Crop Seeding Level: Implications for Weed Management in Sweet Corn

Author(s): Martin M. Williams II and Rick A. Boydston

Source: Weed Science, 61(3):437-442. 2013.
Published By: Weed Science Society of America
DOI: http://dx.doi.org/10.1614/WS-D-12-00205.1
URL: http://www.bioone.org/doi/full/10.1614/WS-D-12-00205.1

Weed Science 2013 61:437–442

Crop Seeding Level: Implications for Weed Management in Sweet Corn

Martin M. Williams II and Rick A. Boydston*

Sweet corn is seeded under a wide range of population densities; however, the extent to which variable population density influences weed suppression is unknown. Therefore, field studies were undertaken to quantify the influence of sweet corn seeding level on growth, seed production, and post-harvest seed germination of wild-proso millet, one of the most problematic weeds in the crop. As crop seeding level increased, path analysis results indicated the crop canopy became taller and thicker, resulting in less wild-proso millet biomass, seed production, and germinability. However, at the level of individual fields, reductions in wild-proso millet growth and seed production were modest, at best, between a crop population currently used by growers and a higher crop population known to optimize yield of certain hybrids. These results indicate near-future increases in sweet corn seeding levels may play a minor role in improving weed management in individual sweet corn fields. Nonetheless, a reduction in crop populations, via weather- or management-driven phenomenon, increases risk of greater wild-proso millet seed production.

Nomenclature: Wild-proso millet, *Panicum miliaceum* L.; sweet corn, *Zea mays* L.

Key words: Competition, germinability, plant population, planting arrangement, seed bank, seed production, seeding density.

Weeds are incompletely controlled in most sweet corn fields. In a survey of the Midwest, nearly all fields had weed plants that escaped control and over one-half of fields had infestations high enough to cause yield loss (Williams et al. 2008). Many of the 56 species observed in this survey produced viable seed within the short time frame to sweet corn harvest, with the most abundant species often shedding numerous seed. No single species dominates the weed community; however, wild-proso millet is one of the most problematic weeds observed in sweet corn in the Midwest (Williams et al. 2008) and Pacific Northwest (Boydston, personal observation); the two regions accounting for nearly all of the sweet corn grown for processing in the U.S.

Management and environmental factors affecting sweet corn can have an effect on weeds that escape control. Planting date alters sweet corn growth and development, such that late-June plantings in Illinois were found to be more weed suppressive compared to early-May plantings (Williams 2006). Incidence of maize dwarf mosaic in sweet corn reduced the crop's canopy density and subsequent ability to suppress wild-proso millet biomass at weed population densities above 100 plants m^{-2} (Williams and Pataky 2012). Commercial sweet corn hybrids vary widely in their weed suppressive ability, and the principal factors associated with this crop trait have been identified, including crop height and leaf area index (LAI) (So et al. 2009). Moreover, the range of crop environments created by different sweet corn hybrids not only influences weed seed production, but also alters germinability of seed produced from wild-proso millet plants competing in these environments (Williams et al. 2012). In addition, regional scale variation in latitude, planting date, and thermal time accumulation of the crop were the primary variables accounting for variation observed in weed interference levels across Midwest sweet corn fields (Williams et al. 2009).

Sweet corn is grown under a range of plant population densities. In the Midwest, plant population densities range from 40,800 to 64,400 plants ha^{-1} (Williams 2012). Average sweet corn population density in the Midwest is currently 56,000 plants ha^{-1}, although yield is optimized for certain hybrids at 70,200 plants ha^{-1} (Williams 2012). Crop seeding levels are generally ~30 to 40% higher in the Pacific Northwest (authors, personal observation). In field corn, there has long been a trend towards seeding improved hybrids at higher levels (Duvick 2005). Indeed, today's sweet corn is planted at higher seeding levels than previously reported (Mack 1972; Morris et al. 2000); however, they remain far below optimal seeding levels of field corn (Stanger and Lauer 2006). These results indicate sweet corn seeding level is based on the region, the hybrid being grown, field-specific conditions, and perhaps grower or processor preference.

Crop seeding level affects weed suppression in field corn. Greater corn leaf area and rate of canopy closure, often the result of increased seeding levels, has been shown to improve field corn's ability to suppress velvetleaf (*Abutilon theophrasti* Medik.) (Lindquist et al. 1998). Indeed, Teasdale (1998) reported a reduction in velvetleaf seed production when field corn populations were increased 50% over the standard seeding level. In more recent work, field corn populations ranging from 75,000 to 90,000 plants ha^{-1} had no effect on biomass of weed communities in southern Ontario (Sikkema et al. 2008). However, others have observed a decrease in biomass of a mixed weed community when field corn populations increase by 25,000 plants ha^{-1} or more (Shrestha et al. 2001; Tollenaar et al. 1994).

Currently, altering sweet corn planting arrangement, such as through seeding level or row spacing, does not factor into weed management decisions made by vegetable processors nor their contracted growers. Nonetheless, seeding levels vary widely in sweet corn and the extent to which this variability influences weed suppression is unknown. Therefore, the objective of this study was to quantify the influence of sweet corn seeding level on weed growth, seed production, and germination. Given the significance of wild-proso millet in sweet corn production, experiments focused on wild-proso millet responses to sweet corn seeding level.

Materials and Methods

Site Characteristics. Experiments were conducted in four fields over two years near Urbana, IL and Prosser, WA.

DOI: 10.1614/WS-D-12-00205.1

* First author: Ecologist, Global Change and Photosynthesis Research, USDA-ARS, 1102 S. Goodwin Ave., Univ. of Illinois, Urbana, IL 61801; second author: Research Agronomist, Vegetable and Forage Crops Research, USDA-ARS, 24106 N Bunn Road, Prosser, WA 99350. Corresponding author's E-mail: mmwillms@illinois.edu

Experiments were located in different fields each year. The soil in Illinois was a Flanagan silt loam (fine, smectitic, mesic Aquic Argiudoll) averaging 3.7% organic matter and pH of 6.0. The soil at Washington was a Warden loam (Coarse-silty, mixed, superactive, mesic Xeric Haplocambid) averaging 1.3% organic matter and pH of 7.0. Fertilization was based on soil test recommendations of each field. In Illinois, 135 kg N ha^{-1} and 129 kg N ha^{-1} were applied as urea April 17, 2008 and March 24, 2009, respectively. In Washington, 280 kg N ha^{-1} and 168 kg N ha^{-1} were applied as urea April 30, 2008 and May 1, 2009, respectively. Urea was mechanically incorporated immediately after application. Prior to planting, fields received one pass each of a disk harrow and field cultivator. Planting dates were May 29, 2008 and June1, 2009 in Illinois, and May 7, 2008 and May 8, 2009 in Washington. Rainfall was supplemented with sprinkler irrigation to ensure crop and weed establishment and facilitate plant growth.

Experimental Methodology. The experimental design was a split-split plot with four replications. Main plot treatments consisted of two sweet corn hybrids (Optimum and Overland) planted in blocks of 20 rows spaced 76 cm apart and 18.3 m in length. The hybrids were chosen because, from previous research, they were found to differ in ability to suppress wild-proso millet growth, with Overland more weed suppressive than Optimum (Y. So and M. Williams, unpublished data). Subplot treatments consisted of five crop seeding levels randomly assigned to four-row subplots. Crop seeding levels were chosen to reflect the wide range of crop seeding levels used in sweet corn production; including seeding levels used in the recent past, currently practiced, or that may be used in the near future. Because of planter equipment limitations, only a small number of crop seeding levels could be utilized across the range of population densities. Crop seeding levels were achieved by adjusting the planter drive assembly to deliver 35,000 to 105,000 seed ha^{-1} in Illinois and 41,300 to 138,800 seed ha^{-1} in Washington. Sub-subplot treatments consisted of weed-free and wild-proso millet infested sweet corn, measuring four rows wide and 9.15 m in length.

Wild-proso millet had not been observed in the fields prior to these experiments. Therefore, seed was collected from a local population the previous year and stored air-dry at room temperature. Wild-proso millet seed was shallowly planted ($\sim$100 seed m^{-1} of row, 1 cm deep) directly in the center two crop rows of appropriate sub-sub plots immediately after sweet corn planting using a cone planter. Weeds other than wild-proso millet in appropriate plots were controlled with a PRE application of atrazine, rotary hoeing after wild-proso millet establishment, interrow cultivation prior to crop canopy closure, and handweeding.

In order to characterize the crop environment, certain crop growth characteristics were measured at the time of sweet corn silking in weed-free plots. Crop height was measured from the soil surface to the apex of the tallest leaf. Sweet corn LAI was estimated under full-sun conditions within two hours of solar noon using a linear ceptometer (AccuPAR Linear Ceptometer; Decagon Devices, Pullman, WA). For each sub-subplot, five measurements of crop height and LAI were made and averaged for analysis. In addition, crop mid-silk dates were identified from daily counts of emerged silks on plants in the center two rows. Thermal time to mid-silk was calculated as the cumulative growing degree days (GDD) from crop emergence to mid-silk date, whereby GDDs were determined using a base temperature of 10 C and daily temperature data from a weather station within 1 km of each field (Illinois State Water Survey, Champaign, IL and Washington Agricultural Weather Network, Prosser, WA).

Wild-proso millet biomass and seed production were determined at the time of sweet corn harvest, approximately 18 days after crop mid-silk. Wild-proso millet plants were clipped at the soil surface from two 1-m lengths of row per plot. Seed were then mechanically removed from plants using a stationary thresher (Seedburo Equipment Company, Des Plaines, IL), cleaned using an air-column separator (South Dakota Seed Blower, Seedburo Equipment Company, Des Plaines, IL), enumerated, and air-dried at room temperature. Threshed wild-proso millet plants were oven-dried at 65 C to constant mass, then weighed.

Germination tests of wild-proso millet seed were conducted six weeks after harvest of each field experiment except the 2009 experiment in Illinois. In each test, 50-seed replicates of each field plot were incubated on filter paper moistened with distilled water in petri dishes at 25/20 C day/night regime with a 12-hour photoperiod. Germinated seedlings were counted and removed daily for seven days; a time after which no additional germination was observed. Germination tests were conducted in a completely randomized design with four replicates and repeated.

Statistical Analysis. Crop seeding level was considered a categorical treatment because levels were based on fixed planter assembly settings which did not allow for a continuous treatment variable. One benefit to this approach was the ability to compare weed response in a present-day crop seeding level to future crop seeding levels. Seeding levels varied by site and year; therefore, data were analyzed separately by site and year. Diagnostic tests of residuals were used to determine if wild-proso millet responses complied with assumptions of ANOVA for homoscedasticity and normality. These assumptions were met after wild-proso millet biomass and seed production were square root transformed and seed germination was arcsine transformed. Data were analyzed using PROC MIXED in SAS (Version 9.2. SAS Institute Inc., Cary, NC). Fixed effects included crop seeding level, hybrid, and their interaction. Random effects included replicate and interactions with replicate. Where only main effects were significant, means were compared using the protected, Bonferroni-corrected multiple comparison procedure (Neter et al. 1996).

Potential links between wild-proso millet response and the sweet corn environment were investigated using path analysis. Path analysis is a multiple regression method used to identify potential causal pathways between independent and dependent variables by quantifying associations between variables and unaccounted sources of error (i.e. latent variables) (Mitchell 2001). Standardized regression coefficients and latent variables were estimated for a path analysis model using the RAMONA subroutine of SYSTAT (SYSTAT Software, Inc. 2004. SYSTAT 11.0. Richmond, CA). Path analysis was conducted on the pooled dataset in order to capture the full variation in sweet corn environments, and in order to have a sufficient number of observations for the path model. Crop terms in the model, potentially driven by seeding level,

Table 1. Significance (P) of sweet corn hybrid (H), crop seeding level (L), and their interaction on wild-proso millet (WPM) biomass and seed production at sweet corn harvest, and seed germination six weeks later. Experiments were conducted in Urbana, IL and Prosser, WA in 2008 and 2009.

Site	Year	Factor	WPM biomass	WPM seed production	WPM germination
IL	2008	H	0.11	0.14	0.63
		L	< 0.01	< 0.01	0.05
		H*L	0.08	0.13	0.02
	2009	H	< 0.01	< 0.01	—
		L	0.01	0.01	—
		H*L	0.35	0.29	—
WA	2008	H	0.97	0.01	0.07
		L	0.40	0.60	0.06
		H*L	0.96	0.26	0.03
	2009	H	0.79	0.48	0.04
		L	< 0.01	< 0.01	0.01
		H*L	0.42	0.39	0.04

included thermal time to mid-silk, height, and LAI. Wild-proso millet response variables included shoot biomass, seed production, and germination.

Results and Discussion

Wild-proso millet establishment varied with location and year. In Illinois, wild-proso millet plant population density five weeks after planting averaged 66 and 133 plants m^{-2} in 2008 and 2009, respectively. At a similar time in Washington, wild-proso millet plant population density averaged 61 and 38 plants m^{-2} in 2008 and 2009, respectively.

Wild-proso Millet Biomass. Wild-proso millet biomass was mainly affected by sweet corn seeding level (Table 1). As expected, weed biomass declined with higher crop seeding levels in most site-years. With the exception of Washington in 2008 where no trend was observed, seeding level 1 allowed the greatest wild-proso millet growth, while seeding level 5 allowed the least (Table 2). For instance in Illinois, wild-proso millet biomass declined 51% (0.289 kg m^{-2} to 0.143 kg m^{-2}) in 2008 and 23% (0.628 kg m^{-2} to 0.484 kg m^{-2}) in 2009 from seeding level 1 to seeding level 5.

These results are generally consistent with previous research on wild-proso millet biomass response to the light environment. Carpenter and Hopen (1985) reported that as shading increased from 0 to 90%, biomass of wild and domesticated proso millet biotypes was reduced approximately 40 to 80%. In this work, even the lowest crop seeding levels created shade conditions, as evidenced by crop LAI ranging from 0.97 to 3.24 at the lowest crop seeding level (data not shown). Averaged across site-years, sweet corn LAI increased 124% across crop seeding levels ($P < 0.01$). With one exception (Washington 2008), crop height also increased across crop seeding levels ($P < 0.02$). Assuming crop height and canopy density favors light interception, less light would be available for wild-proso millet at higher crop seeding levels. The extent to which light was a limiting factor to weed growth in the present work is unknown. Regardless, sweet corn traits that

Table 2. Wild-proso millet (WPM) biomass and seed production at sweet corn harvest, and seed germination six weeks later, as influenced by crop seeding level. Within each site-year, means within a column followed by the same lower-case letter are not significantly different. Wild-proso millet seed germination differences observed in sweet corn hybrids for each crop seeding level are identified in bold. Means separation was determined by Bonferroni-corrected multiple comparisons at $P < 0.05$. Experiments were conducted in Urbana, IL and Prosser, WA in 2008 and 2009.

Site	Year	Crop seeding level	Planter assembly settings			WPM biomass	WPM seed production	WPM seed germination	
			Driver	Driven	Delivery rate			Optimum	Overland
			—	—	no. ha^{-1}	kg m^{-2}	no. m^{-2}	%	
IL[a]	2008	1	14	28	35,000	0.289 a	21,000 a	29.3 b	39.2 a
		2	19	28	52,500	0.273 a	16,700 ab	25.8 b	26.5 b
		3	24	26	70,000	0.189 b	11,000 bc	43.8 a	29.8 ab
		4	26	23	87,500	0.213 ab	11,200 b	23.7 b	**37.8** ab
		5	24	17	105,000	0.143 b	5,800 c	28.2 b	26.7 b
	2009	1	14	28	35,000	0.628 a	30,900 a	—	—
		2	19	28	52,500	0.573 ab	27,500 ab	—	—
		3	24	26	70,000	0.541 ab	25,100 ab	—	—
		4	26	23	87,500	0.515 b	23,700 b	—	—
		5	24	17	105,000	0.484 b	22,400 b	—	—
WA[b]	2008	1	16	18	57,600	0.216 a	26,900 a	61.0 c	**84.5** a
		2	30	22	88,200	0.223 a	25,000 a	66.5 bc	68.8 b
		3	22	14	102,200	0.161 a	24,900 a	79.0 a	79.7 ab
		4	26	14	120,300	0.240 a	22,900 a	69.3 abc	79.8 a
		5	30	14	138,800	0.272 a	21,700 a	71.5 ab	80.5 a
	2009	1	14	22	41,300	1.046 a	45,800 a	**85.5** b	68.3 c
		2	26	28	60,000	0.625 b	21,200 b	**91.8** a	73.2 bc
		3	30	22	88,200	0.506 b	14,700 b	90.3 ab	82.2 a
		4	22	14	102,000	0.431 b	15,500 b	**92.5** a	75.8 ab
		5	26	14	120,300	0.497 b	16,400 b	79.7 b	74.3 abc

[a] In Illinois, a Monosem NG+ planter was used (Monosem Inc., Edwardsville, KS). Plate number was 1837.

[b] In Washington, A Kinze MT planter was used (Kinze Manufacturing Inc., Williamsburg, IA).

Table 3. Wild-proso millet (WPM) biomass and seed production at sweet corn harvest as influenced by sweet corn hybrid. Within each site-year, means within a column followed by an asterisk are significantly different at $P < 0.05$ as determined by Bonferroni-corrected multiple comparisons.

Site	Year	Sweet corn hybrid	WPM biomass	WPM seed production
			kg m^{-2}	no. m^{-2}
IL	2008	Optimum	0.255	14,900
		Overland	0.188	11,400
			ns	ns
	2009	Optimum	0.632	33,100
		Overland	0.464	18,800
			*	*
WA	2008	Optimum	0.227	14,300
		Overland	0.220	34,600
			ns	*
	2009	Optimum	0.647	25,700
		Overland	0.602	20,300
			ns	ns

describe a large, late-maturing crop, including height and LAI, have been implicated in the crop's ability to suppress wild-proso millet growth (So et al. 2009).

Given the range of crop seeding levels used in this work (i.e. approximately three-fold increase from low to high levels), that wild-proso millet biomass wasn't suppressed greater and more consistently at high seeding levels is noteworthy. In general, competitive ability of many crops is believed to improve as population increases. Clay et al. (2009) reported that field corn at 149,000 plants ha^{-1} had greater water and nitrogen use efficiency than when grown at 74,500 plants ha^{-1}. Higher field corn population densities increased maximum intercepted light and decreased time to canopy closure (Westgate et al. 1997). Suppression of the weed community, as a result of elevated field corn populations, has been reported (Shrestha et al. 2001; Tollenaar et al. 1994). Moreover, crop seeding level has been long considered a beneficial tactic to improve overall performance of multi-tactic weed management systems (Jordan 1993; Liebman and Gallandt 1997; Swanton and Weise 1991). While sweet corn seeding level influences wild-proso millet biomass, from a weed management perspective, the contribution to weed suppression appears relatively small.

Sweet corn hybrid influenced wild-proso millet biomass in only a single site-year. Weed biomass in Optimum was 36% higher than Overland in Illinois in 2009 (Table 3). In all other site-years, weed biomass was similar across hybrids, averaging 0.222 to 0.625 kg m^{-2}. This result is somewhat surprising, since Overland was found to be consistently more weed suppressive than Optimum in previous research (Y. So and M. Williams, unpublished data). Intuitively, factors affecting crop growth must result in a significant reduction in crop competitiveness before a corresponding influence on the weed could be detected. For instance, maize dwarf mosaic incidence in sweet corn reduced the crop's competitive ability with wild-proso millet only when the disease severely stunted the crop under high weed population densities (Williams and Pataky 2012). In this work, perhaps environmental conditions in three of the site-years did not favor competitive ability of one hybrid over another. Alternatively, the hybrids' effects on the weed could not be differentiated in the study system.

Seed Production. Similar to biomass, wild-proso millet seed production was mainly affected by sweet corn seeding level (Table 1). Seed production declined with higher crop seeding levels in three of four site-years. With the exception of Washington in 2008 where no trend was observed, seeding level 1 allowed the greatest wild-proso millet seed production, while seeding level 5 allowed the least (Table 2). Even at the highest crop seeding level, as high as 138,800 crop seeds ha^{-1}, wild-proso millet continued to produce 5,800 to 22,400 seed m^{-2}.

These results are consistent with previous research on the effect of crop seeding level on weed seed production. Wheat (*Triticum aestivum* L.) seeded at the high end (200 plants m^{-2}) of recommended levels for Alberta reduced wild oat (*Avena fatua* L.) seed production 46% compared to wheat seeded at the low end (100 plants m^{-2}) of recommended levels (O'Donovan et al. 2006). In field corn, Teasdale (1998) reported 69 to 94% reduction in velvetleaf seed production when crop populations were increased from 64,000 to 96,000 plants ha^{-1}. Although not a direct test of crop seeding level, wild-proso millet seed production decreased linearly as sweet corn canopies produced larger plants, greater LAI, and intercepted more light (Williams et al. 2012).

Sweet corn hybrid had an inconsistent effect on wild-proso millet seed production. Both sites had one year where seed production was unaffected by hybrid, and another year where seed production was affected by hybrid (Table 3). Overland was more suppressive of seed production in 2009 in Illinois, whereas the reverse was observed in 2008 in Washington.

Seed Germination. Fewer trends were observed of wild-proso millet germination of seed from plants grown in individual environments. In general, intermediate crop seeding levels (often levels 3 and 4) produced wild-proso millet seed that was among the most germinable (Table 2). In addition, seed germination was not always similar across hybrids for each crop seeding level. In those instances, hybrid had an inconsistent effect on wild-proso millet germination across site-years.

Path Analysis. Factors that affect sweet corn growth can have an effect on weed growth and seed production, including latitude, hybrid, planting date, disease incidence, and thermal time to harvest (Williams 2006; Williams et al. 2009; Williams and Pataky 2012). Path analysis was conducted in order to investigate potential links between wild-proso millet response and the sweet corn environment that may not be apparent from univariate analyses. Results of path analysis indicated sweet corn seeding level had both direct and indirect effects on wild-proso millet, depending on the weed response variable (Figure 1). For wild-proso millet biomass, crop seeding level had only an indirect effect that was mediated through crop LAI, as evidenced by a negative path coefficient (-0.571) between crop LAI and weed biomass. Apparently crop seeding level itself had minimal direct influence on weed biomass, but increased crop LAI driven by crop seeding level was important. In contrast, both a direct effect of crop seeding level (path coefficient $= -0.332$) and indirect effect, through crop height (path coefficient $= -0.312$), was observed for wild-proso millet seed production. In this case, higher crop seeding levels increased crop height, which was negatively correlated with wild-proso millet seed production.

The different apparent linkages between the crop environment and weed response variables merit consideration. It

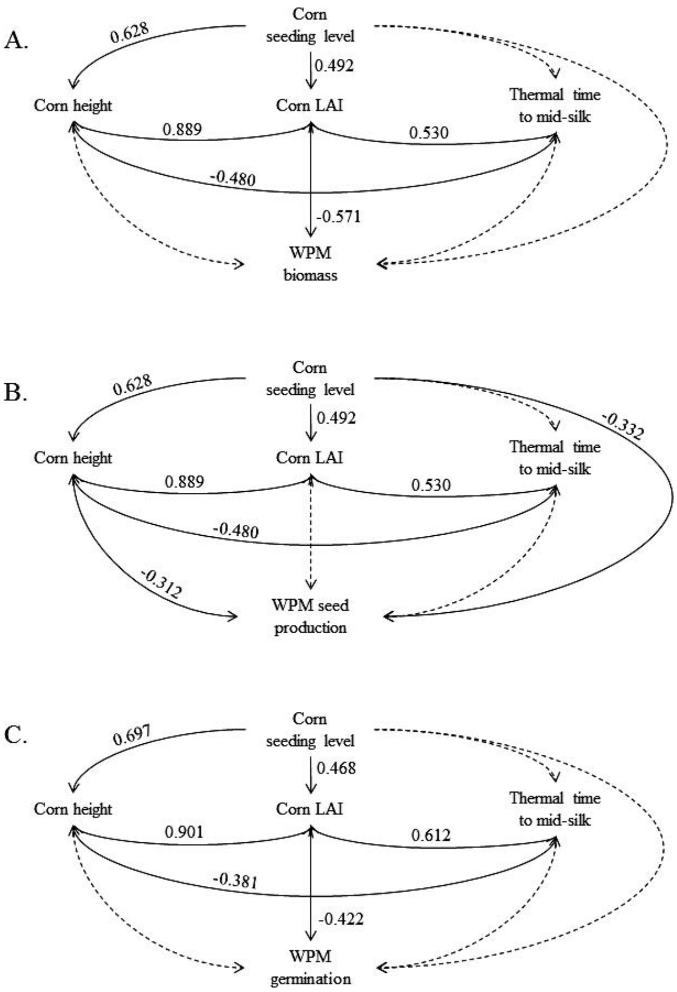

Figure 1. Path analysis model of hypothetical links between sweet corn seeding level, height, LAI, thermal time to mid-silk, and wild-proso millet A) biomass, B) seed production, and C) seed germination. Solid, bold arrows indicate significant associations ($P < 0.05$) between variables, whereas dotted arrows indicate nonsignificant associations. Standardized regression coefficients are reported for significant associations only.

suggests the mechanism by which the crop suppresses wild-proso millet growth may not be identical to the mechanism influencing seed production. Most likely, resource dependent processes are at play for both weed growth and seed production. After all, resources needed for plant growth, such as light, water, and/or nutrients, often become limited during the course of the growing season. Evidence suggests that corn's success at preempting these resources determines its weed suppressive ability (Lindquist et al. 1998). However, perhaps resource independent processes also play a role in wild-proso millet response. For instance, shade avoidance response in field corn contributes to crop competitiveness, particularly when combined with abiotic stresses (Page et al. 2010a,b). The light environment is known to influence seed development in certain weed species (Brainard et al. 2005; Mitrovic et al. 2010), and perhaps also is important in wild-proso millet seed development. Alternatively, processes that influence resource capture (e.g. light absorption) in wild-proso millet behave differently than processes influencing resource utilization (e.g. photosynthate partitioning to seed). Tollenaar et al. (2006) hypothesized field corn compensates better for factors that reduce resource capture than it can for factors influencing resource utilization. In any event, variability in crop seeding levels presents opportunities for wild-proso millet to succeed in sweet corn.

Path analysis results indicated crop seeding level had an indirect effect on wild-proso millet germination, which was mediated through crop LAI. Higher seeding levels increased crop LAI, which was negatively associated (path coefficient = -0.422) with wild-proso millet germination (Figure 1). This observation is consistent with previous research on the weed. For instance, thin sweet corn canopies which poorly intercepted light promoted production of wild-proso millet seed that were more germinable compared to wild-proso millet seed that matured in sweet corn canopies characterized by dense canopies more efficient at light interception (Williams et al. 2012). Although the mechanisms driving maternal environment-mediated differences in seed germinability remain unknown, it was hypothesized that both the physiology of the wild-proso millet embryo and physical structure of the seed coat are involved. Seed viability was not assessed in the present work, which may in part account for germination responses.

Recent research in sweet corn indicates that, in order to maximize yield under weed-free conditions, certain hybrids need to be seeded at higher levels than currently utilized. If field corn serves as an example for sweet corn, future gains in productivity will come largely from improved stress tolerance, especially tolerance to intense competition (Duvick 2005). However, results from this work provide little support to increasing sweet corn seeding level solely for purposes of improving weed management. For instance, few reductions in wild-proso millet response were observed between a crop population currently used by growers in the Midwest (i.e. seeding level 2) and a crop population known to optimize yield of certain hybrids (i.e. seeding level 3). Except perhaps in rare cases, the extent to which crop seeding level could be increased without compromising crop yield would be modest and may not result in a noticeable decrease in wild-proso millet seed production in a given field. One such exception would be in crop production systems where crop seedling mortality is anticipated, such as the use of aggressive physical weed control measures.

Nonetheless, this work shows sweet corn seeding level influences wild-proso millet. As crop seeding level increased, path analysis results indicated the crop canopy became taller and thicker, resulting in less wild-proso millet biomass, seed production, and germinability. Even at the highest sweet corn seeding levels tested, 105,000 seed ha^{-1} in Illinois and 138,000 seed ha^{-1} in Washington, wild-proso millet continued to produce over 5,000 seed m^{-2} when no other intervention was made. These results provide evidence that conditions that reduce crop population density, such as weather- or management-driven phenomenon, increase risk of greater wild-proso millet seed production. While higher crop seeding levels are anticipated in the near-future, any gains this provides in the crop's ability to preempt limited resources appears to offer a limited role in improving weed management in individual fields.

Acknowledgments

The authors wish to thank Jim Moody, Encarnacion Rivera, Treva Anderson, and the students participating in this research. We also thank the Crookham Company and Syngenta for providing seed. Mention of a trademark, proprietary product, or vendor does not constitute a guarantee or warranty of the product by the U.S. Dept. of Agriculture and does not imply its approval to the exclusion of other products or vendors that also may be suitable.

Literature Cited

Brainard, D. C., R. R. Bellinder, and A. DiTommaso. 2005. Effects of canopy shade on the morphology, phenology, and seed characteristics of Powell amaranth (*Amaranthus powellii*). Weed Sci. 53:175–186.

Carpenter, J. L. and H. J. Hopen. 1985. A comparison of the biology of wild and cultivated proso millet (*Panicum miliaceum*). Weed Sci. 33:795–799.

Clay, S. A., D. E. Clay, D. P. Horvath, J. Pullis, C. G. Carlson, S. Hansen, and G. Reicks. 2009. Corn responses to competition: growth alteration vs. yield limiting factors. Agron. J. 101:1522–1529.

Duvick, D. N. 2005. The contribution of breeding to yield advances in maize (*Zea mays* L.). Adv. Agron. 86:83–145.

Jordan, N. 1993. Prospects for weed control through crop interference. Ecol. Appl. 3:84–91.

Liebman, M. and E. R. Gallandt. 1997. Many little hammers: ecological management of crop-weed interactions. Pp. 291–343 *in* L. E. Jackson, ed. Ecology in Agriculture. San Diego, CA: Academic.

Lindquist, J. L., D. A. Mortensen, and B. E. Johnson. 1998. Mechanisms of corn tolerance and velvetleaf suppressive ability. Agron. J. 90:787–792.

Mack, H. J. 1972. Effects of population density, plant arrangement, and fertilizers on yield of sweet corn. J. Amer. Soc. Hort. Sci. 97:757–760.

Mitchell, R. J. 2001. Path analysis: pollination. Pp. 217–234 *in* S. M. Scheiner and J. Gurevitch, eds. Design and analysis of ecological experiments. New York: Oxford University Press.

Mitrovic, A., J. Bogdanovic, Z. Giba, and L. Culafic. 2010. Effect of photoperiod during growth of *Chenopodium rubrum* mother plants on properties of offspring. Biol. Plant. (Prague) 54:735–739.

Morris, T. F., G. Hamilton, and S. Harney. 2000. Optimum plant population for fresh-market sweet corn in the northeastern United States. HortTechnology 10:331–336.

Neter, J., M. H. Kutner, C. J. Nachtsheim, and W. Wasserman. 1996. Applied linear statistical models. Irwin, Chicago, 1408 p.

O'Donovan, J. T., R. E. Blackshaw, K. N. Harker, and G. W. Clayton. 2006. Wheat seeding rate influences herbicide performance in wild oat (*Avena fatua* L.). Agron. J. 98:815–822.

Page, E. R., M. Tollenaar, E. A. Lee, L. Lukens, and C. J. Swanton. 2010a. Shade avoidance: an integral component of crop-weed competition. Weed Res. 50:281–288.

Page, E. R., M. Tollenaar, E. A. Lee, L. Lukens, and C. J. Swanton. 2010b. Timing, effect, and recovery from intraspecific competition in maize. Agron. J. 102:1007–1013.

Shrestha, A., I. Rajcan, K. Chandler, and C. J. Swanton. 2001. An integrated weed management strategy for glufosinate-resistant corn (*Zea mays*). Weed Techol. 15:517–522.

Sikkema, P. H., R. E. Nurse, T. Welacky, and A. S. Hamill. 2008. Reduced herbicide rates provide acceptable weed control regardless of corn planting strategy in Ontario field corn. Can. J. Plant Sci. 88:373–378.

So, Y. F., M. M., II. Williams, 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.

Stanger, T. F. and J. G. Lauer. 2006. Optimum plant population of bt and non-bt corn in Wisconsin. Agron. J. 98:914–921.

Swanton, C. J. and S. F. Weise. 1991. Integrated weed management: the rationale and approach. Weed Technol. 5:657–663.

Teasdale, J. R. 1998. Influence of corn (*Zea mays*) population and row spacing on corn and velvetleaf (*Abutilon theophrasti*) yield. Weed Sci. 46:447–453.

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

Tollenaar, M., A. A. Dibo, A. Aguilera, S. F. Weise, and C. J. Swanton. 1994. Effect of crop density on weed interference in maize. Agron. J. 86:591–595.

Westgate, M. E., F. Forcella, D. C. Reicosky, and J. Somsen. 1997. Rapid canopy closure for maize production in the northern U.S. corn belt: radiation-use efficiency and grain yield. Field Crops Res. 49:249–258.

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. 2012. Agronomics and economics of plant population density on processing sweet corn. Field Crops Res. 128:55–61.

Williams, M. M., II, A. S. Davis, T. L. Rabaey, and C. M. Boerboom. 2009. Linkages among agronomic, environmental, and weed management characteristics in North American sweet corn production. Field Crops Res. 113:161–169.

Williams, M. M., II and J. K. Pataky. 2012. Maize dwarf mosaic can reduce weed suppressive ability of sweet corn. Weed Sci. 60:577–582.

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

Williams, M. M., II, B. J. Schutte, and Y. F. So. 2012. Maternal corn environment influences wild-proso millet (*Panicum miliaceum*) seed characteristics. Weed Sci. 60:69–74.

Received December 19, 2012, and approved March 18, 2013.