Biological Significance of Low Weed Population Densities on Sweet Corn

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Some weed plants escape current weed management systems in nearly all sweet corn (*Zea mays* L.) fields. Decisions to target escaped weeds, and justify the added expense, require knowledge of the biological significance of low weed population densities on the crop. The objectives were to (i) quantify giant ragweed (*Ambrosia trifida* L.) area of influence (AOI) on sweet corn, and (ii) investigate potential links among giant ragweed AOI and crop growth, development, and yield attributes. All measured crop attributes were influenced by giant ragweed AOI, including plant height near silk emergence (HT), thermal time to silk emergence, green ear mass (GMASS), husked ear mass (HMASS), filled ear length (LENGTH), ear width at midpoint (WIDTH), and kernel moisture (MOIST). Proportion of silked plants declined for sweet corn within 160 cm of giant ragweed, with less than one-half of the crop plants producing a marketable ear within 42 cm of giant ragweed. Weed interference harmed ear attributes most when crop development was delayed, as evidenced by path analysis of giant ragweed's direct and indirect associations with yield attributes. Even the lowest population density of giant ragweed can be costly, with yield loss estimates ranging from \$0.86 to \$8.75 per weed plant, depending on crop market type.

Total weed control in most vegetable crops is difficult to obtain, despite extensive targeting of weed seedlings with mechanical and chemical control tactics. Over one-half of sweet corn fields suffer yield loss due to weed interference, as evidenced by surveys of 175 grower's fields throughout Illinois, Minnesota, and Wisconsin (Williams et al., 2008). In recent years, giant ragweed has become one of the most competitive weeds of vegetable and agronomic crops in the north central United States. When giant ragweed occurred in sweet corn fields, a relatively low population density was observed (e.g., 0.49 plants m^{-2}); nonetheless, yield losses as high as 37% were incurred (Williams and Masiunas, 2006, Williams et al., 2008). Such high yield losses may justify additional expense for control of a low weed population density, including the use of hand weeding or additional postemergence herbicide application.

Decisions about managing sparse densities of weeds include considering the impact of noncontrolled weed populations. Most giant ragweed plants emerging with or after sweet corn emergence rarely have time to produce viable seed by crop harvest (Williams et al., 2008); therefore, the major threat of noncontrolled giant ragweed is losses in crop yield or quality. Several crop quality attributes are affected by weed interference. For instance, consumer expectations for fresh market dictate that certain attributes such as uniformity in maturity (i.e., MOIST) and appearance (e.g., tipfill) can be more important than yield. The sweet corn harvest period is short and quality begins to decline immediately following harvest, particularly in *sugary* (*su*) endosperm types (Tracy, 2001). Recent studies have quantified yield response of sweet corn to weed density; however, response of important quality attributes to low weed density is poorly known. Because of postharvest changes in crop quality, researchers have limited time to characterize specific ear attributes. Often, far fewer ears can be individually characterized for quality than the total number of ears used to determine yield (e.g., up to 70 ears per experimental unit) (Williams and Masiunas, 2006).

The AOI experiments overcome challenges of studying low densities of weeds by measuring the effect of a single weed plant on crop growth on all sides of the weed plant (Jordan, 1989). Observations of the crop are taken at regularly spaced intervals from the weed. However, lack of independence among sampling points complicates the use of traditional statistical analyses. For instance, significance testing of curves fit to different treatments using regression is invalid when sampling points are dependent. Correlated responses, including spatial autocorrelation between adjacent sampling points along the row, can be analyzed using MANOVA (Johnson and Wichern, 2002). Jordan (1989) demonstrated the use of "profile" MANOVA on AOI experiments, whereby a set of multivariate tests are applied to biologically important hypotheses. These hypotheses can address practical questions such as whether a crop attribute was influenced by weed interference or if weed AOI differentially affected crop cultivars.

The aim of this work was to elucidate the effects of low weed population density on sweet corn development and yield

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Abbreviations: AOI, area of influence; GDD, growing degree days, thermal time from emergence to silking; GMASS, green ear mass; HMASS, husked ear mass; HT, plant height near silk emergence; IPAR, intercepted photosynthetically active radiation; LAI, leaf area index; LENGTH, filled ear length; MOIST, kernel moisture; WCF, weed-competition free; WIDTH, ear width at midpoint.

attributes important to marketability. Using AOI experiments, the objectives were to (i) quantify giant ragweed AOI on sweet corn and (ii) investigate potential links among giant ragweed AOI and crop growth, development, and yield attributes.

Materials and Methods

Experimental Methodology

Field experiments were conducted in 2007 and 2008 at the University of Illinois Vegetable Research Farm near Urbana, IL. Experiments were conducted in separate fields each year, and the previous crop was soybean [*Glycine max* (L.) Merr.]. The soil was a Flanagan silt loam (fine, smectitic, mesic Aquic Argiudolls) averaging 3.5% organic matter and pH of 6.2. Fields received 129 kg N ha^{-1}, 113 kg P ha^{-1}, and 135 kg K ha^{-1} shortly before planting each year. Seed of giant ragweed was collected in the previous fall of each year near Dekalb, IL, stored at 4°C, and cold stratified 2 mo before planting.

Two *su* sweet corn hybrids of similar maturity, Quickie and Spirit, were arranged in a randomized complete block design with seven replications. Plot size measured 9.1 by 9.1 m, with the crop planted at 83,300 seed ha^{-1} on 76-cm rows oriented north-to-south on 23 Apr. 2007 and 22 Apr. 2008. Immediately after crop planting, approximately 15 seed of giant ragweed were hand-planted 5 cm deep in the center two rows, at exactly one-half the length of the plot. Three weeks after crop emergence, sweet corn was thinned to 70,000 plants ha^{-1} and giant ragweed was thinned to a single plant per plot. Weeds other than giant ragweed were controlled with a preemergence application of 1.78 kg *S*-metolachlor (2-chloro-*N*-(2-ethyl-6-methylphenyl)-*N*-(2-methoxy-1-methylethyl)acetamide) ha^{-1} and hand weeding as needed. One month after emergence, 12 individual sweet corn plants per plot, within the same row as giant ragweed, were labeled, targeting the following distances along both sides of giant ragweed: 8, 23, 53, 99, 160, and 236 cm.

Data Collection

Labeled plants were monitored daily for silk emergence beginning before sweet corn tassle emergence through crop harvest. Cumulative growing degree days (GDD) were determined beginning with crop emergence through silk emergence using a base temperature of 10°C (Illinois State Water Survey, Champaign, IL). After silk emergence in weed-competition-free (WCF) plants (≥236 cm away from giant ragweed), leaf area index (LAI) and intercepted photosynthetically active radiation (IPAR) were quantified near solar noon using a linear ceptometer (AccuPAR Linear Ceptometer PAR-80; Decagon Devices, Pullman, Wash.) in weed-free areas of each plot to characterize crop canopy density. The HT was measured on each labeled plant.

Labeled plants were harvested 3 wk after WCF plants silked; 2 July 2007 and 14 July 2008. The primary ear of each labeled plant was hand-harvested, regardless of size. Harvested ears ≥ 4.4 cm in diameter were considered marketable. All harvested ears were measured for GMASS, HMASS, LENGTH, and WIDTH. Kernels were removed from the cob with a power corn cutter, and percentage MOIST was determined gravimetrically using a 20-g sample of kernels.

Statistical Analyses

Crop response to giant ragweed AOI was calculated for HT, GDD, GMASS, HMASS, LENGTH, WIDTH, and MOIST. To standardize crop variables for comparison purposes, a relative crop response was calculated using WCF plant response. The observation at each interval away from giant ragweed was divided by the average WCF plant response, for each hybrid and year. For both observed and relative crop responses, variances were found to be homogeneous between years using the modified Levene's test (Neter et al., 1996). Diagnostic tests of residuals found that the data also complied with assumptions of homoschedasticity and normality; therefore, data were not transformed before analyses. Weed-competition-free HT, LAI, and IPAR were analyzed using a RCB ANOVA model that included replicates nested within year, year, and hybrid effects using the generalized linear models (GLM) subroutine of SYSTAT 11.0.1 (SYSTAT Software Inc., Chicago, IL).

Relative crop responses (HT, GDD, GMASS, HMASS, LENGTH, WIDTH, and MOIST) were individually analyzed with profile MANOVA (Jordan, 1989) using a RCB ANOVA model that included replicates nested within year, year, and hybrid effects. Three biologically important hypotheses were tested. The first hypothesis was that giant ragweed had no effect on the crop attributes. The second hypothesis was the crop response to giant ragweed AOI (i.e., spatial distribution of the interference effects) was similar between sweet corn hybrids. Hypotheses 1 and 2 were tested using the MANOVA subroutine of SYSTAT 11.0.1 and the multivariate test statistic used was the Wilks' Lambda statistic. A third hypothesis was that the magnitude of crop response was similar between hybrids. The third hypothesis was tested by summing the multiple measurements along the crop row of each and analyzed with a RCB ANOVA model that included replicates nested within year, year, and hybrid effects using the GLM subroutine of SYSTAT 11.0.1. Analyses were conducted on crop response matrices from all 12 distance intervals established in the study, with one exception. Very few ears on sweet corn plants located within 23 cm of giant ragweed produced kernels; therefore, MOIST was analyzed using distance intervals > 23 cm away from giant ragweed. Data were pooled across years since no effect related to year was detected at $\alpha = 0.05$. Relative crop response also was regressed against giant ragweed AOI using nonlinear regression in SigmaPlot 10.0 (SYSTAT Software, Inc., Chicago, IL) to describe functional relationships between the crop and weed, pooling data across hybrids when hybrids were not significant ($\alpha = 0.05$) according to hypothesis testing described above. A corrected R^2 ($\sim R^2$) was calculated as unity minus residual sum of squares divided by corrected total sum of squares.

The number of plants silked within 5 d of WCF plants and the number of marketable ears were evaluated using cumulative frequency distributions. Frequency distributions of silked plants and marketable ears were calculated for both hybrids, as a fraction of total plants and ears observed, respectively. Frequency distributions for the hybrids were then examined for similarity using the Kolmogorov-Smirnov (KS) statistic, which can be used to test the agreement (central tendency, dispersion, and skewness) between empirical frequency distributions (Kiefer, 1959). The nonparametric test evaluates maximum differences between corresponding intervals of two or more numerical distributions. The hypothesis being tested was that the sweet corn hybrids had a similar response to giant ragweed AOI.

Table 1. Results from MANOVA (Hypotheses 1 and 2) and ANOVA (Hypothesis 3) for the effect of giant ragweed area of influence (AOI) on sweet corn attributes. Hypothesis 1: Giant ragweed AOI had no effect on crop attribute. Hypothesis 2: Shape of AOI responses was similar between hybrids. Hypothesis 3: Magnitude of AOI responses was similar between hybrids.

Attribute†	Hypothesis 1			Hypothesis 2			Hypothesis 3	
	Wilks' Lambda	*F* ratio	*P* value	Wilks' Lambda	*F* ratio	*P* value	*F* ratio	*P* value
HT	0.001	918.4	<0.001	0.662	0.511	0.871	0.278	0.603
GDD	<0.001	3118.7	0.014	0.064	1.218	0.617	0.034	0.857
GMASS	0.008	97.8	<0.001	0.326	1.548	0.260	1.779	0.197
HMASS	0.005	155.1	<0.001	0.488	0.787	0.658	1.957	0.177
LENGTH	0.006	135.5	<0.001	0.328	1.540	0.262	7.968	0.011
WIDTH	0.001	1262.1	<0.001	0.466	0.860	0.605	1.192	0.288
MOIST	<0.001	4231.1	<0.001	0.478	1.364	0.317	4.302	0.056

† HT, plant height near silk emergence; GDD, thermal time from emergence to silking; GMASS, green ear mass; HMASS, husked ear mass; LENGTH, filled ear length; WIDTH, ear width at midpoint; MOIST, kernel moisture.

Potential links between giant ragweed AOI, crop development, and response of ear attributes were investigated using path analysis. Path analysis is a multiple regression method that specifies associations between two or more independent and dependent variables, accounting for correlations between variables and unexplained sources of error (Mitchell, 2001). Akaike's Information Criterion (Burnham and Anderson, 2002) was used to identify the most parsimonious path analysis model assembled using several candidate variables including distance from giant ragweed, HT, GDD, GMASS, HMASS, LENGTH, WIDTH, and MOIST. To aid in interpretation of results, observed values (not relative responses) were used in path analyses. The RAMONA subroutine of SYSTAT version 11.0.1 was used to estimate standardized regression coefficients and latent variables for each hybrid and yield attribute.

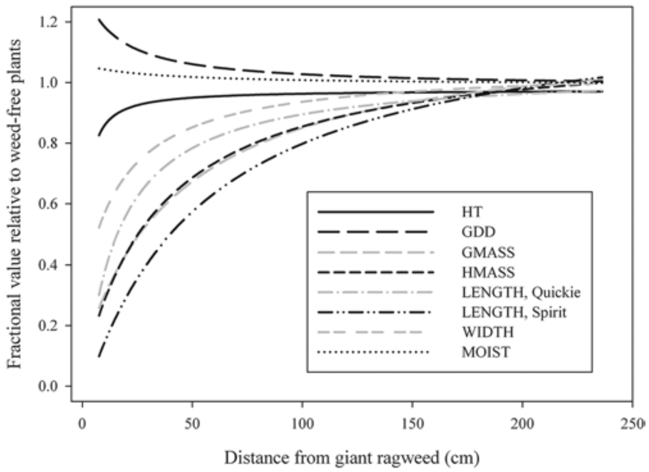

Fig. 1. Effect of distance from giant ragweed on sweet corn height near silk emergence (HT), thermal time to silk emergence (GDD), green ear mass (GMASS), husked ear mass (HMASS), filled ear length (LENGTH), ear width at midpoint (WIDTH), and kernel moisture (MOIST), relative to sweet corn plants without weed competition. Regressions for LENGTH are presented separately for each hybrid, since response varied by hybrid ($P = 0.011$). Regression equations are: HT = $0.976 \times [x/(1.386 + x)]$, $\sim R^2 = 0.777$; GDD = $0.985 + 0.343 \times 14.128/(14.128 + x)$, $\sim R^2 = 0.911$; GMASS = $0.099 + 1.084x/(44.300 + x)$, $\sim R^2 = 0.957$; HMASS = $0.036 + 1.107x/(35.097 + x)$, $\sim R^2 = 0.958$; LENGTH (Quickie) = $-0.077 + 1.117x/(14.856 + x)$, $\sim R^2 = 0.974$; LENGTH (Spirit) = $-0.066 + 1.330x/(54.028 + x)$ $R^2 = 0.862$; WIDTH = $0.295 + 0.756x/(17.802 + x)$, $\sim R^2 = 0.953$; MOIST = $0.992 + 0.068 \times 31.920/(31.920 + x)$, $\sim R^2 = 0.734$. A corrected R^2 ($\sim R^2$) was calculated as unity minus residual sum of squares divided by corrected total sum of squares.

Results

In both years, giant ragweed and sweet corn emerged 30 April and 2 May, respectively. From crop emergence to harvest, cumulative thermal time and cumulative rainfall averaged 710 growing degree days and 340 mm, respectively. Weed-free yields were similar between hybrids, averaging 16.8 Mt ha^{-1}. Hybrids were also similar in weed-free LAI (2.43) and IPAR (65.8%); however, Spirit grew 33 cm taller than Quickie by the time of silking ($P < 0.001$). At the time of sweet corn harvest, giant ragweed height and biomass averaged 198 cm and 554 g plant^{-1}, respectively, though no viable seed were observed.

Giant Ragweed Area of Influence

All measured crop attributes were affected by giant ragweed as evidenced by significant *P* values (≤0.014) for the test of Hypothesis 1, that giant ragweed AOI had no effect (Table 1). Plant HT, GMASS, HMASS, LENGTH, and WIDTH decreased as distance from giant ragweed decreased (Fig. 1). In contrast, GDD and MOIST increased in those sweet corn plants closest to giant ragweed.

In general, hybrids responded similarly to giant ragweed interference. Hypothesis 2, the shape of giant ragweed AOI responses were similar between hybrids, could not be rejected ($P \geq 0.260$; Table 1). Therefore, when individual sweet corn plant attributes were plotted against proximal distance from giant ragweed, hybrid responses were parallel or overlapping. Hypothesis 3, the magnitude of giant ragweed AOI responses were similar between hybrids, could not be rejected for most individual sweet corn plant attributes at $\alpha = 0.05$. One exception was LENGTH ($P < 0.011$), where Quickie was more resilient than Spirit to giant ragweed, influencing its ability to fill the entire length of the ear (Fig. 1).

Sweet corn plants closest to giant ragweed were delayed developmentally, and based on a minimum ear diameter of 4.4 cm, produced fewer marketable ears. Based on KS tests, the cumulative frequency distributions of fraction of silked plants and fraction of marketable ears were similar between hybrids ($P > 0.05$). Relative to noncompetitive conditions, plants within giant ragweed AOI required more time to silk, and often failed to silk with closer proximity to the weed. For instance, the proportion of silked plants declined steadily for plants in closest proximity to giant ragweed (Fig. 2). As a result, production of marketable ears was influenced greatly by giant ragweed AOI, with less than one-half of crop plants producing a marketable ear within 42 cm of giant ragweed (Fig. 2).

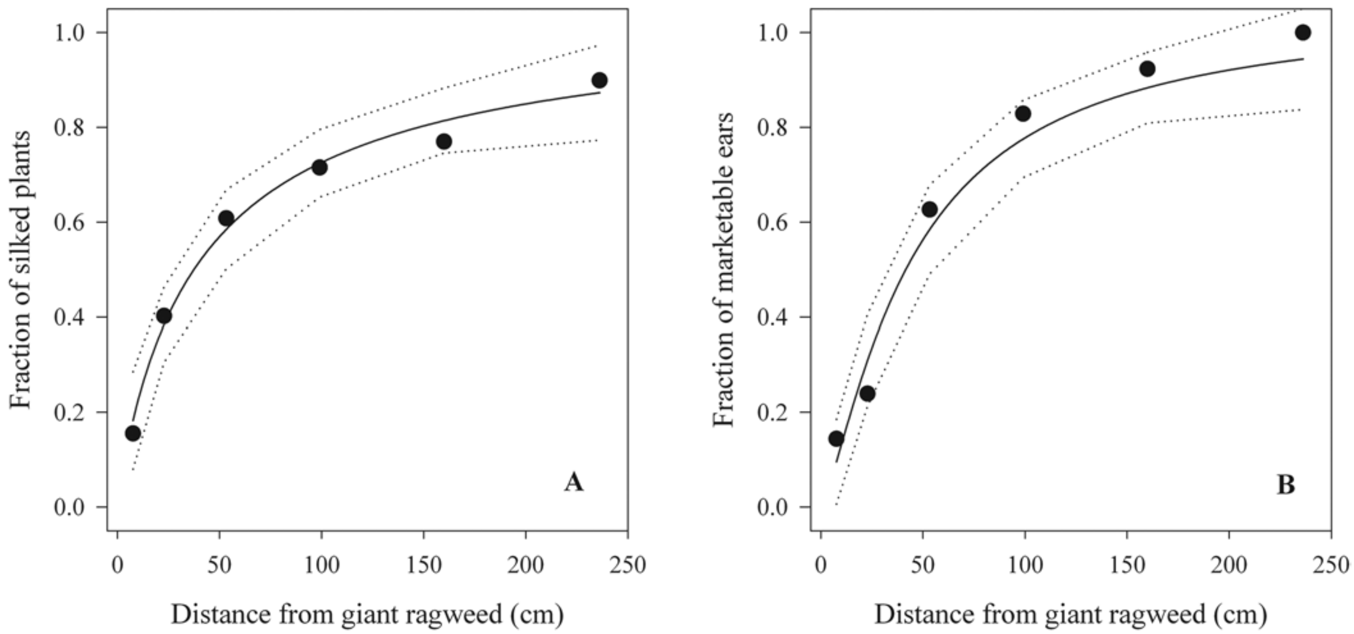

Fig. 2. Effect of distance from giant ragweed on (A) fraction of plants silking within 5 d of weed-competition-free plants, to all plants, and (B) fraction of marketable ears, to all ears. Dotted lines are 95% confidence intervals for (A) fraction of silked plants: $Y = 1.050/[1 + (x/41.562)^{-0.918}]$, $\sim R^2 = 0.869$, and (B) fraction of marketable ears: $Y = 1.054/[1 + (x/45.009)^{-1.297}]$, $\sim R^2 = 0.922$. A corrected R^2 ($\sim R^2$) was calculated as unity minus residual sum of squares divided by corrected total sum of squares.

Path Analysis

The most parsimonious path analysis model related the associations of giant ragweed AOI both directly and indirectly on crop growth, development, and yield (Fig. 3). Results showed that GMASS, HMASS, LENGTH, and WIDTH were strongly associated with thermal time up to silk emergence. For instance, path coefficients for GDD's direct effect on yield attributes ranged from −0.622 to −0.937 (Table 2). Delays in crop development in response to weed interference were associated with smaller ears of sweet corn. While giant ragweed AOI also had a direct association with these attributes (path coefficients 0.148 to 0.364), the indirect association of AOI mediated through GDD was greater, indicating weed interference harms ear attributes most when crop development is delayed. In addition, thermal time to silk emergence was directly associated with giant ragweed AOI (path coefficients −0.225 to −0.302) and indirectly by AOI influence on crop height growth (path coefficients −0.489 to −0.529). Therefore, developmental delays in the crop were observed when giant ragweed suppressed sweet corn height growth.

The path analysis models showed a slightly different relationship between weed interference and MOIST. Thermal time to silking appeared to have the largest association to MOIST (Table 2). As expected, delays in thermal time to silking resulted in greater MOIST at harvest (path coefficients 0.906 to 0.939). In contrast to other attributes, giant ragweed AOI did not have a direct association to MOIST. Instead, only weaker associations were observed between height growth and MOIST, which was missing or inconsistent in other attributes.

Similar AOI responses among hybrids are further evidenced by path analysis models. Path coefficients were largely consistent between hybrids, with minor differences occurring only in weak pathways.

Discussion

This work concurs with Tollenaar et al. (2006), in that maize can partially compensate for factors that influence resource capture (e.g., stem elongation in a light-impoverished environment), but cannot equally compensate for factors that influence resource utilization (e.g., biomass partitioning to the ear). Under light-limiting conditions, corn plants dominated by intraspecific competition apply assimilates to stem elongation at the expense of ear biomass (Pagano and Maddoni, 2007). Our results show that only the highest level of giant ragweed interference overwhelmed crop height growth and shade avoidance response (including elongated internodes and heavier stems), thereby reducing crop height in plants closest to the weed. Yet, even plants that compensated for the altered environment and maintained plant height were unable to support normal resource utilization, as evidenced by competitive effects of reduced ear size with giant ragweed AOI.

Weed interference had a relatively subtle effect on crop development, as measured by time of silk emergence, though even small delays in silking were of significant consequence to ear attributes.

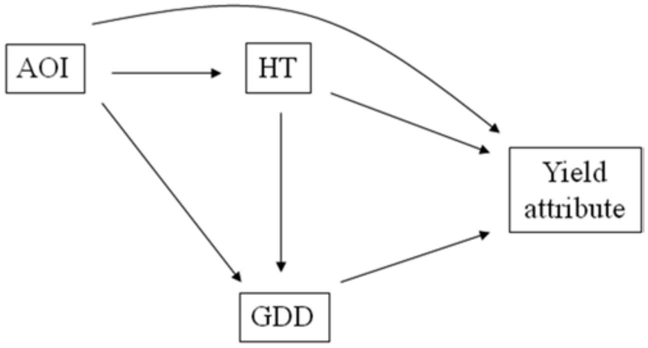

Fig. 3. Path analysis model for comparing giant ragweed area of influence (AOI), sweet corn plant height (HT), and thermal time to silk emergence (growing degree days, GDD) contributions to sweet corn yield.

Table 2. Standardized regression coefficients for path analysis of area of influence (AOI) of giant ragweed, crop height at silking (HT), thermal time from emergence to silking (GDD), and ear attributes of two sweet corn hybrids.

Attribute†	Hybrid	Standardized regression coefficients					
		AOI→HT	AOI→GDD	HT→GDD	HT→attribute	GDD→attribute	AOI→attribute
GMASS	Quickie	0.239**	−0.225**	−0.489**	0.022	−0.622**	0.318**
	Spirit	0.219**	−0.302**	−0.529**	−0.044	−0.638**	0.364**
HMASS	Quickie	0.239**	−0.225**	−0.489**	0.001	−0.668**	0.288**
	Spirit	0.219**	−0.302**	−0.529**	−0.094**	−0.772**	0.281**
LENGTH	Quickie	0.239**	−0.225**	−0.489**	−0.018	−0.799**	0.148**
	Spirit	0.219**	−0.302**	−0.529**	0.005	−0.717**	0.190**
WIDTH	Quickie	0.239**	−0.225**	−0.489**	−0.113**	−0.852**	0.183**
	Spirit	0.219**	−0.302**	−0.529**	−0.188**	−0.937**	0.166**
MOIST	Quickie	0.210**	−0.044	−0.538**	0.198**	0.939**	−0.045
	Spirit	0.145	−0.149**	−0.570**	0.343**	0.906**	−0.056

** Standardized regression coefficients significant at $P \leq 0.01$ level.

† GMASS, green ear mass; HMASS, husked ear mass; LENGTH, filled ear length; WIDTH, ear width at midpoint; MOIST, kernel moisture.

Average thermal time to silking for plants in closest proximity to giant ragweed (~8 cm) was delayed 17% relative to WCF plants. In contrast, ear mass and marketable ear number was reduced 64 and 86%, respectively. Weeds delay sweet corn silk emergence only in environments where crop competitive ability was poor and yield loss was high, such as early-May plantings in a temperate climate (Williams, 2006; Williams and Lindquist, 2007). Weed interference-induced delays in crop silking may be the combined result of the cost of shade avoidance response (Liu et al., 2009), reduced photosynthate supply, and the weed's concomitant use of soil moisture or nutrients, predisposing the crop to stress and delayed silking (see Bruce et al., 2002).

Sweet corn's ability to tolerate weed interference varies widely among commercial hybrids, depending in large part on differences in plant size and architecture. So et al. (2009) showed the principal factor accounting for crop competitive ability with wild-proso millet (*Panicum miliaceum* L.) described crop maturity and canopy size. Therefore, hybrids of similar maturity and canopy size were predicted to have comparable ability to compete with weeds. In this work, hybrids Quickie and Spirit were nearly identical in maturity, LAI, and IPAR. The hybrids also responded similarly to giant ragweed AOI for most ear attributes, consistent with recent findings on competitive ability among hybrids (So et al., 2009).

While the intent of this work was not to develop economic thresholds for weed management, even a low density of giant ragweed can be costly to ignore. For instance, under the conditions of this research, which were typical of sweet corn production in the north-central United States, an isolated giant ragweed plant resulted in an average loss of 35 marketable ears. This is calculated from the fraction of marketable ears lost within the giant ragweed AOI (based on the integral of the equation reported in Fig. 2B). For growers selling directly to consumers at \$3 per dozen ears, each giant ragweed plant reduced profits \$8.75; a substantial sum for an individual weed. The cost per individual giant ragweed in sweet corn grown for processing is \$0.86, assuming a value of \$105 Mt^{-1} for sweet corn (personal communication, Nick George, Midwest Food Processors Association, 2009). Therefore, the *economic* significance of a low weed density, and the basis for additional control measures, will be determined in part by crop market type. An economic analysis of the impact of low weed densities should also consider factors that reduce weed competitive ability and yield loss potential. For instance, competitive ability of giant ragweed is likely to decline in some situations, including delayed weed emergence relative to crop emergence (Harrison et al., 2001), and the effect of selective postemergence herbicide application (Terra et al., 2007).

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References

Bruce, W.B., G.O. Edmeades, and T.C. Barker. 2002. Molecular and physiological approaches to maize improvement for drought tolerance. J. Exp. Bot. 53:13–25.

Burnham, K.P., and D.R. Anderson. 2002. Model selection and inference: A practical information-theoretic approach. Springer Verlag, New York.

Harrison, S.K., E.E. Regnier, J.T. Schmoll, and J.E. Webb. 2001. Competition and fecundity of giant ragweed in corn. Weed Sci. 49:224–229.

Johnson, R.A., and D.W. Wichern. 2002. Applied multivariate statistical analysis. 5th ed. Prentice Hall, Upper Saddle River, NJ.

Jordan, N. 1989. A statistical analysis for area-of-influence experiments. Weed Technol. 3:114–121.

Kiefer, J. 1959. K-sample analogues of the Kolmogorov-Smirnov and Cramer-von mises tests. Ann. Math. Stat. 30:420–447.

Liu, J.G., K.J. Mahoney, P.H. Sikkema, and C.J. Swanton. 2009. The importance of light quality in crop-weed competition. Weed Res. 49:217–224.

Mitchell, R.J. 2001. Path analysis: Pollination. p. 217–234. *In* S.M. Scheiner and J. Gurevitch (ed.) Design and analysis of ecological experiments. Oxford Univ. Press, New York.

Neter, J., M.H. Kutner, C.J. Nachtsheim, and W. Wasserman. 1996. Applied linear statistical models. Irwin, Chicago.

Pagano, E., and G.A. Maddoni. 2007. Intra-specific competition in maize: Early established hierarchies differ in plant growth and biomass partitioning to the ear around silking. Field Crops Res. 101:306–320.

So, Y.F., M.M. Williams, II, J.K. Pataky, and A.S. Davis. 2009. Principal canopy factors of sweet corn and relationships to competitive ability with wild-proso millet (*Panicum miliaceum*). Weed Sci. 57:296–303.

Terra, B.R.M., A.R. Martin, and J.L. Lindquist. 2007. Corn-velvetleaf (*Abutilon theophrasti*) interference is affected by sublethal doses of postemergence herbicides. Weed Sci. 55:491–496.

Tollenaar, M., W. Deen, L. Echarte, and W. Liu. 2006. Effect of crowding stress on dry matter accumulation and harvest index in maize. Agron. J. 98:930–937.

Tracy, W.F. 2001. Sweet corn. p. 155–197. *In* A.R. Hallauer (ed.) Specialty corns. 2nd ed. CRC Press, Boca Raton, FL.

Williams, M.M., II. 2006. Planting date influences critical period of weed control in sweet corn. Weed Sci. 54:928–933.

Williams, M.M., II, and J.L. Lindquist. 2007. Influence of planting date and weed interference on sweet corn growth and development. Agron. J. 99:1066–1072.

Williams, M.M., II, and J.B. Masiunas. 2006. Functional relationships between giant ragweed interference and sweet corn yield and ear traits. Weed Sci. 54:948–953.

Williams, M.M., II, T.L. Rabaey, and C.M. Boerboom. 2008. Residual weeds of sweet corn in the north central region. Weed Technol. 22:646–653.