept weed-free with an application of glyphosate (Roundup WeatherMax, Monsanto, St. Louis, MO) at 870 g ae ha^{-1} with ammonium sulfate at 2.8 kg ha^{-1} applied June 14, 2011, and June 1, 2012. Corn was harvested with a plot combine from the center 1.5 m of each 3-m wide plot on October 14, 2011, and September 28, 2012. Corn yields were determined and adjusted to 15% moisture.

Volunteer Soybean Control. Soybean seed was scattered by hand (about 3 g m^{-2}) and corn was established as described above. After soybean emergence, it was determined that the average soybean density was 10 plants m^{-2}.

Herbicide treatments included tembotrione (Laudis, Bayer CropScience, Monheim, Germany) at full (30.6 g ai ha^{-1}) and half rate (15.3 g ai ha^{-1}), dicamba + diflufenzopyr (Status, BASF, Ludwigshafen, Germany) at full (56 + 22 g ae ha^{-1}) or half rate (28 + 11 g ae ha^{-1}), atrazine (Aatrex, Syngenta, Basel, Switzerland) at full (1,120 g ai ha^{-1}) or half rate (560 g ai ha^{-1}), dicamba (Clarity, BASF) at 280 g ae ha^{-1}, and rimsulfuron (Resolve, DuPont, Wilmington, DE) at 8.8 g ai ha^{-1}. The tembotrione, atrazine, and rimsulfuron treatments included nonionic surfactant at 0.25% v/v. All treatments included glyphosate at 870 g ae ha^{-1} with ammonium sulfate at 470 g ha^{-1} to control weeds other than volunteer soybean. Treatments were applied with a bicycle sprayer using 187 L ha^{-1} at 207 kPa and TeeJet 8003XR nozzles (TeeJet Technologies, Glendale Heights, IL).

In 2011, herbicides were applied on June 25. Corn was about 25 cm tall and was at the V5 stage. Volunteer soybean ranged from 10- to 15-cm tall at the two-trifoliate stage (V2). In 2012, herbicides were applied on June 12. Corn ranged from 30- to 36-cm tall, and was at the V4 to V5 stage. Volunteer soybean ranged from 15- to 20-cm tall and was at the three- to four-trifoliate stage (V3 to V4). Volunteer soybean control was rated visually on a scale of 0 (no control) to 100% (complete plant necrosis) on August 23, 2011, and July 11, 2012. No corn yield data were taken from this study.

Statistical Analysis. Volunteer soybean densities and maximum corn yield in weed-free control plots differed between years. However, the percent corn yield loss by volunteer soybean density data were used for regression analysis across years. The 0 soybean plants m^{-2} density plots were used to calculate the percent corn yield loss by soybean density and year in each replicated block. Density (dependent variable) versus corn yield loss (independent variable) was fit to the rectangular hyperbolic yield-loss function (Cousens 1985):

$$YL = (I^{*}\mathrm{D})/\left(1 + (I^{*}\mathrm{D})/A\right)$$

using the Solver program in Microsoft Excel (Clay et al. 2012). Solver uses an iterative approach to fit the A and I parameters so that error is minimized and R^2 is maximized. YL is % yield loss, D is the volunteer soybean density, I describes the slope of the curve at low volunteer soybean density, and A estimates maximum corn yield loss.

Treatment means for volunteer soybean control in the herbicide study were arc-sine transformed and analyzed by ANOVA and compared with the Student–Newman–Keuls test at the 0.05 probability level. The random effect was year, and the fixed effect was herbicide treatment. Control differences were observed between years, which may have been due to differences in application (larger plants in 2012) or observation (1 mo earlier in 2012) date or both. Regardless of the specific reason for the differences, data for each year are reported separately.

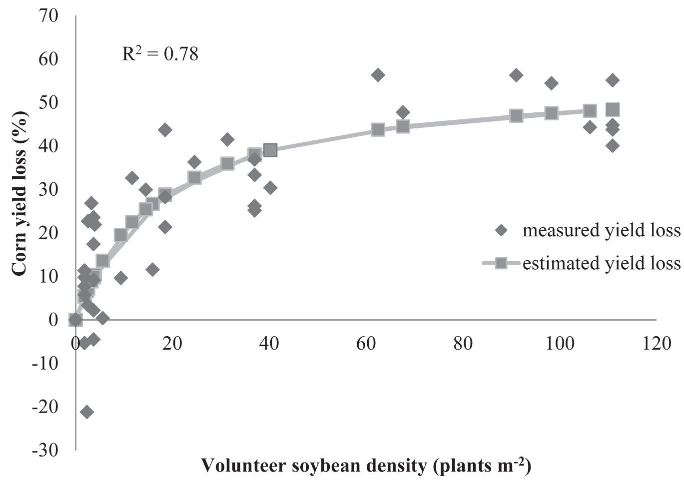

Figure 1. Measured and estimated corn yield loss at various volunteer soybean densities in 2011 and 2012. Measured data points represent the yield loss for individual volunteer soybean density and yield loss measured in an individual plot. Estimated yield loss values were calculated using the hyperbolic model equation: $YL = (I^{*}D)/(1 + (I^{*}D)/A)$. YL is % yield loss, D is the density, I is a variable that describes incremental yield loss at low densities, and A is the estimated maximum yield. The I value was 3.2, and the A value was 56 ($R^2 = 0.78$).

Results and Discussion

Corn Yield Loss. Corn yield in volunteer soybean-free control plots averaged 11,054 kg ha^{-1} in 2011 and 8,796 kg ha^{-1} in 2012. Corn yield was reduced consistently when volunteer soybean plant density was > 5 plants m^{-2} (Figure 1). At lower densities, corn yield was, at times, greater or equal to the volunteer soybean-free control. Corn yield loss ranged from 0 to 53% in 2011 and from 0 to 56% in 2012. Using the hyperbolic model, the incremental yield loss (I) at low soybean density was 3.2%, and the maximum yield loss (A) was 56% ($R^2 = 0.78$). The I and A values indicate that season-long volunteer soybean presence in corn can result in substantial yield losses.

A range of soybean densities were included in this study to provide a wide array of yield loss values. Based on soybean seed yield losses ranging from 57 to 175 kg ha^{-1} (Tukamuhabwa et al. 2002), 6,000 soybean seed kg^{-1}, and 30% plant establishment observed in this study, the range of volunteer soybean densities would be estimated to be between

0 and 31 soybean plants m^{-2}. The parameters for the recalculated equation using the lower densities from this data set were $A = 42$ and $I = 3.9$ ($R^2 = 0.63$). Using an F test (Steel and Torrie 1980), it was calculated that these two hyberbolic yield loss equations were similar ($P = 0.59$). Therefore, the yield loss estimates at low volunteer soybean densities were similar and should be of concern to a producer. Averaging the I values for the two yield loss equations, results indicated that about 3.5 volunteer soybean plants m^{-2} would reduce corn yield by 10%.

The presence of volunteer soybean had less influence on corn yield than some broadleaf weed species including: giant ragweed (*Ambrosia trifida* L.), which had an estimated I value of 13.6 (Harrison et al. 2001); Palmer amaranth (*Amaranthus palmeri* S. Wats) (Massinga et al. 2001) with 91% corn yield loss at 10.5 plants m^{-2}; and common cocklebur (*Xanthium strumarium* L.) (Beckett et al. 1988) where about 6 plants m^{-2} caused 27% yield loss. The corn yield loss to volunteer soybean, however, was similar to common lambsquarters (*Chenopodium album* L.) with one plant m^{-2} resulting in 2.8 to 5.7% yield loss of corn and high densities having 13 to 50% yield loss (Moechnig et al. 2003). Volunteer soybean yield loss was also similar to velvetleaf (Scholes et al. 1995) and redroot pigweed (Knezevic et al. 1994). About 3 velvetleaf plants m^{-2} reduced corn yield by 10%, although the maximum yield loss was about 33% (Scholes et al. 1995). Redroot pigweed densities of 2 to 32 plants m^{-2} reduced corn yield from 5 to 34% (Knezevic et al. 1994) if the weed emerged at the same time as corn.

Volunteer soybean in corn appears to be more competitive than grass weeds in corn at low densities. Clay et al. (2012) summarized the results of several studies of grass weeds in corn and reported the I values to range from 0.32 to 2.04% for green foxtail [*Setaria viridis* (L.) Beauv.], 0.11 to 2.9% for yellow foxtail [*Setaria pumila* (Poir.) Roemer & J.A. Schultes], 1.29 to 2.69% for giant foxtail (*Setaria faberi* Herrm.), and 2.15% for barnyardgrass [*Echinochloa crus-galli* (L.) Beauv.]. All of these I values for grasses are below the I value of 3.2 to 3.5% found for volunteer soybean in this study. The maximum yield loss (A) due to grass interference at high densities was similar to, or somewhat greater than, the maximum loss observed with volunteer soybean (56%). For example, A values for green, yellow, and giant foxtail species ranged from 30 to 53%, 45 to 81%, and 26 to 65%, respectively, whereas the A value for barnyardgrass was about 33% (Clay et al. 2012). These data suggest that volunteer soybean may be more competitive than many grass weeds at lower densities, but at higher densities grass weed presence may result in greater corn yield loss.

Volunteer Soybean Control. The results of the volunteer soybean control study varied between years (Table 1). Control ranged from 65 to 99% in 2011 and from 48 to 96% in 2012. Greater volunteer soybean control in 2011 was likely due to the earlier application, although control ratings were taken about 1 mo later in 2011 compared with 2012. In 2011, the treatments were applied at the V2 growth stage, whereas in 2012, treatments were applied at the V3 to V4 stage. Poorer control at later growth stages has been reported in studies that applied herbicides at younger (V2 to V3) and older (V4 toV6) growth stages in the same growing season (Jhala et al. 2013; Knezevic et al. 2014; Zollinger and Ries 2004).

Most of the herbicides and combinations with glyphosate in 2011 provided $\geq$ 90% control. Exceptions included the low rate of tembotrione (15.3 g ai ha^{-1}) and rimsulfuron (8.8 g ai ha^{-1}), which resulted in about 84 and 65% control, respectively. In 2012, control was more variable when treatments were applied at the V3 to V4 soybean growth stage. Only three treatments (dicamba + diflufenzopyr at two rates, and dicamba alone) provided greater than 90% control. Atrazine treatments in 2012 resulted in poor volunteer soybean control (48 to 59%).

Zollinger and Ries (2004) reported 99% volunteer soybean control when dicamba (with crop oil concentrate) was applied at either 140 or 175 g ae ha^{-1} at the V2 to V3 soybean growth stage. In our study, similar control (96 to 99%) was observed at 280 g ae ha^{-1}; however, this application did not include an adjuvant. Volunteer soybeans may be controlled with a lower dicamba rate if adjuvants are included.

Knezevic et al. (2014) also reported from 90 to 100% control of volunteer glyphosate-resistant soybean 2 wk after application with: glufosinate (594 g ae ha^{-1}); mesotrione + atrazine (105 + 560 g ai ha^{-1}); tembotrione + atrazine (92 + 560 g ai ha^{-1}); and topramezone + atrazine (24.5 + 560 g ai ha^{-1}) when applied at the V2 to V3 growth stage. These same treatments when applied at the V4 to V6 growth stage in their study resulted in 85, 66, 69, and 68% control, respectively. In this research, the high rate of tembotrione (30.6 g ai ha^{-1}) applied

Table 1. Visual evaluation (0 [no control] to 100% [complete control]) of volunteer soybean control in 2011 and 2012 in eastern South Dakota plots using several different herbicides, although all treatments included glyphosate at 870 g ae ha^{-1} and ammonium sulfate at 470 g ha^{-1}. Control ratings were recorded 8 wk after application (WAA) in 2011 and 4 WAA in 2012, with ratings compared within a year. Ratings for treatments were arc-sine transformed for analysis and mean separation with back-transformed data and results reported.

Treatment			Volunteer soybean control	
Chemical name	Trade name	Application rate	2011[a]	2012[b]
			%	
Check			0e[d]	0g
Tembotrione + NIS[c]	Laudis	30.6 g ai ha^{-1}	93.7ab	89.3cd
Tembotrione + NIS	Laudis	15.3 g ai ha^{-1}	84.5c	86.8d
Dicamba + diflufenzopyr	Status	56 + 22 g ae ha^{-1}	99.0a	93.6b
Dicamba + diflufenzopyr	Status	28 + 11.2 g ae ha^{-1}	97.9ab	91.8bc
Atrazine + NIS	Aatrex	1,120 g ai ha^{-1}	97.8ab	58.8e
Atrazine + NIS	Aatrex	560 g ai ha^{-1}	91.3bc	47.5f
Dicamba	Clarity	280 g ae ha^{-1}	98.8a	96.1a
Rimsulfuron + NIS	Resolve	8.8 g ai ha^{-1}	65.4d	88.3cd
P value			< 0.001	< 0.001

[a] Volunteer soybean treated at the V2 growth stage.

[b] Volunteer soybean treated at the V3/V4 growth stage.

[c] NIS is nonionic surfactant added at 0.25% v/v.

[d] Means followed by the same letter within a column are not significantly different based on Fisher's Protected LSD test on arc-sine transformed data at $P < 0.05$. Values reported were back-transformed.

at V3/V4 or V2 growth stage provided 89 or 94%, respectively, which suggests that tembotrione alone may provide acceptable volunteer soybean control.

Previous South Dakota State University research examined some of the same treatments used in this study (Wrage et al. 2004) with applications applied to V2/V3 soybeans. Volunteer soybean control with dicamba + diflufenzopyr at 56 g ae + 22 g ae ha^{-1} ranged from 88 to 92%, which was somewhat lower than our rating of 94 to 99% control. Atrazine at 1,120 g ai ha^{-1}, mixed with crop oil concentrate, provided 85 to 99% control, but when tank-mixed with dicamba at 157 g ae ha^{-1} provided excellent (99%) control (Wrage et al. 2004). Atrazine applied at 1,120 g ai ha^{-1} with a nonionic surfactant in the current study resulted in 59% control when applied to V3/V4 soybean and 98% control when applied to V2 soybean. Wrage et al. (2004) also evaluated dicamba application at 140 g ae ha^{-1} (half-label rate) and reported marginal to poor (45 to 75%) control. At the labeled rate of 280 g ae ha^{-1} used in this study, control ranged from 96 to 99% control. This indicates that dicamba at the full labelled rate is needed to control volunteer soybeans.

Corn yield was not measured in the herbicide efficacy study; however, the corn yield loss study indicated that volunteer soybean in corn can result in yield losses that would impact financial returns. Of course the decision to control volunteer soybean control will depend on the density of the volunteer soybeans, the cost of the herbicide, and the selling price of corn, all of which varies from year to year. Targeting volunteer soybean at an earlier, rather than later, developmental stage provided better control, in this and other studies. Based on 2015 costs, the treatments used in this study added \$5 to 16 ha^{-1} to a glyphosate application (that would not control glyphosate-resistant volunteer soybean). However, based on an estimated 10% loss even to a moderate corn yielding area (12,000 kg ha^{-1}), the yield loss cost of volunteer soybean would be about \$220 ha^{-1} (based on a selling price of \$0.18 kg^{-1} of corn). Therefore, the added herbicide and surfactant costs would be justified.

It must be noted that as new soybean varieties with different herbicide resistant traits are marketed, it will be critical to keep accurate records of the soybean resistant types planted in individual fields so that effective herbicides can be recommended. For example, dicamba products will not effectively control volunteer dicamba-resistant soybean. No matter which variety is planted, however, control should start with prevention by minimizing seed losses during soybean harvest. Atrazine, PRE (not tested in this study), or early POST may be the most cost-effective herbicidal control for any type of volunteer soybean in corn at this time.

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