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Weed Biology and Competition

Volunteer Glyphosate-Resistant Corn Interference and Control in Glyphosate-Resistant Sugarbeet

Andrew R. Kniss, Gustavo M. Sbatella, and Robert G. Wilson*

Glyphosate-resistant (GR) sugarbeet is commonly grown in rotation with GR corn, but there is limited information relating to volunteer GR corn interference or control in GR sugarbeet. Field studies were conducted near Lingle, WY and Scottsbluff, NE in 2009 and 2010 to quantify sugarbeet yield loss in response to volunteer corn density and duration of interference, and determine appropriate control practices for use in GR sugarbeet. Hybrid corn resulted in a similar competitive effect on sugarbeet sucrose yield as clumps of F_2 volunteer corn. Clumps of volunteer corn were controlled 81% compared with 73% for individual plants. Linear regression indicated sucrose yield loss of 19% for each corn plant m^{-2} up to 1.7 plants m^{-2} at three of four experimental sites. Pearson correlation coefficients between percentage sucrose yield loss and proportion of sunlight reaching the top of the sugarbeet canopy ranged from -0.42 to -0.92. The duration of corn interference required to cause a 5% sucrose yield loss (Y_{L5}) ranged from 3.5 to 5.9 wk after sugarbeet emergence (WAE) for hand-weeding or herbicide removal, respectively, due to the length of time herbicide-treated volunteer corn continued to shade sugarbeet plants. Differences between herbicide and hand-removal methods were attributed to the time lag between when the treatments were applied and when the corn ceased to block light from the sugarbeet canopy. Sethoxydim generally provided less volunteer corn control compared with either quizalofop or clethodim, and control increased with the addition of an oil adjuvant. If a grower were to implement a volunteer corn control practice 3.5 WAE, economic sugarbeet yield loss would be avoided. In eastern Wyoming and western Nebraska, the sugarbeet crop will typically have between four to eight true leaves at 3.5 WAE, and therefore this would be an optimal time to control volunteer corn. If volunteer corn is being hand weeded, the Y_{L5} estimate will also increase, and thus the window of time to control volunteer corn would be wider.

Nomenclature: Clethodim; glyphosate; quizalofop; sethoxydim; volunteer corn, *Zea mays* L. ZEAMX; sugarbeet, *Beta vulgaris* L.

Key words: Critical period, weed competition, crop rotation, adjuvant.

La remolacha azucarera resistente al glifosato (GR) es comúnmente cultivada en rotación con maíz GR, pero existe información limitada relacionada a la interferencia o control del maíz voluntario GR en remolacha azucarera GR. En 2009 y 2010 se realizaron estudios de campo cerca de Lingle, Wyoming y Scottsbluff, Nebraska para cuantificar la pérdida en el rendimiento de la remolacha en respuesta a la densidad del maíz voluntario y a la duración de la interferencia, así como para determinar prácticas apropiadas de control para su uso en la remolacha GR. El maíz híbrido tuvo un efecto competitivo similar al de grupos de plantas de maíz voluntario F2 sobre el rendimiento de la sacarosa en la remolacha. Los grupos de plantas de maíz voluntario se controlaron 81% en comparación al 73% de plantas individuales. Una regresión lineal indicó que había una pérdida en el rendimiento de la sacarosa de 19% por cada planta de maíz por m^2 hasta 1.7 plantas por m^2 en tres de los cuatro sitios experimentales. Los coeficientes de correlación Pearson entre el porcentaje de pérdida de rendimiento de la sacarosa y la porción de luz solar que alcanzó el dosel de la remolacha, variaron de -0.42 a -0.92. La duración de la interferencia de maíz requerida para causar un 5% de pérdida en el rendimiento de la sacarosa (Y_{L5}) varió de 3.5 a 5.9 semanas después de la emergencia de la remolacha(WAE) en el caso de remoción por herbicida o deshierba manual, respectivamente, debido a la duración del tiempo que el maíz voluntario tratado con herbicida continuó dando sombra a las plantas de la remolacha. Las diferencias entre el herbicida y la deshierba manual fueron atribuidas al intervalo de tiempo entre cuando los tratamientos se aplicaron y cuando el maíz dejó de bloquear la luz en el dosel de la remolacha. El sethoxydim generalmente proporcionó menor control del maíz voluntariocomparado ya sea con quizalofop o clethodim, y el control se incrementó con la adición de un aceite adyuvante. Si un agricultor fuera a implementar una práctica de control de maíz voluntario 3.5 WAE, la pérdida económica en el rendimiento podría evitarse. En el este de Wyoming y oeste de Nebraska, la remolacha tendría típicamente entre 4 y 8 hojas a las 3.5 WAE, y por lo tanto, este sería un tiempo óptimo para controlar el maíz voluntario. Si el maíz voluntario se elimina manualmente, la estimación Y_{L5} se incrementaría, y por lo tanto, la ventana de oportunidad para controlar el maíz voluntario sería más amplia.

Sugarbeet is an economically important crop in several regions of the United States including southeast Wyoming and western Nebraska. Shortly after its commercial introduction in 2007, adoption of glyphosate-resistant (GR) sugarbeet became widespread, reaching over 95% of U.S. sugarbeet production by 2010 (Kniss 2010). GR sugarbeet adoption occurred rapidly due to its weed control efficacy and economic benefits compared with conventional production practices commonly used in non-GR sugarbeet (Guza et al. 2002; Kemp et al. 2009; Kniss 2010; Kniss et al. 2004; Wilson et al. 2002). In many sugarbeet-growing regions, GR

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corn represents approximately 70% of corn acreage (USDA-ERS 2011) and it is now common for GR sugarbeet to follow GR corn in the crop rotation.

Volunteer GR corn is a problem in other GR rotational crops such as GR soybean and GR cotton. Before the introduction of GR crops, the interference of volunteer corn in soybean had been well documented (Andersen et al. 1982; Beckett and Stoller 1988). In Illinois, volunteer corn density of 5,380 plants ha^{-1} caused up to a 25% soybean yield loss (Beckett and Stoller 1988). In Minnesota, a uniform corn density of 0.4 plants m^{-1} of soybean row caused soybean yield reduction from 14 to 49% depending on location and year, with an average yield loss of 31% across three locations and 2 yr (Andersen et al. 1982). In the same study, volunteer corn densities of 0.8 plants m^{-1} of soybean row caused yield loss ranging from 31 to 78% (Andersen et al. 1982). Cotton appears to be more competitive with volunteer corn compared with soybean. One GR corn plant m^{-1} of GR cotton row reduced cotton lint yield 5 to 8% depending on location (Thomas et al. 2007). Glufosinate-resistant corn caused similar yield loss in glufosinate-resistant cotton, with one corn plant m^{-1} of cotton row decreasing cotton lint yield by 5 to 7% at three locations (Clewis et al. 2008). The duration of corn interference also affects crop yield losses. In soybean, yield loss due to volunteer corn ranged from 2 to 27% when interference occurred from 2 to 10 wk after emergence, respectively (Beckett and Stoller 1988).

Control of volunteer corn in crops can be influenced by many factors, including the F_2 hybrid (Andersen and Geadelmann 1982), adjuvant system (Beckett et al. 1992; Deen et al. 2006; Tao et al. 2007), and the specific herbicide and application rate (Soltani et al. 2006; VanGessel et al. 1997; Young and Hart 1997). Additionally, Deen et al. (2006) theorized that the pattern of volunteer corn distribution (clumps vs. individual plants) could affect the response to graminicides. There is some debate as to the influence of single plants compared with clumps of corn as it relates to both crop interference and control with herbicides. Clewis et al. (2008) used hybrid corn, and theorized that this may have overestimated yield loss. Conversely, Andersen et al. (1982) stated that in a preliminary study, clumps of corn reduced soybean yields much more than single corn plants, and also that clumps of volunteer corn "should be more difficult to control with herbicides than single plants…" However, to date, there are few published accounts directly comparing single plants vs. clumps either with respect to competitive effects or control with herbicides.

Sugarbeet yield is reduced by many broadleaf weed species including tall-statured weeds such as kochia, common lambsquarters, and pigweed (Schweizer 1981), as well as low-statured weeds such as Venice mallow, wild buckwheat, lanceleaf sage, and redstem filaree (Odero et al. 2009, 2010a,b, 2011). Grass weeds are generally considered less competitive with sugarbeet compared with broadleaf weeds (Mesbah et al. 1994, 1995). However, volunteer corn has much broader leaves and a taller growth habit compared with annual grass weeds such as wild oat and green foxtail; therefore it is unclear how competitive volunteer corn will be with the sugarbeet crop on the basis of data published on other weed species.

Although volunteer corn interference and control studies have been conducted in soybean, cotton, and corn, there is limited information relating to volunteer GR corn in GR sugarbeet. Therefore, the objectives of these studies were to (1) compare hybrid corn with volunteer corn with respect to sugarbeet yield reduction potential; (2) quantify sugarbeet yield loss in response to volunteer corn density and duration of interference; and (3) determine appropriate control practices for use in GR sugarbeet.

Materials and Methods

Field studies were conducted at the Sustainable Agriculture Research and Extension Center near Lingle, WY and the Panhandle Research and Extension Center near Scottsbluff, NE in 2009 and repeated in 2010. At Lingle, 'BTS 66RR60' sugarbeet was planted in 76-cm rows at a rate of 173,000 seed ha^{-1} on April 22, 2009 and April 14, 2010. Volunteer corn was planted by hand on May 5, 2009 and April 14, 2010. Corn planting dates were chosen to simulate a realistic emergence timing of volunteer corn. Due to a killing frost (−8 C) on May 8, 2010, all sugarbeet trials at Lingle were rotary hoed and sugarbeet was replanted on May 11 and corn was replanted on May 18, 2010. Soil at Lingle was a Heldt clay (43% sand, 37% silt, 20% clay, 1.9% organic matter, pH 7.8), and plots were 3 by 9 m. sugarbeet was harvested mechanically from one row per plot on October 1, 2009 and September 30, 2010. At Scottsbluff, 'BTS 66RR70' sugarbeet was planted into 56-cm rows at a density of 128,000 seed ha^{-1} on April 28, 2009 and April 27, 2010. Corn was planted by hand on May 11 in 2009 and May 14 in 2010. Soil at Scottsbluff was Glenberg loamy sand (78% sand, 14% silt, 8% clay, 0.9% organic matter, pH 8.1). Plots at Scottsbluff were 3.3 by 9 m, and sugarbeet was harvested mechanically from the center two rows on October 6, 2009 and October 7, 2010. Subsamples from each plot at each location were sent to Western Sugar Cooperative tare laboratory to quantify sucrose content. All trials were kept free of weeds other than GR corn with applications of glyphosate as needed.

Hybrid vs. F_2 Seed Clump Study. A field study was conducted to determine whether interference of hybrid corn plants was similar to clumps of F_2 volunteer corn that would be typical in production fields. At Lingle in both years, corn harvested the previous year was seeded by hand next to the sugarbeet row at a uniform density of 1.2 clumps m^{-2}; a clump contained 50 F_2 corn seed. Hybrid corn seed was planted in the same manner at 1.2 plants m^{-2}. Light measurements were collected on September 8, 2009 and August 14, 2010 using a SunScan canopy analysis system (Model SS1-BF3-C, Delta-T Devices Ltd., Cambridge, UK) by taking four readings at the top of the sugarbeet canopy in a diagonal pattern from the center two rows of each plot and averaging the readings from each plot. Dates were chosen so that light was measured when the sugarbeet crop was near peak photosynthetic capacity: after canopy closure, but before any significant leaf senescence. It was presumed that light interference during this period would be most detrimental to

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sugarbeet yield. At each reading, an ambient light sensor simultaneously took a reading above the volunteer corn canopy, so that the percentage of full sunlight transmitted through the corn canopy and reaching the sugarbeet canopy could be calculated. Corn was allowed to grow season-long, and sugarbeet plots were harvested to determine whether sugarbeet yield was similar between corn treatments.

Density Study. Hybrid corn seed was planted by hand next to the sugarbeet row at densities of 0, 0.3, 0.6, 0.9, 1.2, and 1.7 plants m^{-2}. Light measurements at Lingle were collected on September 8, 2009 and August 14, 2010 using a SunScan canopy analysis system in a similar manner as the hybrid vs. clump study. Corn canopy measurements at Scottsbluff were collected on August 27, 2009 and August 19, 2010 using an LAI-2000 plant canopy analyzer (LI-COR Biosciences, Lincoln, NE 68504) by taking one reading above the corn canopy followed by four readings at the top of the sugarbeet canopy in a diagonal pattern between the two center rows of each plot and averaged. The diffuse noninterceptance values calculated by the LAI-2000 were used as an estimate of the proportion of light reaching the sugarbeet canopy (Anonymous 1992).

Duration Study. Hybrid corn seed was planted by hand next to the sugarbeet row at a uniform density of 1.2 plants m^{-2}, with the exception of the control, in which no corn was planted. Corn was then removed at 3, 6, 9, or 12 wk after sugarbeet emergence (WAE). A season-long interference treatment was also included where corn was not removed. At each removal timing, corn was either sprayed with quizalofop (Assure II ®, E. I. Du Pont de Nemours and Company, Wilmington, DE 19898) at a rate of 62 g ha^{-1} or removed by hoeing the plants to determine whether the method of removal influenced sugarbeet yield loss.

Volunteer Corn Control Studies. Two separate studies were conducted to evaluate the effect of herbicide, adjuvant, and timing on volunteer corn control in sugarbeet. The first study was conducted in 2009 and 2010 at Lingle, WY with the objective to compare various adjuvant systems and application timings for each of four different herbicides when tank-mixed with glyphosate. F_2 seed harvested the previous year was broadcast across the trial area by hand and then incorporated into the soil with light tillage before sugarbeet planting in both years. Two commercial formulations of clethodim were used. Clethodim-240 (Select 2 EC®, Valent U.S.A. Corporation, Walnut Creek, CA 94596) contains 240 g ai L^{-1}; clethodim-116 (SelectMax®, Valent U.S.A. Corporation, Walnut Creek, CA 94596) contains 116 g ai L^{-1}. The clethodim-116 label does not require or recommend an adjuvant other than ammonium sulfate (AMS) when tank-mixed with glyphosate for control of volunteer corn (Anonymous 2010c), and therefore no adjuvant treatments were included with this product. Clethodim-240 recommends use of AMS and crop oil concentrate (COC) (Anonymous 2007), and thus clethodim-240 was applied with and without COC. The quizalofop label recommends either COC or nonionic surfactant (NIS) (Anonymous 2010a); quizalofop was applied with either COC, NIS, high-surfactant oil concentrate (HSOC), or without additional adjuvants. HSOC is a relatively new adjuvant type, promoted as less antagonistic to glyphosate compared with COC. The sethoxydim (Poast®, BASF Corporation, Florham Park, NJ 07932) label recommends COC or methylated seed oil (MSO) (Anonymous 2010b), and therefore sethoxydim was applied with either COC, MSO, or no additional adjuvants. All treatments in this study included glyphosate (Roundup WeatherMax®, Monsanto Company, St. Louis, MO 63167) at 840 g ae ha^{-1} plus AMS at 20 g L^{-1}. A factorial arrangement of 11 herbicide treatments and 2 application timings (sugarbeet two true-leaf stage and sugarbeet eight true-leaf stage) was used.

The second volunteer corn control study was conducted at Scottsbluff, NE in 2009 and 2010 with the objective of determining the best herbicide rate, oil requirement, and application timing for volunteer corn control in GR sugarbeet when not tank-mixed with glyphosate. A factorial treatment arrangement was used, with factors including herbicide (quizalofop, clethodim-116, or clethodim-240); COC (0 or 1% v/v); herbicide rate (low or high end of the recommended rate range on the herbicide label); timing (at the sugarbeet six true-leaf growth stage, or at sugarbeet canopy closure); and volunteer corn distribution (individual plants or clumps). The low and high rate for quizalofop was 47 and 64 g ai ha^{-1}, respectively; 108 and 144 g ai ha^{-1} for clethodim-240, respectively; and 72 and 108 g ai ha^{-1} for clethodim-116, respectively. Volunteer corn was planted next to the sugarbeet row by hand in either clumps or as individual seeds similar to the hybrid seed vs. F_2 clump study. Glyphosate was applied as needed to control weeds other than volunteer corn in the Nebraska study.

In both studies, volunteer corn plants were counted in each plot 2 wk after the final herbicide application. Volunteer corn counts from treated plots were divided by the number of plants in control plots to calculate percent volunteer corn control.

Statistical Analysis. For all studies, treatments were arranged in a randomized complete block design with four replicates. For the hybrid vs. clump study, total sucrose yield, root yield, sucrose content, and the percentage of full sunlight reaching the sugarbeet canopy was calculated, then a *t* test was used to determine whether these variables were affected differently by hybrid corn and clumps of F_2 corn.

ANOVA was conducted on total sucrose production per acre for the density and duration studies. Locations were analyzed separately when a location-by-treatment interaction was observed. For the density study, the effect of location, volunteer corn density, and the interaction between these terms were considered fixed effects. Linear and nonlinear regression models were used to describe the relationship between sugarbeet sucrose yield loss and volunteer corn density. Akaike's information criterion (AIC) was used for model selection, and linear regression models were determined to provide the best fit to the density data. Pearson's correlation analysis was conducted to determine the relationship between sucrose yield loss and the percentage of full sunlight transmitted to the top of the sugarbeet canopy.

For the duration of interference study, location, method of volunteer corn removal, timing of volunteer corn removal, and all interactions were considered fixed effects. After ANOVA, nonlinear regression was used to describe the

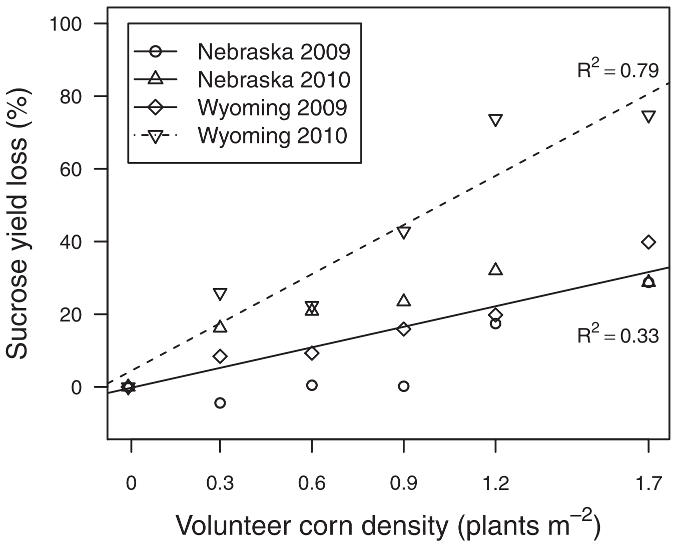

Figure 1. Sugarbeet sucrose yield loss in response to corn density at four experimental sites in Wyoming and Nebraska in 2009 and 2010. Each point represents four replicates within a site. Linear regression equation for Wyoming, 2010: $y = 4.0 + 45x$. Linear regression for the combined Nebraska and Wyoming 2009 sites: $y = -0.4 + 19x$. Intercepts were not significantly different from 0 for either regression ($P < 0.4$); slopes were significantly different from 0 for both regressions ($P < 0.0001$).

relationship between sugarbeet sucrose yield loss and timing and method of volunteer corn removal. A three-parameter log-logistic equation similar to that proposed by Seefeldt et al. (1995) was used:

$$Y_L = d/\{1 + \exp[b(\log(x) - \log(e))]\} \qquad [1]$$

where Y_L is the percentage of sugarbeet sucrose yield loss, x is the volunteer corn removal time expressed in WAE, b is a slope parameter indicating the steepness of the curve around the inflection point, d is the upper asymptote, and e indicates the value of x where the inflection point occurs. The duration of interference required to cause a 5% yield loss (Y_{L5}) was then calculated from the model. A likelihood ratio test was used to determine whether the method of volunteer corn removal significantly affected the time required to observe a 5% sucrose yield loss. All statistical analysis was conducted using the R language (R Development Core Team 2009) and nonlinear regression was conducted using the drc package in R (Ritz and Streibig 2005). For volunteer corn control studies, ANOVA was conducted on volunteer corn control data, and means were separated using Fisher's Protected LSD test where appropriate.

Results and Discussion

Hybrid vs. F_2 Seed Clump Study. Hybrid corn resulted in a similar competitive effect on sugarbeet as clumps of F_2 volunteer corn. Within each year of the study, no differences were observed between hybrid corn and clumps of F_2 volunteer corn for sugarbeet root yield ($P > 0.16$), sugarbeet sucrose content ($P > 0.16$), total sucrose production per hectare ($P > 0.11$), or percentage of full sunlight reaching the sugarbeet canopy ($P > 0.28$). Therefore, even though hybrid corn seed was used in the duration and density studies, the results were representative of true F_2 volunteer corn, and thus conclusions drawn here will be applicable to sugarbeet producers for decision making.

Density Study. A significant interaction between location and volunteer corn density was observed ($F_{3,85} = 9.5$, $P < 0.0001$) when all data were combined. Several previous studies have also documented a strong effect of location on yield losses due to volunteer corn (Beckett and Stoller 1988; Clewis et al. 2008). When the Wyoming 2010 site was removed, no location-by-corn density interaction was present ($F_{2,64} = 0.71$, $P = 0.49$); therefore, the Wyoming 2010 site was analyzed separately and the other three sites were combined for analysis. When the remaining three sites were analyzed, the main effect of location had a significant effect on total sucrose production ha^{-1} ($F_{2,64} = 80.8$, $P < 0.0001$). Total sucrose production in the absence of corn interference averaged 15,000 and 11,300 kg ha^{-1} at Nebraska in 2009 and 2010, respectively, and 9,600 and 13,000 kg ha^{-1} at Wyoming in 2009 and 2010, respectively.

The effect of corn density was significant at the Wyoming site in 2010 ($F_{1,20} = 82.5$, $P < 0.0001$), and when the other three sites were combined for analysis ($F_{1,64} = 38.8$, $P < 0.0001$). On the basis of AIC, linear regression on the replicate data provided a better fit to the sucrose yield loss data compared with nonlinear regression models. Linear relationships describing crop yield loss due to volunteer corn interference have been described previously by Beckett and Stoller (1988) in soybean. When the Wyoming site in 2009 was combined with both sites in Nebraska, the slope for the regression indicated a 19% sucrose yield loss for each corn plant m^{-2} up to 1.7 plants m^{-2} (Figure 1).

The slope for the Wyoming 2010 site predicted a 45% sucrose yield loss for each corn plant m^{-2} up to 1.7 plants m^{-2} (Figure 1). The Wyoming site in 2010 was replanted because of a killing frost, and this is the most probable source of the location-by-corn density interaction, as well as the large differences in corn interference effects. Although corn was replanted after the second sugarbeet planting, some of the corn planted at the first timing was not killed by the freezing temperatures, and was able to emerge at the same time or slightly after sugarbeet planting, and thus some corn emerged before sugarbeet. The large difference in slope between the Wyoming site in 2010 and the other three sites may be an area for future research. If the increased interference observed at the Wyoming 2010 site was indeed a function of time of emergence, it would illustrate the importance of starting with a weed-free field, as sugarbeet was less susceptible to corn interference when it was able to emerge at a similar time as or before the corn. Future research should be directed to determine the effect of relative emergence dates on volunteer corn interference in sugarbeet. Although the yield loss observed at Wyoming in 2010 is much greater than at the other three sites, this level of yield loss is similar to previous reports in soybean. For each additional clump of volunteer corn per hectare, soybean yield was reduced by 0.0035 to 0.0045%, depending on the year (Beckett and Stoller 1988); this is a 35 to 45% yield reduction for each volunteer corn clump m^{-2}, which is similar to the Wyoming site in 2010.

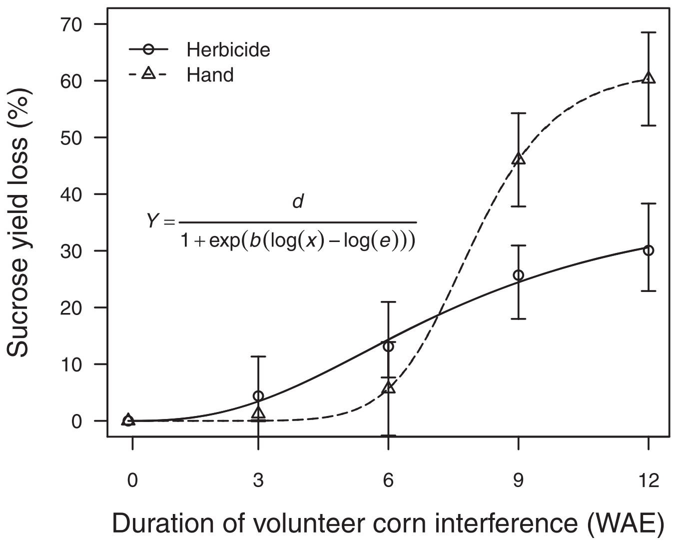

Figure 2. Effect of duration of corn interference on sugarbeet sucrose yield as influenced by corn removal method near Lingle, WY in 2010. Model parameters (and standard error) for herbicide removal: $b = -2.6$ (1.96), $d = 39.7$ (22.72), $e = 7.5$ (3.99). Model parameters (and standard error) for hand removal: $b = -8.2$ (2.38), $d = 62.2$ (5.48), $e = 7.9$ (0.41).

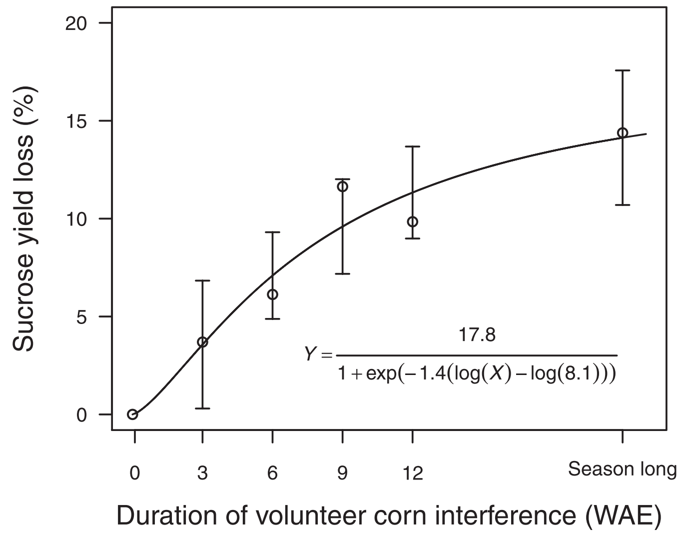

Figure 3. Effect of duration of corn interference on sugarbeet sucrose yield loss averaged over two removal methods and three locations near Lingle, WY in 2009, and Scottsbluff, NE in 2009 and 2010.

Shading caused by weeds growing taller than the sugarbeet reduces root yields (Dotzenko and Arp 1971). In this study, the correlation between percentage sucrose yield loss and proportion of sunlight reaching the top of the sugarbeet canopy was much stronger for the Wyoming 2010 site ($r = -0.92$, $P < 0.0001$) compared with any of the other sites, which ranged from -0.42 to -0.43. This could be attributed to a greater shading effect by the corn plants that emerged before the replanted sugarbeet. Nevertheless, when sugarbeet emerged before or at a similar time as corn, such as the case of the remaining three sites, competition for light appeared to still be a significant component of yield loss.

Duration Study. A significant three-way interaction between location, method of corn removal, and duration of corn interference was observed ($F_{3,107} = 5.0$, $P = 0.0028$) when all data were combined. When the Wyoming 2010 site was removed, no location interactions were observed ($P > 0.1$); therefore, the Wyoming 2010 site was analyzed separately and the other three sites were combined for analysis. The main effect of location had a significant effect on total sucrose production when the three locations were combined for analysis ($F_{2,79} = 187.7$, $P < 0.0001$). In the absence of corn interference, total sucrose production was 15,800 and 12,400 kg ha^{-1} at the Nebraska 2009 and Nebraska 2010 sites, respectively, and 10,300 and 12,000 kg ha^{-1} at the Wyoming 2009 and Wyoming 2010 sites, respectively.

At the Wyoming 2010 site, there was a significant interaction between method of corn removal and duration of corn interference ($F_{1,27} = 8.9$, $P = 0.0061$). The three-parameter log-logistic equation was used to describe sucrose yield loss data as influenced by duration of corn interference for each removal method (Figure 2). The duration of corn interference required to cause a 5% sucrose yield loss (Y_{L5}) was estimated to be 3.5 and 5.9 WAE for the herbicide and hand-removal methods, respectively. A likelihood ratio test indicated that the Y_{L5} values were significantly different between the two removal methods ($P = 0.0316$). Unlike the hand-removal method, herbicide removal of corn plants does not immediately stop the corn plants from intercepting sunlight from the sugarbeet canopy. Previous studies in soybean have indicated a similar effect. Hand removal of volunteer corn resulted in greater soybean yield compared with herbicide removal with either fluazifop or wick applications of glyphosate (Beckett and Stoller 1988). The authors attributed this difference to herbicide-treated plants continuing to interfere with soybean after the volunteer corn was removed by hand.

The light interception data in the density study indicated that competition for light was extremely important at the Wyoming site in 2010, and thus the difference between removal methods at this site can be attributed to the time lag between when the treatments were applied and when the corn ceased to block light from the sugarbeet canopy. Quizalofop took 7 to 10 d to desiccate moderately sized corn plants, and even then the standing residue of the corn plant may have blocked some sunlight from reaching the sugarbeet canopy. Conversely, the effect of hand removal was immediate, and light began reaching the sugarbeet canopy as soon as the treatment was applied.

When the remaining three sites were analyzed together, there was not a significant interaction between corn removal method and duration of corn interference ($F_{1,79} = 0.79$, $P = 0.3754$); therefore main effects of removal method and duration of interference are presented for these locations. The three-parameter log-logistic model was fit to sucrose yield loss data averaged over both removal methods and three locations (Figure 3). The estimated d parameter indicated a maximum sugarbeet sucrose yield loss of 17.8% in response to season-long corn interference. The Y_{L5} when averaged over the three locations and two removal methods was estimated to be 4.1

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Table 1. Volunteer corn control with four different herbicides and various adjuvant systems tank-mixed with glyphosate applied at two sugarbeet growth stages near Lingle, WY, 2009 and 2010.

Year	Herbicide	Rate	Adjuvant	Volunteer corn control	
				Two true-leaf[a]	Eight true-leaf
		g ai ha^{-1}		%	
2009	Quizalofop[b]	124	AMS[c]	53	97
	Quizalofop	124	AMS + COC	45	99
	Quizalofop	124	AMS + HSOC	23	100
	Quizalofop	124	AMS + NIS	49	99
	Sethoxydim	54	AMS	52	79
	Sethoxydim	54	AMS + COC	61	69
	Sethoxydim	54	AMS + MSO	39	75
	Clethodim-116	54	AMS	64	100
	Clethodim-240	108	AMS	80	97
	Clethodim-240	108	AMS + NIS	56	96
LSD (0.05) for 2009				29	
2010	Quizalofop	124	AMS	100	67
	Quizalofop	124	AMS + COC	100	100
	Quizalofop	124	AMS + HSOC	100	67
	Quizalofop	124	AMS + NIS	100	78
	Sethoxydim	54	AMS	50	56
	Sethoxydim	54	AMS + COC	94	74
	Sethoxydim	54	AMS + MSO	94	52
	Clethodim-116	54	AMS	100	82
	Clethodim-240	108	AMS	94	67
	Clethodim-240	108	AMS + NIS	100	85
LSD (0.05) for 2010				22	

[a] Application timings relate to sugarbeet growth stage, not volunteer corn growth stage.

[b] All herbicide treatments were applied with glyphosate (Roundup Weathermax) at 840 g ae ha^{-1}.

[c] Abbreviations: AMS, ammonium sulfate; COC, crop oil concentrate; HSOC, high-surfactant oil concentrate; NIS, nonionic surfactant; MSO, methylated seed oil.

WAE, which is similar to the Y_{L5} values at the Wyoming site in 2010. This suggests that even though the maximum yield loss was greater for the Wyoming site in 2010 compared with the other three sites, the duration of interference required to observe a 5% yield loss was similar across all four experimental sites.

The main effect of removal method was marginally significant when data for the three sites were pooled ($F_{1,79}$ = 3.6, P = 0.0608). When averaged over duration of interference and the three sites excluding Wyoming in 2010, hand removal resulted in less sugarbeet sucrose yield loss (6.6%) compared with herbicide removal (8.6%). This is consistent with the early-season findings of the Wyoming site in 2010, and is probably attributable to the time lag between herbicide application and when light interference ceased.

Volunteer Corn Control Studies. In the Wyoming study, a significant year-by-treatment-by-timing interaction was observed ($F_{9,80}$ = 2.2, P = 0.0336); therefore volunteer corn control was analyzed separately by year. In 2009, there was a highly significant effect of application timing ($F_{1,40}$ = 74.8, P < 0.0001), but only a marginal effect of herbicide treatment ($F_{9,40}$ = 1.9, P = 0.0857) or herbicide-by-timing interaction ($F_{9,40}$ = 1.9, P = 0.0832). When averaged over herbicide treatments in 2009, volunteer corn control was 91% at the eight true-leaf application timing, compared with 52% when treatments were applied at the two true-leaf stage of sugarbeet. In 2009, spring conditions were relatively cool, and sugarbeet emerged before most of the volunteer corn. When sugarbeet reached the two true-leaf stage, not all of the corn had yet emerged. When sugarbeet reached the eight true-leaf stage, a majority of the corn had emerged, but was still relatively small, and thus greater control was observed at this later application timing because more of the volunteer corn was exposed. At the eight true-leaf application timing, all herbicides except sethoxydim provided ≥ 96% volunteer corn control, regardless of adjuvant system (Table 1). Within a herbicide, the adjuvant system had no significant effect on volunteer corn control in 2009.

In the 2010 Wyoming study, highly significant effects of herbicide treatment ($F_{9,40}$ = 5.7, P < 0.0001) and application timing ($F_{1,40}$ = 36.4, P < 0.0001) were observed with respect to volunteer corn control, with a marginal interaction between the two factors ($F_{9,40}$ = 1.9, P = 0.0788). Application timing had the opposite effect in 2010 as in the 2009 study, with the two true-leaf application timing resulting in 93% volunteer corn control when averaged over herbicide treatments compared with 73% control at the eight true-leaf application

Table 2. Volunteer corn control with three different herbicides as influenced by crop oil concentrate averaged over 2 yr, two herbicide rates, and two application timings, near Scottsbluff, NE, 2009 and 2010.

Herbicide	Volunteer corn control	
	Without crop oil concentrate	With crop oil concentrate
	%	
Quizalofop	66	83
Clethodim-240	67	82
Clethodim-116	83	80
LSD (0.05)	12	

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timing. Sugarbeet had to be replanted in 2010 and most volunteer corn emerged at a similar time as the crop. Nearly all volunteer corn had emerged by the time sugarbeet had reached the two true-leaf stage, and the volunteer corn was relatively large ($\geq$ 40 cm) by the time the eight true-leaf application was made. Thus, volunteer corn control was related to the size of volunteer corn at the time of application in 2010.

Because of the potential for crop phytotoxicity of many conventional sugarbeet herbicides, sugarbeet growers have become accustomed to choosing herbicide rates and making herbicide applications based on sugarbeet growth stage rather than weed size. Knowing the crop stage was a critical factor in reducing the potential for crop injury. Although this is less important in GR sugarbeet, sugarbeet growers, researchers, and crop consultants still often discuss herbicide application timing in relation to crop stage. The differences between years in the Wyoming control study illustrate one of the weaknesses of this approach. The differences between years and herbicide timings was less a result of herbicide efficacy, but rather a difference in the proportion of the volunteer corn population that was actually exposed to the herbicide.

The adjuvant system had no effect on volunteer corn control with quizalofop or clethodim at the two true-leaf application timing (Table 1). Volunteer corn control with sethoxydim was increased by adding either COC or MSO compared with only AMS. At the eight true-leaf application timing, COC increased control of volunteer corn with quizalofop to 100% compared with $\leq$ 78% for other adjuvant systems. Similarly to 2009, volunteer corn control with clethodim was not influenced by adjuvant system, and sethoxydim generally provided less control compared with quizalofop or clethodim.

In the Nebraska study, there was a significant interaction between herbicide and COC ($F_{2,239} = 5.5$, $P = 0.0046$), and significant main effects of herbicide rate ($F_{1,239} = 4.6$, $P = 0.0324$), volunteer corn distribution ($F_{1,239} = 7.0$, $P = 0.0087$), and application timing ($F_{1,239} = 132.2$, $P < 0.0001$). Adding COC increased volunteer corn control with quizalofop and clethodim-240 by 17 and 15%, respectively (Table 2). Volunteer corn control with clethodim-116 was not affected by adding COC. When averaged over herbicides, COC presence, and spatial distribution, the earlier application timing (six true-leaf) controlled volunteer corn 93%, compared with only 61% when the application was made at canopy closure. This was similar to the Wyoming study in 2010, where the earlier application timing provided greater control of volunteer corn. However, the earlier timing in the Nebraska study was more similar to the latest timing in the Wyoming study (six true-leaf compared with eight true leaf, respectively). In both studies the greatest corn control was obtained when herbicides were applied after most of the volunteer corn had emerged, but before it had reached 40 cm in height.

Increasing the herbicide rate would often be the easiest way to increase volunteer corn control if applications are made later than optimal; however, only a modest increase in corn control was achieved by increasing the herbicide rates in the Nebraska study. When averaged over herbicides, COC, timing, and spatial distribution, the higher end of the rate range resulted in 80% volunteer corn control compared with 74% control at the lower rates. The relatively small response to herbicide rate makes timely control of volunteer corn imperative. Clumps of volunteer corn were controlled 81% compared with 73% for the individual plants. Although this difference was statistically significant, it would probably not have practical implications, especially if volunteer corn densities are great enough to warrant treatment. Most volunteer corn growing in producer fields will be clumps, and thus treatments that control single plants should perform similarly to slightly better on clumps of corn.

The results of the control studies are largely consistent with several previous reports in the literature, including Deen et al. (2006), who found that when tank-mixed with glyphosate, adding COC to quizalofop or NIS to clethodim increased volunteer corn control in multiple experiments. When tank-mixed with glyphosate, quizalofop control of volunteer corn was enhanced by NIS and petroleum oil concentrate (Tao et al. 2007). However, petroleum oil concentrate antagonized glyphosate control of velvetleaf in the same study. The addition of AMS reduced this antagonism, and the combination of AMS and petroleum oil concentrate provided greater volunteer corn control compared with either adjuvant alone (Tao et al. 2007). Petroleum oil concentrate increased volunteer corn control with quizalofop compared with either no adjuvant or NIS (Beckett et al. 1992).

Sethoxydim provided the least volunteer corn control in both years of the Wyoming study. Similar results have been found by Beckett et al. (1992). Sethoxydim at 56 g ai ha^{-1} controlled volunteer corn $\leq$ 13% regardless of surfactant system compared with 94 to 99% control with quizalofop plus petroleum oil concentrate (Beckett et al. 1992). Quizalofop has been shown to provide greater control of volunteer corn compared with clethodim and sethoxydim when the recommended adjuvants were used in glyphosate tank mixes (Soltani et al. 2006). However, clethodim has been shown in two separate studies to provide greater control of sethoxydim-resistant corn hybrids compared with quizalofop (VanGessel et al. 1997; Young and Hart 1997).

The results of these studies, when taken together, can be used to define thresholds for controlling volunteer corn in sugarbeet. In the density study, sucrose yield loss at three of the four sites was approximately 19% for each additional corn plant m^{-2}. At these three sites, corn emerged slightly after sugarbeet. At the fourth site, corn emerged simultaneously or slightly before sugarbeet, and sucrose yield loss reached 45% for each corn plant m^{-2}. From an economic standpoint, if the economic loss caused by volunteer corn is greater than or equal to the cost of controlling volunteer corn, then it will be financially beneficial to implement the control practice. Therefore the decision on whether to control volunteer corn will depend not only on the sugarbeet yield loss, but the price the grower receives for the crop as well as the cost of herbicide and application or hand labor.

Results from the control studies indicated that there are several effective options for controlling volunteer corn. Currently, these products cost approximately \$37 ha^{-1}. If expected sugarbeet root yields were 56 Mg ha^{-1} at a price of \$44 Mg^{-1}, volunteer corn density of 0.03 to 0.08 plants m^{-2}

would cause an economic loss equal to the cost of control (assuming a 19% or 45% yield loss for each corn plant m^{-2}, respectively). As the cost of control increases, the critical density will also increase; likewise, if the price the grower is paid or the expected yield increases, the critical density will decrease.

In the duration of interference study, Y_{L5} values ranged from 3.5 to 5.9 WAE, depending on the site and method of volunteer corn removal. A relatively high corn density was used in the duration of interference studies, and thus the Y_{L5} estimates are conservative compared with volunteer corn densities that a sugarbeet grower would typically encounter. Lower volunteer corn density would result in greater Y_{L5} estimates; therefore in most practical situations, if a grower were to implement a control practice at or before 3.5 WAE, economic yield loss would be avoided. In eastern Wyoming and western Nebraska, the sugarbeet crop will typically have between four to eight true leaves at 3.5 WAE, and therefore this would be an optimal time to control volunteer corn on the basis of the volunteer corn control studies. If volunteer corn is being hand weeded, the Y_{L5} estimate will also increase, and thus the window of time to control volunteer corn would be wider.

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