Plant Spacing and Weed Control Affect Sunflower Stalk Insects and the Girdling Behavior of *Dectes texanus* (Coleoptera: Cerambycidae)

J. P. MICHAUD,[1,2] P. W. STAHLMAN,[3] J. L. JYOTI,[1] AND A. K. GRANT[1]

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ABSTRACT We conducted a 2-yr study to determine the effects of crop density and weeds on levels of damage caused by stalk-boring insects in rain-fed sunflowers in west-central Kansas. Weed-free sunflower had higher seed weight and oil content in 2007, but not in 2006, but weeds did not affect infestation by stalk-boring insects in either year. High-density sunflower had lower estimated seed yield per unit area than low-density sunflower in both years, but percentage oil was slightly greater in the high-density treatment in 2006. Sunflowers were more heavily infested by larvae of *Ataxia hubbardi* Fisher, *Cylindrocopturus adspersus* (Leconte), and *Pelochrista womanana* (Kearfott) in 2006 than in 2007, ostensibly as a result of being planted earlier. Larvae of *Dectes texanus* LeConte appeared unaffected by planting date and were present in >70% of plants in both years. Conditions during the period of crop maturity were much drier in 2006 than in 2007 and were associated with higher seed oil content and earlier and faster progression of stalk girdling by *D. texanus* larvae in both low- and high-density plots. There was also a strong effect of plant density on girdling behavior that seemed to be mediated by effects on soil moisture. Stalk girdling began earlier in high-density plots and a larger proportion of plants were girdled compared with low-density plots on all sampling dates in both years. Certain cultural tactics, in particular reduced plant spacing, have potential to delay the onset of girdling behavior by *D. texanus* larvae and thus mitigate losses that otherwise result from the lodging of girdled plants.

KEY WORDS *Ataxia hubbardi*, *Cylindrocopturus adspersus*, lodging, plant population, soil moisture

Sunflower, *Helianthus annuus* L., is a crop native to the Americas that is grown for both oil and confectionary uses. On the High Plains of the United States, it is an alternative summer crop useful for planting in rotation with wheat, corn, soybeans, and sorghum. Sunflower is capable of rooting to depths of 2.5 m (Stone et al. 2001), allowing it to access residual moisture and plant nutrients that remain below the reach of more shallow-rooted crops. It also makes very efficient use of moisture, making it well suited for rain-fed agriculture in drought-prone regions (Robinson et al. 1980). Although sunflowers are very competitive plants, early season weed control is considered essential for stand establishment and high seed yields (Robinson 1978). In addition, commercial production of sunflowers is plagued by various native insect pests that can cause serious yield losses (Schultz 1978, Charlet 1996). A diverse complex of Coleoptera and Lepidoptera cause direct damage by boring flower heads and seeds and indirect damage by boring and girdling stalks that, in turn, leads to preharvest lodging of plants. One of the most important causes of lodging in commercial sunflowers on the High Plains is the longhorned beetle *Dectes texanus* LeConte (Coleoptera: Cerambycidae) (Rogers 1985), the primary subject of this study.

The domestication of *H. annuus* as a monopodial plant with a single, large inflorescence has increased its susceptibility to particular herbivores such as the sunflower moth, *Homoeosoma electellum* (Hulst) (Lepidoptera: Pyralidae), probably the most serious pest causing direct damage in commercial production (Chen and Welter 2003). Chen and Welter (2007) showed that various features of cultivated flowers and seeds provide improved refuge for moth larvae and impede the foraging efficacy of their parasitoids. Similarly, certain stem boring species such as the sunflower stem weevil, *Cylindrocopturus adspersus* (LeConte) (Coleoptera: Curculionidae), are found in much greater abundance in cultivated than in wild *H. annuus* plants and tend to have lower rates of parasitism in the former (A.K.G., unpublished data). It is also very rare to find *D. texanus* infesting wild *H. annuus* in Kansas (Michaud and Grant 2005), whereas it is common for 70–80% of sunflowers in cultivated fields to be infested (Michaud et al. 2007a).

Dectes texanus is also a pest of soybean (Hatchett et al. 1975), although it exhibits a marked preference for feeding and ovipositing on cultivated sunflowers (Michaud and Grant 2005, Michaud et al. 2007b). In both crops, yield losses occur when a late instar larva migrates to the base of its plant and cuts a transverse radial incision, or "girdle," in the interior of the stalk base or root

[1] Department of Entomology, Kansas State University, Hays, KS 67601.
[2] Corresponding author, e-mail: jpmi@ksu.edu.
[3] Agricultural Research Center-Hays, Kansas State University, Hays, KS 67601.

crown, causing the plant to lodge. The problem is especially acute in sunflowers that are top-heavy plants already predisposed to lodge in windy conditions, even without factors that reduce stalk strength.

Because cultural modifications of the sunflower plant have increased its susceptibility to various insect pests, it is not surprising that selected cultural approaches can also be effective in mitigating their impact. For example, Charlet and Knodel (2003) showed an effect of planting date on infestation by the defoliator *Zygogramma exclamationis* (F.) (Coleoptera: Chrysomelidae). Similarly, Charlet et al. (2007a) showed that early planting increased stalk infestation by *C. adspersus.* Charlet et al. (2007b) found that irrigation of sunflowers could reduce end-of-season larval infestation by both *C. adspersus* and a root moth, *Pelochrista womanana* (Kearfott) (Lepidoptera: Tortricidae), presumably by strengthening plant resistance to larval development. In addition, Qureshi et al. (2007) observed that sunflowers in high-density plots suffered more preharvest girdling by larvae of *D. texanus* than did plants in low-density plots and noted that this difference was associated with lower soil moisture in high-density plots. Given that factors linked to soil moisture can apparently influence the impact of sunflower pests, this study was undertaken to determine whether weed control measures or variation in plant spacing could affect the onset of larval girdling by *D. texanus* and whether these treatments might interact via their respective effects on soil moisture content.

Materials and Methods

The study was conducted on land at the Kansas State University Agricultural Research Center at Hays, KS (38°51′ N, 99°20′ W) in 2006 and 2007, on conventionally tilled land. The soil was a Crete silty clay loam (22% sand, 48% silt, and 30% clay) with pH 6.2 and 1.8% organic matter. Experimental areas were fertilized with urea (28–0-0) at rates needed to achieve ≈75 kg N/ha (residual plus supplemental nitrogen).

Each experiment was a factorial arrangement of two crop populations and three weed populations with five replicates. Plots were 6.1 by 18.3 m and contained six rows of sunflower spaced 76 cm apart. The natural weed seed bank was supplemented by overseeding one third of all plots with a mixture of annual grass weed seeds, one third received a mixture of annual broadleaf weed seeds, and the remaining plots were not overseeded. Grass weed seeds were a 2:1:1 mixture (by volume) of green foxtail (*Setaria viridis* L. Beauv.), stinkgrass [*Eragrostis cilianensis* (All.) E. Mosher], and large crabgrass (*Digitaria sanguinalis* L. Scop.), and broadleaf weed seeds were a 3:1:1 mixture (by volume) of kochia (*Kochia scoparia* L. Schrad), Russian thistle (*Salsola iberica* Sennen and Pau), and pigweed (*Amaranthus*) species. Plots overseeded with grass weed seeds also received sulfentrazone (Spartan DF; FMC Corporation, Philadelphia, PA) at 180 g (AI)/ha to control broadleaf weeds, and plots receiving broadleaf weed seeds also received *S*-metolachlor (Dual Magnum; Syngenta Crop Protection, Wilmington, DE) at 1.9 kg (AI)/ha to control grass weeds. Remaining plots received both sulfentrazone and *S*-metolachlor supplemented by occasional hand weeding for complete weed control. Herbicides were applied to soil as a broadcast spray preemergence to crop and weeds with a tractor-mounted sprayer delivering 90 liters/ha. Experimental areas were planted on 8 May 2006 and 6 June 2007 to an oilseed sunflower hybrid 'Triumph 660CL' at an average depth of 3.8 cm using a John Deere 7000 Max Emerge planter (Deere & Co., Moline, IL). Plant emergence was noted on 16 May and 11 June, respectively, and plots were subsequently thinned by hand to one of two plant density treatments (high/low). The final plant populations were 36,390 and 23,600 plants/ha, respectively, in 2006, and 38,840 and 25,560 plants/ha in 2007.

When plants reached the V8 stage (Schneiter and Miller 1981), alleys were mowed to delineate blocks and facilitate access to plots. As flowers began to open (R5 stage), 15 plants were randomly selected in each treatment plot for assessment of protected yield. The heads and stalks of each plant were tagged with a piece of colored flagging tape and numbered with an identifying code. The distance to each neighboring plant within the row was also recorded, and the two values were averaged to determine nearest-neighbor distance. Within 3 d of 100% bloom, the field received an application of insecticide to protect against damage by sunflower moth, *H. electellum.* In 2006, this consisted of 17.0 g (AI)/ha of lamda cyhalothrin (Proaxis) applied from the ground using a Hi-boy sprayer on 29 July. In 2007, 21.0 g (AI)/ha of zeta-cypermethrin (Mustang Max) was applied from the air on 1 August. Moth pressure was particularly high in 2007, resulting in a second aerial application of 69.0 g (AI)/ha of gamma cyhalothrin (Warrior with Zeon technology) on 9 August. At petal fall, the heads of all protected yield plants were covered with brown paper bags stapled closed around the neck of the flower to protect against bird damage.

Weed biomass was estimated on 7 July 2006 and 31 August 2007 by harvesting all weeds within each of four 1.0-m^2 quadrats randomly located within each treatment plot. Weeds from each quadrat were bagged for transport to the laboratory where they were identified to species, separated, and dried for 4 d at 60°C before weighing on an analytical balance.

The heads and stalks of all protected yield plants were harvested on 23 August 2006 and 30 August 2007. After harvest, rates of stalk girdling by larvae of *D. texanus* were assessed in three rows arbitrarily selected in each plot on each sampling date by walking down a row and manually applying a lateral force of 2–3 kg at the top of each stalk. Preliminary testing showed that this was sufficient force to snap the stalk of girdled plants in >95% of cases. The presence of a girdle was verified by visual examination of each snapped stalk at the point of breakage, and the number of girdled plants in each row was recorded, as well as the number of total plants in the row. In 2006, the stalk girdling assessment was performed on 23 August and 5 September. In 2007, stalk girdling was assessed on 30 August and 7, 14, and 20 September. All rows were

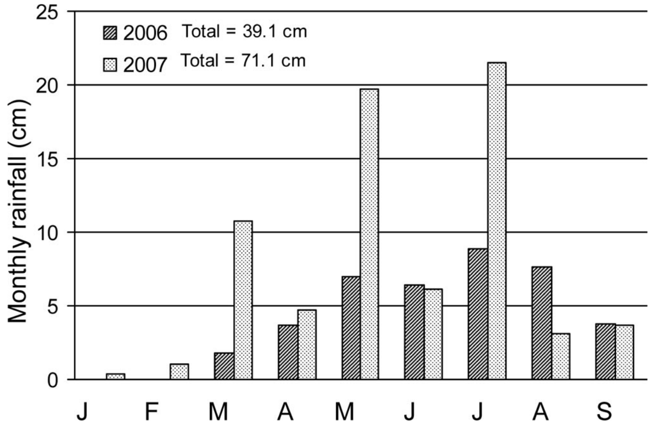

Fig. 1. Total monthly rainfall over 9 mo in each of 2 yr at Hays, KS.

sampled for girdling only once, including protected yield plants. Stalks of protected yield plants were harvested, along with their tap roots, and transported to the laboratory. Each stalk was measured for basal circumference at soil level (to provide an estimate of relative plant size) and carefully dissected to identify and tally all the stalk-boring insect larvae.

Sunflower heads in their respective bags were placed in a drying room at 38°C for a period of 20–30 d. After completion of the drying process, flower heads were removed from bags, measured vertically and horizontally to estimate flower diameter, and threshed individually using an improvised mechanical single-head threshing machine. The seed was cleaned, analyzed for moisture content using a Grain Analytical Computer (GAC 2000; Dickey-John Corporation, Aubum, IL), and weighed on an analytical balance. A sample of 100 randomly selected seeds was weighed to provide an estimation of individual seed weight. All seed weights were corrected for moisture content before analysis. Samples of 40 ml of seed were taken from each flower head and placed in a labeled envelope for subsequent determination of oil content by nuclear magnetic resonance (Gambhir and Agarwala 1985) at the Sunflower Research Unit, USDA–ARS, Fargo, ND.

Data were analyzed by factorial analysis of variance (ANOVA) in a randomized complete block design using the general linear model procedure (SAS Institute 2003). The least significant difference test was used for separation of means when independent variables had more than two categories. ANOVA for repeated measures was used to analyze changes in percentage plants girdled over time. Relationships between weeds and insects and between number plants per row and percentage plants girdled were analyzed by linear regression (SPSS 1998).

Results

Weather. The months of July and August correspond to the period of flowering and seed set in sunflower. Soil moisture levels were much higher in late summer 2007 than in 2006 because of exceptionally high rainfall during the months of March, May, and July (Fig. 1). Comparing mean temperatures between years for the months of June and July, 2006 averaged 2°C warmer than 2007 (25.9 ± 0.35 versus 23.9 ±

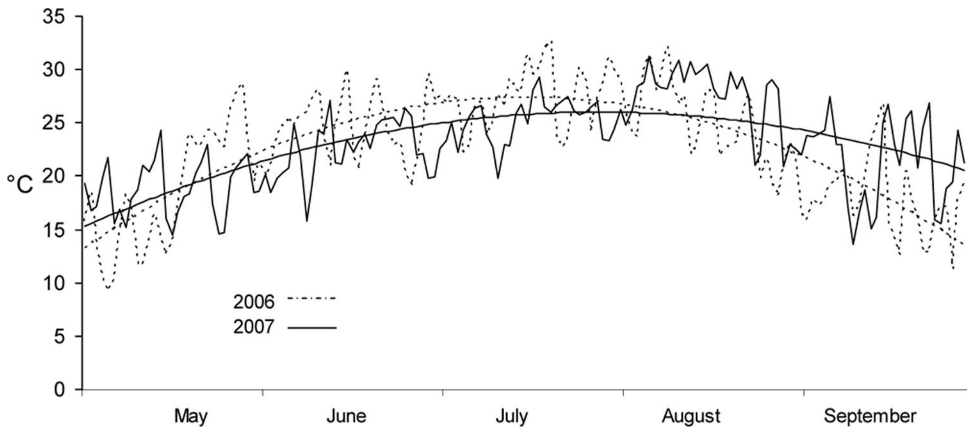

Fig. 2. Mean daily temperatures during the growing season in each of 2 yr at Hays, KS.

Table 1. ANOVA of sunflower yield components in each of 2 yr at Hays, Kansas

Source of variation	df	2006		2007	
		F	*P*	*F*	*P*
Basal stalk circumference (cm)					
Block	4	1.20	0.3403	0.68	0.6133
Density	1	224.46	0.0001	130.49	0.0001
Herbicide	2	2.84	0.0824	4.57	0.0233
Density × herbicide	2	0.84	0.4460	0.07	0.9367
Error term	20				
Head diameter (cm)					
Block	4	0.84	0.5174	2.27	0.0981
Density	1	98.40	0.0001	294.83	0.0001
Herbicide	2	0.78	0.4708	1.40	0.2692
Density × herbicide	2	1.26	0.3045	0.43	0.6589
Error term	20				
Dry weight of seed (g)					
Block	4	6.16	0.0021	0.86	0.5057
Density	1	174.70	0.0001	124.25	0.0001
Herbicide	2	0.89	0.4253	1.55	0.2374
Density × herbicide	2	0.44	0.6509	1.31	0.2924
Error term	20				
Dry weight of 100 seeds (g)					
Block	4	12.77	0.0001	0.83	0.5203
Density	1	128.11	0.0001	204.60	0.0001
Herbicide	2	0.88	0.4304	1.49	0.2485
Density × herbicide	2	0.49	0.6201	0.86	0.4396
Error term	20				

Oil content (%) was not significantly affected ($P > 0.05$) by any factor within years.

0.42°C; $F = 14.3$; df = 1,120; $P < 0.001$; Fig. 2). In contrast, the period of crop maturity (5 August to 5 September) averaged 3°C cooler in 2006 than 2007 (23.9 ± 0.8 versus 27.0 ± 0.6°C, respectively; $F = 9.975$; df = 1,60; $P = 0.002$). Results of the ANOVA showed significant effects of year on basal stalk circumference ($F = 520.11$; df = 1,45; $P < 0.001$), head diameter ($F = 1795.66$; df = 1,45; $P < 0.001$), seed dry weight ($F = 14.97$; df = 1,45; $P = 0.018$), and oil content ($F = 76.75$; df = 1,45; $P < 0.001$). Consequently, effects of plant density and weed control on components of yield, including stalk diameter, were analyzed separately for each year.

Components of Yield. The results of the ANOVA showed no interaction between crop density and weed presence for any plant component in either year (Table 1). With the exception of the weight of 100 seeds, which was higher in 2007 than in 2006, all plant components were significantly higher in 2006 in both low- and high-density plots (Table 2), so each year was analyzed separately. The low-density plots produced plants with larger components of yield in both years except for oil content in 2006 that was greater in high density plots. The effects of weed presence and weed population composition were inconsistent. The stalk circumference of weed-free sunflower in 2006 was greater compared with the stalk circumference of sunflower grown in association with either broadleaf or grass weeds, but in 2007, sunflower infested with grass weeds had greater stalk circumference than sunflower infested with broadleaf weeds, whereas neither differed from weed-free sunflower. Weed interference (neither broadleaf, grass, nor both) did not affect head diameter in 2006, but grass weed interference affected head diameter less than broadleaf weed interference in 2007. However, as with stalk circumference, neither broadleaf nor grass interference differed from the weed-free treatment. Weed presence or absence did not affect total seed weight or individual seed weight in 2006, but in 2007, both weed-free and grass-infested sunflower produced more seed weight and heavier seeds than did broadleaf-infested sunflower. In 2006, broadleaf weed control produced seed with a higher oil content than the combination treatment and grass control was not different from other treatments.

By averaging the mean number of plants per row in the various plots, we determined that plant populations were 36,390 and 23,600 plants/ha in high- and low-density plots, respectively, in 2006 and 38,840 and 25,560 plants/ha in 2007. Multiplying these values by mean seed weights produced yield estimates of 903 and 1,156 kg/ha for low- and high-density plots, respectively, in 2006 and 971 and 707 kg/ha, respectively, in 2007.

The average distance from adjacent plants on either side in the row explained 50% of the variation in basal stalk circumference in 2006 ($F = 464.63$; df = 1,448; $P < 0.001$; $r^2 = 0.509$) and 48% in 2007 ($F = 410.22$; df =

Table 2. Means ± SEM of sunflower yield components in each of 2 yr at Hays, Kansas

Year	Treatment	Basal stalk circumference (cm)	Head diameter (cm)	Seed dry weight (g)	Dry weight 100 seeds (g)	Oil content (%)
Plant density						
2006	Low	7.9 ± 0.1a	18.2 ± 0.5a	49.0 ± 1.3a	3.1 ± 0.0a	39.3 ± 0.4b
	High	6.3 ± 0.0b	13.3 ± 0.2b	24.8 ± 0.7b	2.5 ± 0.0b	40.9 ± 0.4a
2007	Low	6.9 ± 0.0a	7.1 ± 0.0a	38.0 ± 0.8a	3.3 ± 0.0a	32.4 ± 0.1a
	High	5.8 ± 0.0b	5.2 ± 0.0b	18.2 ± 0.4b	2.5 ± 0.0b	31.5 ± 0.1b
Herbicide (weeds controlled)						
2006	S-metolachlor (grasses)	7.0 ± 0.1b	15.6 ± 0.2a	35.6 ± 1.6a	2.8 ± 0.0a	39.9 ± 0.4ab
	Sulfentrazone (broadleaf)	7.0 ± 0.1b	15.3 ± 0.3a	38.6 ± 1.7a	2.9 ± 0.0a	40.9 ± 0.5a
	S-metolachlor + sulfentrazone (all)	7.3 ± 0.1a	16.1 ± 0.8a	36.4 ± 1.6a	2.8 ± 0.0a	39.4 ± 0.4b
2007	S-metolachlor (grasses)	6.2 ± 0.1b	6.1 ± 0.1b	26.2 ± 1.1b	2.8 ± 0.0b	31.3 ± 0.1b
	Sulfentrazone (broadleaf)	6.5 ± 0.1a	6.3 ± 0.1a	30.0 ± 1.3a	2.9 ± 0.0a	32.4 ± 0.1a
	S-metolachlor + sulfentrazone (all)	6.5 ± 0.1ab	6.2 ± 0.1ab	28.4 ± 1.0a	3.0 ± 0.0a	32.2 ± 0.1a

Means with the same letter were not significantly different between treatments within years (LSD, $\alpha = 0.05$).

Table 3. ANOVA of effects of year, crop density, and herbicide treatment on broad leaf and grass weeds

Source of variation	df	F	P
Dry weight of broad leaf weeds			
Year	1	4.57	0.099
Block	4	0.57	0.703
Year × block [error (a)]	4		
Plant density	1	1.23	0.273
Herbicide	2	43.92	<0.001
Plant density × herbicide	2	1.04	0.362
Block × density × herbicide × year [error (b)]	45		
Dry weight of grass weeds			
Year	1	0.02	0.906
Block	4	0.35	0.835
Year × block [error (a)]	4		
Plant density	1	1.35	0.252
Herbicide	2	29.65	<0.001
Plant density × herbicide	2	1.27	0.291
Block × density × herbicide × year [error (b)]	45		

1,444; $P < 0.001$, $r^2 = 0.4809$), and a similar relationship was observed with head diameter in both years ($F = 390.54$; df = 1,404; $P < 0.001$; $r^2 = 0.492$ and $F = 437.93$; df = 1,448; $P < 0.001$; $r^2 = 0.495$, respectively). Head diameter was not correlated with oil content in 2006 ($F = 1.58$; df = 1,404; $P = 0.210$) but was positively correlated in 2007 ($F = 63.43$; df = 1,444; $P < 0.001$; $r^2 = 0.125$).

Weeds. There was a significant effect of herbicide treatment on the dry weight of broadleaf and grass weeds per square meter, but effects of year and crop density were not significant (Table 3). The biomass of broadleaf weeds was significantly reduced by both treatments containing sulfentrazone in both years, whereas the biomass of grass weeds was reduced by both treatments containing *S*-metolachlor in both years (Table 4).

In 2006, the following broadleaf weeds were observed, in order of total biomass: kochia, *Kochia scoparia;* redroot pigweed, *Amaranthus retroflexus;* tumble pigweed, *Amaranthus albus;* puncturevine, *Tribulus terrestris;* devil's claw, *Harpagophytum procumbens;* ground cherry, *Physalis pruinosa;* leafy spurge, *Euphorbia esula;* common purslane, *Portulaca oleracea;* and field bindweed, *Convolvulus arvensis.* Kochia and the two pigweed spp. combined comprised 96.8% of broadleaf weed biomass. Grass weeds were comprised of green foxtail, *Setaria viridis;* prairie cupgrass, *Eriochloa contracta;* longspine sandbur, *Cenchrus longispinus;* large crabgrass, *Igitaria sanguinalis;* and a small number of unidentified species. Green foxtail, cupgrass, and sandbur together comprised 95% of grass weed biomass.

In 2007, the following broadleaf weeds were observed, in order of biomass: Russian thistle, *Salsoa iberica;* puncturevine, kochia, redroot pigweed, and tumble pigweed, with Russian thistle comprising 94% of biomass. The grass weeds observed were green foxtail, large crabgrass, and longspine sandbur, with green foxtail comprising 80% of biomass.

Grass weeds were less abundant and produced considerably less biomass than broadleaf weeds in both years. Broadleaf weed biomass did not correlate with any component of crop yield in either 2006 or 2007 (P values not shown).

Insects. There were no significant interactions between planting density and herbicide treatment for any stalk insect species in either year ($P > 0.20$ in all cases). There were significantly more larvae per stalk of *C. adspersus* ($F = 48.26$; df = 1,45; $P = 0.002$) and *P. womanana* ($F = 28.12$; df = 1,45; $P = 0.006$) in 2006 than in 2007. In contrast, numbers of *D. texanus* per stalk were significantly higher in 2007 ($F = 7.97$; df = 1,45; $P = 0.048$) and those of *A. hubbardi* were not different between years ($F = 2.97$; df = 1,45; $P = 0.160$). Two larvae of the tumbling flower beetle, *Mordellistena* sp. (Coleoptera: Mordellidae), were found in 2006 and none in 2007. Low-density plants had significantly more larvae of *C. adspersus* and *P. womanana* in 2006, but there was no difference in 2007 (Table 5). Herbicide treatment did not affect infestation by insects except in 2006 when broad leaf weed control resulted in more *D. texanus* larvae than the combination of broad leaf and grass control, with grass control alone not different from either.

Plant basal circumference was linearly correlated with numbers of stem weevil larvae ($F = 32.76$; df = 1,448; $P < 0.001$; $r^2 = 0.07$) and the numbers of root moth larvae ($F = 4.61$; df = 1,448; $P = 0.032$; $r^2 = 0.10$) in 2006 but not in 2007 ($F = 0.46$; df = 1,446; $P = 0.499$ and $F = 0.52$; df = 1,446; $P = 0.470$, respectively).

Stalk Girdling by *D. texanus*. Crop density had an effect on the number of plants girdled by *D. texanus* larvae on all sampling dates in both years, whereas the effect of herbicide treatment was not significant (Table 6). A higher percentage of plants were girdled in high-density plots than in low-density plots on all dates in both years. The percentage of girdled plants increased over time in both 2006 ($F = 1158.49$; df = 1,140; $P < 0.001$) and 2007 ($F = 348.82$; df = 3,309; $P <$

Table 4. Effects of herbicide treatments on mean ± SEM dry weight of broad leaf and grass weeds

Herbicide	Dry weight of weeds (g/m^2)			
	2006		2007	
	Broadleaf	Grass	Broadleaf	Grass
S-metolachlor	99.4 ± 29.0a	0.90 ± 0.28b	227.69 ± 31.13a	0.17 ± 0.17b
Sulfentrazone	8.1 ± 4.0b	4.63 ± 0.76a	4.55 ± 1.14b	5.38 ± 1.51a
S-metolachlor + sulfentrazone	2.2 ± 0.8b	0.30 ± 0.10b	0.04 ± 0.04b	0.03 ± 0.03b

Means with the same letter were not significantly different among herbicide treatments (LSD, $\alpha = 0.05$).

Table 5. Mean ± SEM numbers of stalk insects per plant in each of 2 yr at Hays, Kansas

Year	Treatment	*Cylindrocopturus adspersus*	*Pelochrista womanana*	*Dectes texanus*	*Ataxia hubbardi*
Crop density					
2006	Low	6.20 ± 0.40a	0.29 ± 0.04a	0.64 ± 0.03a	0.053 ± 0.020a
	High	3.90 ± 0.20b	0.18 ± 0.03b	0.72 ± 0.03a	0.053 ± 0.015a
2007	Low	0.14 ± 0.02a	0.02 ± 0.01a	0.79 ± 0.03a	0.004 ± 0.004a
	High	0.13 ± 0.03a	0.03 ± 0.01a	0.75 ± 0.03a	0.004 ± 0.004a
Weeds present					
2006	Broadleaf	4.83 ± 0.46a	0.23 ± 0.04a	0.70 ± 0.04ab	0.033 ± 0.014a
	Grasses	4.97 ± 0.42a	0.27 ± 0.05a	0.74 ± 0.04a	0.047 ± 0.017a
	None	5.41 ± 0.46a	0.21 ± 0.04a	0.61 ± 0.04b	0.080 ± 0.022a
2007	Broadleaf	0.10 ± 0.03a	0.02 ± 0.01a	0.75 ± 0.04a	0.013 ± 0.009a
	Grasses	0.15 ± 0.05a	0.03 ± 0.01a	0.83 ± 0.03a	0.000 ± 0.000a
	None	0.17 ± 0.04a	0.03 ± 0.01a	0.74 ± 0.04a	0.000 ± 0.000a

Means with the same letter were not significantly different among treatments within years (LSD, $\alpha = 0.05$).

0.001). The interaction between density and sampling date was significant in both 2006 ($F = 8.39$; df = 1,140; $P = 0.004$) and 2007 ($F = 4.42$; df = 3,309; $P = 0.005$), reflecting the more rapid progression of girdling in high-density plots (Fig. 3). The number of plants per row was positively correlated with the percentage of plants girdled on both sampling dates in 2006 (23 August: $F = 156.12$; df = 1,88; $P < 0.001$; $r^2 = 0.640$; 5 September: $F = 123.57$; df = 1,88; $P < 0.001$; $r^2 = 0.584$; Fig. 4) and all sampling dates in 2007 (30 August: $F = 50.94$; df = 1,88; $P < 0.001$; $r^2 = 0.367$; 7 September: $F = 19.03$; df = 1,88; $P < 0.001$; $r^2 = 0.178$; 14 September: $F = 84.51$; df = 1,85; $P < 0.001$; $r^2 = 0.499$; 21 September: $F = 96.32$; df = 1,88; $P < 0.001$; $r^2 = 0.523$).

Table 6. Effects of crop density and weeds on percentage of plants girdled by larvae of *D. texanus* on various dates in 2006 and 2007

Source of variation	df	*F*	*P*
2006			
23 Aug.			
Block	4	0.93	0.453
Crop density	1	55.81	<0.001
Weed presence	2	1.58	0.231
Crop density × weeds	2	0.51	0.605
Error	20		
5 Sept.			
Block	4	12.73	<0.001
Crop density	1	76.53	<0.001
Weed presence	2	1.29	0.296
Crop density × weeds	2	2.55	0.103
Error	20		
2007			
30 Aug.			
Block	4	4.58	0.003
Crop density	1	46.52	<0.001
Weed presence	2	0.19	0.826
Crop density × weeds	2	0.23	0.800
Error	20		
7 Sept.			
Block	4	0.68	0.608
Crop density	1	20.83	0.001
Weed presence	2	0.12	0.888
Crop density × weeds	2	0.12	0.886
Error	20		
14 Sept.			
Block	4	3.04	0.024
Crop density	1	54.50	<0.001
Weed presence	2	0.03	0.970
Crop density × weeds	2	0.27	0.765
Error	20		
20 Sept.			
Block	4	1.12	0.355
Crop density	1	38.36	<0.001
Weed presence	2	0.96	0.401
Crop density × weeds	2	0.00	0.997
Error	20		

Linear regression of mean percentage of plants girdled on the last sampling date versus mean total weed biomass per square meter was not significant for plants in low-density plots in 2006 ($F = 0.26$; df = 1,13; $P = 0.616$), but yielded a significant negative correlation in high-density plots ($F = 11.63$; df = 1,13; $P = 0.005$; $r^2 = 0.472$). These regressions were not significant in low- or high-density plots in 2007 ($F = 0.40$; df = 1,13; $P = 0.840$ and $F = 1.36$; df = 1,13; $P = 0.264$, respectively).

Discussion

Exceptionally wet weather in the spring of 2007 delayed planting by almost 1 mo relative to 2006, and this late planting is likely responsible for the lower numbers of stem weevils and root moths in 2007 (Charlet et al. 2007a). Delayed planting is also known to negatively affect seed weight and oil content (Meyer et al. 2005) and probably accounts for some of the difference between years in these yield components. Infestation by *D. texanus* was not affected by planting date because this species has extended periods of adult emergence and activity in the crop (Michaud and Grant 2005). The larger numbers of stem weevils and root moths per plant in low-density plots in 2006 reflects the fact that larger plants typically host larger numbers of these insects (Michaud et al. 2007a). Excessive soil moisture can also reduce the oil content of sunflower seed (Unger 1982, Nielsen 2005), and the wet conditions in 2007 may have contributed to the 7–9% reduction in oil content relative to 2006. A similar pattern of lower seed oil content after wet summer conditions was observed in a previous study conducted at the same location (Michaud et al. 2007a).

Control of broadleaf weeds increased seed oil content in 2006 compared with the weed-free treatment and control of grass weeds improved stalk circumference (Table 2). In 2007, all components of yield were

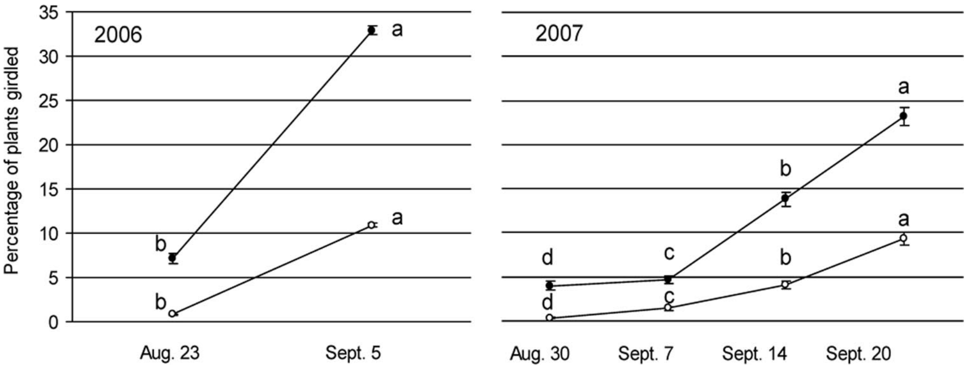

Fig. 3. Mean (±SEM) percentage of plants girdled by larvae of *D. texanus* in high (solid symbols) and low (open symbols) density plots in each of 2 yr at Hays, KS. High-density plots had a greater percentage of plants girdled than low-density plots on all sampling dates, and values with different letters were significantly different among dates within a plant density treatment (ANOVA, $\alpha = 0.05$).

increased by broadleaf weed control compared with grass control and the weed-free treatment provided no additional benefits. These results suggest that broadleaf weeds may have been more competitive with the crop in the wet year than in the dry year. The absence of any benefit from *S*-metolachlor in terms of seed weight or oil content suggests that grass weeds were not competitive with the crop in either year. However, it must be noted that grass weed density was lower than broadleaf weed density and grass weeds generally emerged later in the growing season than broadleaf species. Earlier studies at the same site in Kansas found as many as 60 longspine sandbur plants/m^2 transplanted within 7 d after sunflower emergence did not reduce sunflower seed yield (Perugini 2005). Furthermore, the growth and competitiveness of sandbur plants emerging ≥2 wk later than sunflower were severely reduced compared with sandbur plants that emerged simultaneously with sunflower. The relatively small benefits of broadleaf weed control in 2007, combined with the lack of correlations between weed biomass and yield components at plot level, suggest that the crop remained very competitive at the observed levels of weed pressure.

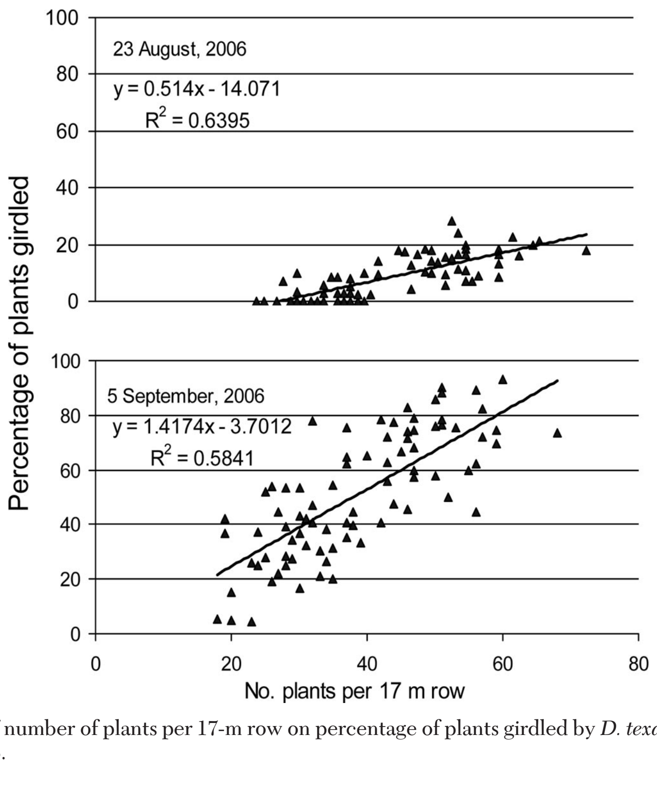

Fig. 4. Regressions of number of plants per 17-m row on percentage of plants girdled by *D. texanus* larvae on each of two dates in 2006 at Hays, KS.

The absence of any effect of weed control on stalk insect abundance suggests that the presence of weeds did not influence the selection of host plants for oviposition by these insects. The marginally lower rate of *D. texanus* infestation in weed-free plots relative to plots with grass weeds in 2006 (Table 5) is not likely to be biologically meaningful, because the only significant difference in weeds between these and plots with broadleaf weed control was an extra ~5 g of grass biomass per square meter (Table 4). The absence of any significant interactions between weed control and crop density suggests that any effects of crop density on insect abundance or behavior occurred independent of weed control treatments.

Plants in high-density plots did not differ in rate of infestation by *D. texanus* compared with those in low-density plots (Table 5), but larvae began girdling high-density plants earlier and the progression of girdling occurred more rapidly in both years (Fig. 3). All stalks that broke as a consequence of lateral force applied to the top of the stalk proved to be girdled by *D. texanus.* Plant size, as estimated by basal stalk circumference, was positively correlated with interplant distance and negatively correlated with the number of plants per row. Because the number of plants per row explained 50% or more of the variation in proportion of plants girdled on any date, we conclude that plant size is an important factor determining the onset of girdling behavior by *D. texanus* larvae, smaller plants being girdled earlier. Girdling behavior is performed by larvae that have finished feeding and its purpose is ostensibly to defend the overwintering chamber against possible invasion by competing larvae of the same or different species, e.g., *A. hubbardi* (Michaud and Grant 2005). However, the behavior does not seem to be directly dependent on the larvae attaining any specific size or stage of development, because girdled plants contain nonfeeding larvae of many different size classes that subsequently undergo anywhere from zero to two additional molts before pupation in the spring. Michaud and Grant (2005) also reported that *D. texanus* larvae refuse to feed on dry stalk pith, raising the possibility that stalk desiccation signals the end of a suitable food supply and cues the onset of girdling behavior. This inference is consistent with anecdotal observations that plants in unirrigated portions of fields begin to lodge earlier than those in irrigated portions, despite having similar rates of *D. texanus* infestation.

The results of this study support previous inferences that stalk desiccation is one factor that seems to cue the onset of girdling behavior by *D. texanus* larvae in mature sunflower plants (Qureshi et al. 2007). High-density plants have more slender stalks with a much larger surface area to biomass ratio than those of larger, low-density plants and would be expected to dry out much more rapidly when exposed to the hot, desiccating winds that typically prevail during late summer in this region. It is also reasonable to expect that the rate of stalk desiccation in mature plants will be affected by soil moisture levels. Lower soil moisture (Fig. 1) likely accounts for the more rapid girdling of plants in 2006 when more plants were girdled 2 wk after crop maturity than were girdled 4 wk after crop maturity in 2007, despite significantly higher ambient temperatures in the latter year.

We had anticipated that weed extraction of soil moisture might result in weedy plots becoming drier and experiencing an earlier onset of girdling, but this does not seem to be the case. Anecdotal observations of fields with poor weed control indicate that *D. texanus*–induced lodging of plants can be considerably delayed by the presence of abundant weeds. Whereas live weeds may compete with the crop for soil moisture to some degree, dead weeds present during crop dry down likely serve the same function as crop residues in diminishing evaporative water loss from the soil surface. We suspect that this effect may account for the observed negative correlation between total weed biomass and the proportion of high-density plants girdled on the last sampling date in 2006 when dry conditions prevailed. Assuming farmers are diligent in controlling weeds to maximize yield potential, mature sunflowers represent a crop with very little surface cover to impede evaporative loss of soil moisture during the period of crop maturity. Planting sunflowers "no-till" is probably the best approach for maximizing conservation of soil moisture throughout the growing season when irrigation is not an option.

These findings have important agronomic implications for sunflower production, especially under rainfed conditions. Preharvest lodging of plants girdled by *D. texanus* is frequently a major cause of yield loss. Despite the fact that larval boring has no impact on plant productivity (Michaud et al. 2007a), each lodged plant becomes unharvestable and represents a complete loss. Our results clearly show a strong correlation between plant population and progression of girdling by *D. texanus* larvae; small, closely spaced plants are girdled much earlier than larger, widely spaced ones, ostensibly because of more rapid desiccation of their stalks. Thus, the dry conditions during crop maturity that favor accumulation of high oil concentrations in seeds also exacerbate girdling problems—precisely when yields are of highest value. Because the harvest of sunflowers is considered impractical before seed moisture declines to 10%, strategies for minimizing losses to lodging should focus either on accelerating the desiccation of seed or retarding the desiccation of stalks, to allow ample opportunity for harvest before the onset of girdling by *D. texanus* larvae. Indeed, any means of sufficiently delaying larval girdling behavior would decouple yield losses from the presence of *D. texanus* and render it a noneconomic insect in sunflowers.

One management option indicated by this study is to increase plant spacing to produce plants with larger stalks that dry more slowly after crop maturity. Furthermore, larvae appear physically limited to cutting girdles in a radius of ~1 cm (J.P.M., unpublished data), meaning that stout stalks are only partially girdled and able to retain considerable tensile strength, whereas slender stalks may be completely severed. Various field trials in the region suggest that sunflower yields are relatively insensitive to plant population across densities ranging from 27,000 to 54,000 plants/ha (Meyer et al. 2005), so there is considerable latitude for increasing plant spacing and plant size without sacrificing yield. Previous work has shown a good correlation between per-plant and per-unit-area yield estimates (Qureshi et al. 2007), and our estimates of per hectare seed yield were greater in low- than in high-density plots in both years, with only a 1.6% penalty in oil content in 2006. The recent advent of various commercial seed treatments has also improved seedling emergence and survival in the face of early season pressure from insects and diseases, reducing the need for heavier seeding as an insurance policy against poor stand establishment. Thus, farmers dealing with large *D. texanus* populations in rain-fed plantings should target plant populations within the low range, especially in drought-prone regions, while keeping in mind that weed control becomes increasingly important in sparser stands. However, flowers >20 cm across are undesirable for oil seed production because oil content tends to be negatively correlated with flower diameter in larger size classes, likely because oil content declines in very large seeds (Michaud et al. 2007a).

Desiccants or defoliants are sometimes applied to mature sunflowers to speed drying of seed and facilitate earlier harvests. In light of our findings, the most suitable materials would be selective for the desiccation of seed, leaving stalks unaffected to not accelerate onset of girdling by *D. texanus.* Another tactic worthy of study for delaying girdling is the "stay-green" stalk trait that is already available in several commercial cultivars. This trait is characterized by delayed senescence of vegetative plant parts relative to the flower so that harvestable seed moisture can be obtained while stalks remain green and succulent. Combinations of these various approaches would seem well suited for integration and, if combined with improved understanding of the factors influencing girdling behavior and more comprehensive data on the relative rates of seed and stalk desiccation in plants of various sizes, could lead to development of an integrated pest management (IPM) program that effectively prevents yield losses associated with *D. texanus* infestation without the need for lethal control.

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