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Effects of Common Wheat (*Triticum aestivum*) Management Alternatives on Weed Seed Production[1]

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Abstract: Common management alternatives were compared in a factorial arrangement for 2 yr to determine their effects on green foxtail and yellow foxtail seed production in spring wheat in the Northern Great Plains of the United States. Seed production was measured twice, at wheat harvest (in August) and postharvest (after first lethal frost in autumn). Management alternatives were early, middle, and late crop-sowing dates; no-till, chisel, and moldboard plow tillage systems; and broadleaf herbicide only and broadleaf herbicide plus fenoxaprop applications. Fenoxaprop reduced foxtail seed production at wheat harvest but not at postharvest. Early sowing also decreased seed production at wheat harvest but increased postharvest seed production. Tillage system had no consistent effects on foxtail seed production. Postharvest seed production often was greater than or equal to that at wheat harvest regardless of management system. These results indicate that in-crop management alternatives, such as postemergence grass herbicide and early crop sowing, may lower the number of foxtail seeds at harvest substantially, but they must be accompanied by postharvest weed control to reduce overall seed production.

Nomenclature: Fenoxaprop; green foxtail, *Setaria viridis* (L.) Beauv. #[3] SETVI; yellow foxtail, *Setaria pumila* (Poir.) Roem. & Schult. [=*Setaria glauca* (L.) Beauv.] # SETLU; spring wheat, *Triticum aestivum* L. 'Sharpe'.

Additional index words: Sowing date, tillage regime.

Abbreviations: CP, chisel plow; GDD, growing degree-days; MP, moldboard plow; NT, no-till.

INTRODUCTION

Green foxtail and yellow foxtail are two of the most abundant and troublesome annual weeds in spring wheat production systems of the Northern Great Plains of the United States (Donald and Nalewaja 1990; Fay 1990) and the Prairie Provinces of Canada (Hunter et al. 1990). Foxtail species became an important problem, partly because of the adoption of limited tillage (Banting et al. 1973) or reduced tillage practices or both, which probably delay foxtail seedling emergence (Spandl et al. 1998). Prolonged emergence often allows the late-emerging portion of the population to escape control (Spandl et al. 1999) by many postemergence-applied herbicides.

Sowing spring wheat early in the season when soil temperatures are low can minimize foxtail-induced yield losses (Blackshaw et al. 1981). Early sowing gives wheat a competitive advantage over foxtail because wheat emergence is not as sensitive to low soil temperature as is foxtail (Vanden Born 1971). In contrast, when sown late, wheat establishment is slower than that of foxtail, thereby giving the competitive edge to the foxtail (Rahman and Ashford 1972).

Foxtail effects also can be minimized either by increasing the sowing rate of spring wheat (Blackshaw et al. 1981; Khan et al. 1996) or by applying herbicides (Ashford et al. 1990; O'Sullivan 1990). However, regardless of the approach used, some foxtail plants escape control, complete their life cycle, produce numerous seeds that enter the seedbank, and provide the potential for future infestations.

The dispersal of seeds from foxtail plants that escape control is probably the most significant factor contributing to the foxtail infestations in spring wheat. Plants that are not controlled early produce large, many-seeded panicles; however, abundant seeds can be produced even

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[3] Letters following this symbol are a WSSA-approved computer code available from *Composite List of Weeds*, Revised 1989. Available only on computer disk from WSSA, 810 East 10th Street, Lawrence, KS 66044-8897.

when postemergence herbicides are used (Forcella et al. 2000). Moreover, in the Northern Great Plains, most foxtail plants present at the time of wheat maturity (July and August), even those damaged during wheat harvest, still grow, flower, and produce seed between harvest and the first killing frost in autumn (Kegode et al. 1999).

Mowing does not stop seed production of late-growing plants. For example, giant foxtail (*Setaria faberi* L.) survived several cuttings to a height of 5 cm and still produced seeds (Schreiber 1965). However, if glyphosate is applied, or soil is tilled, within 10 d after spring wheat harvest, foxtail seed production is minimized (Kegode et al. 1999). Whether the level of inhibition of seed production achieved by these types of postharvest management techniques represents a significant proportion of total foxtail seed production is not known. Thus, more information is needed regarding the influence of common wheat management practices on foxtail seed production. Such information will help provide the necessary framework for modelers to design decision aids for foxtail management in wheat. Consequently, the objective of this study was to determine how the integrated effects of sowing date, tillage system, and postemergence herbicide application influence foxtail density, height, panicle length, and, ultimately, seed production in spring wheat.

MATERIALS AND METHODS

Studies were conducted in 1996 and 1997 at the University of Minnesota West Central Research and Outreach Center, Morris, MN, in plots originally established in 1978 to determine the long-term effects of tillage regime on soil properties. The cropping system was a soybean–wheat rotation, with both crops represented each year. The soil was a gently undulating ($<$ 1-m topographic relief) Aastad clay loam (Pachic Udic Haploboroll; fine, loamy, mixed) with about 6% organic matter and a pH of 6.4 in the surface soil horizon.

The experiment was configured as a split–split-plot design with four replications. The whole plots consisted of three tillage systems: moldboard plow (MP), chisel plow (CP), and no-till (NT). Preparation of whole plots included autumn plowing and secondary tillage with a field cultivator in spring (MP and CP plots only) the day before sowing. Subplots consisted of two postemergence herbicide treatments: (1) mixture of fenoxaprop + MCPA ester + 2,4-D ester at rates of 0.05 kg ai + 0.25 kg ae + 0.08 kg ae/ha to control grass and broadleaf weeds and (2) 2,4-D ester, low volatile formulation, at a rate of 0.5 kg ae/ha to control only broadleaf weeds. Herbicides were applied to all sub-subplots on the same day, when spring wheat was at about the six- and three-leaf stages in early- and late-sown plots, respectively. The stages were within the range of times specified on the herbicide label. Herbicides were applied through a 3-m-wide boom of a tractor-mounted shielded sprayer that delivered 187 L/ha solution at 200 kPa. Sub-subplots consisted of three wheat-sowing dates that were timed to correspond with late-April, early-May, and mid-May operations that are common to the region. Fertilizer was broadcast applied yearly at 60, 13, and 13 kg/ha of N, P, and K, respectively. Hard red spring wheat, cv. 'Sharpe', was sown at 135 kg/ha with a NT drill, which placed seeds 2.5 cm deep in rows 18 cm apart. Individual sub-subplot size was 3 by 9 m.

In 1996 the early, mid, and late sowings were on April 28, May 13, and May 20, respectively. Grain harvest for these three sowing dates was on August 12, 20, and 28, respectively. All herbicides were applied on June 6 and fertilizer on April 27, and final postharvest collection of foxtail seed was on October 5 to 9 in 1996. In 1997, the early, mid, and late sowings were on April 29, May 6, and May 15, respectively. Grain harvest for these three sowing dates was on August 12, 21, and 26, respectively. All herbicides were applied on June 10 and fertilizer on April 28, and final postharvest collection of foxtail seed was on October 7 to 8 in 1997.

Foxtail density was determined at spring wheat harvest by using three 0.1-m^2 (25 by 40 cm) quadrats randomly placed in each sub-subplot. It was not possible to determine the density of each foxtail species separately; nonetheless, both species were estimated to be of equal proportion. Wheat grain was harvested from a 1.5- by 9-m area in the center of each sub-subplot using a small-plot combine, screens of which were set purposefully to retain both crop and weed seeds, as well as chaff. Green and yellow foxtail seeds were separated from wheat grain samples, and the number of viable seeds for each was determined. Immediately after wheat harvest, a maximum of 50 panicles of green foxtail and yellow foxtail were collected from the nonharvested portions of each sub-subplot, and average panicle length was determined. On collection of foxtail panicles, the remaining wheat was harvested, and plots were left idle until measurement of postharvest foxtail seed production. Natural seed shed at wheat harvest in these plots was nil because foxtail typically does not begin to shed seeds until 1,000 growing degree-days (GDD) after crop sowing (Forcella et al. 1996). This GDD value did not occur until September, after wheat harvest, in both years (Table 1).

Table 1. Monthly rainfall and cumulative growing degree-days (GDD; base temperature 10 C) from May to October in 1996 and 1997 and 30-yr average at Morris, MN.

	Monthly rainfall			Cumulative GDD		
Month[a]	1996	1997	30-yr average[b]	1996	1997	30-yr average
	mm			C		
May	116	32	71	102	77	168
June	26	54	94	411	415	435
July	92	115	86	705	634	783
August	57	94	81	911	888	1,093
September	53	37	61	1,003	1,098	1,195
October[c]	0	3	1	1,019	1,150	1,215
Total	344	335	394	1,019	1,150	1,215

[a] No precipitation or GDD recorded in April, in both years.

[b] Data are averages for 1961–1990 from West Central Research and Outreach Center, Morris, MN.

[c] Data are for October 1–5, 1996, October 1–7, 1997, and October 1–7 for the 30-yr average.

Postharvest foxtail seed production was estimated from the soil surface using a vacuum cleaner. To facilitate vacuuming of seeds, three plastic pipe sections, each measuring 15 cm in diameter, were randomly positioned within the center of each sub-subplot, and contents from the soil surface within the pipe sections were vacuumed. Vacuumed samples were suspended in 100-ml solution of sodium hexametaphosphate, sodium bicarbonate, and magnesium sulphate to disperse clay particles (Malone 1967). Suspensions were stirred for 15 min and subsequently rinsed over a series of screens. The seed material that was retained by a 0.85-mm screen was washed onto cheesecloth and placed overnight in an oven set at 30 C to dry. Dry samples were identified by species (green foxtail and yellow foxtail) and separated into ‘‘viable’’ and ‘‘nonviable’’ categories, and only viable seeds were counted. Nonviable seeds were those that crushed when probed with fine-tipped forceps, whereas viable seeds remained firm under pressure. Nearly all seeds isolated in this manner had the bright yellow or tan appearance of recently produced seeds. Consequently, we assumed that none of these seeds were produced in previous years.

Daily precipitation and daily maximum and minimum air temperature for late April to early October were recorded from a permanent weather station at the site (Table 1). GDD, base 10 C, were calculated from air temperatures. Data for the 30-yr average monthly precipitation and cumulative GDD (1961 to 1990) were recorded at the West Central Research and Outreach Center, Morris, MN, which was approximately 1 km from the study site.

Data for overall foxtail density, green foxtail and yellow foxtail plant height, panicle length, and seed production at and after spring wheat harvest were subjected to analysis of variance of split–split plots (Gomez and Gomez 1984). LSD procedures were used to detect and separate mean treatment differences at P = 0.05. Because of differences in rainfall and GDD (Table 1), data for foxtail density, panicle length, and seed production at and after wheat harvest were not pooled to allow for analysis across years (Tables 2 and 3). Only green foxtail and yellow foxtail plant height data were pooled because of consistency in data across years (Table 3).

RESULTS AND DISCUSSION

Foxtail Density. Densities were influenced by postemergence herbicide application in both years but by sowing date and tillage in only 1 yr each (Table 2). All fenoxaprop-treated subplots appeared foxtail free on casual inspection. Fenoxaprop reduced foxtail densities by only 44% in 1996 and 20% in 1997, as averaged over all other experimental variables (for simplicity of presentation). However, surviving foxtail plants were short and not robust in comparison with nontreated plants. Late sowing of spring wheat in 1996 reduced the foxtail population by 58%, averaged over tillage and herbicide variables. In 1997, MP reduced foxtail density by 47% relative to CP when averaged across all herbicide and sowing date variables.

Foxtail densities were slightly higher in 1996 than in 1997, which probably reflects differences in growing conditions during the critical period of seedling establishment between the 2 yr. In 1996, 42% of the total growing-season precipitation was received in May and June compared with only 26% during the same period in 1997 (Table 1). Lower precipitation in the earlier part of 1997 probably reduced foxtail growth and establishment after emergence, and application of fenoxaprop thereafter did not lower foxtail densities appreciably. Less control in 1997 was likely due to foxtail experiencing some moisture stress and, therefore, not actively growing. Herbicide uptake and activity can be reduced significantly if target plants are stressed (Levene and Owen 1995; Rossi et al. 1993).

The highest foxtail density occurred in 1996 with the second spring wheat sowing (Table 2) that was done at a time when moisture was abundant (Table 1). Blackshaw et al. (1981) reported that in wet soils, green foxtail emerged faster than wheat when soil temperatures were high. In addition, foxtails can be serious competitors under wet conditions (Donald and Nalewaja 1990). The low foxtail density after late wheat sowing in 1996 (Table 2) was most likely caused by soil disruption at sow-

Table 2. Main effects of tillage system, postemergence herbicide, and sowing date of spring wheat on foxtail density and green and yellow foxtail panicle size at Morris, MN, in 1996 and 1997.

			Foxtail panicle length			
	Foxtail density[a]		Green foxtail		Yellow foxtail	
Experimental variable	1996	1997	1996	1997	1996	1997
	plants/m²		cm			
Tillage regime						
No-till	520	295	5.4	7.6	5.3	6.0
Chisel plow	473	449	6.8	7.6	6.3	5.6
Moldboard plow	308	237	6.3	7.3	6.8	6.2
LSD (0.05)	NS[b]	74	0.9	NS	1.0	NS
Postemergence herbicide[c]						
Fenoxaprop + MCPA + 2,4-D	312	290	5.6	7.4	5.3	5.5
2,4-D	556	363	6.7	7.6	7.0	6.3
LSD (0.05)	112	63	0.3	NS	0.8	0.7
Spring wheat sowing date[d]						
Early	451	327	6.7	8.9	5.3	6.1
Mid	600	343	5.9	8.2	6.3	6.3
Late	250	311	6.0	5.9	6.8	5.3
LSD (0.05)	152	NS	0.6	0.7	0.5	0.3

[a] Pooled over both green and yellow foxtail.

[b] NS, not significant.

[c] 2,4-D ester was applied at 0.5 kg ae/ha; Fenoxaprop + MCPA ester + 2,4-D ester were applied at 0.05 kg ai + 0.25 kg ae + 0.08 kg ae/ha.

[d] Early, mid, and late sowing dates were April 28, May 13, and May 20, 1996, respectively; and April 29, May 6, and May 15, 1997, respectively.

ing when the majority of foxtails were emerging. Subsequent foxtail emergence after late sowing of wheat was presumably from a depleted seedbank, which resulted in low foxtail densities.

Foxtail Plant Height. Herbicides had the greatest and most consistent effects on foxtail height compared with other experimental variables. All fenoxaprop-treated subplots appeared foxtail free on casual inspection, although weeds were present below the spring wheat canopy. Averaged across other treatments and years, application of fenoxaprop reduced green foxtail height from approximately 85 to 60 cm and yellow foxtail height from approximately 90 to 70 cm (Table 3). The wheat canopy was about 80 cm in both years, so fenoxaprop applications maintained foxtail below the crop canopy, whereas foxtail exceeded the crop canopy in the absence of fenoxaprop.

Sowing date had inconsistent and relatively small effects on foxtail heights but only in the absence of fenoxaprop, which stabilized heights. Without fenoxaprop, foxtail heights tended to increase with delayed sowing in 1996 but tended to decrease with sowing date in 1997 (Table 3). These trends occurred in both foxtail species, and their explanations are not known. Tillage had no measurable effects on foxtail height.

Foxtail Panicle Length. Fenoxaprop decreased panicle lengths of yellow foxtail in both years but those of green foxtail in only 1 yr (Table 2). Reductions ranged from 13 to 25%.

Sowing date consistently influenced panicle lengths but not always in the same direction. Late sowing reduced green foxtail panicle length in both years (by 10 to 34%) but that of yellow foxtail only once (16%). In the remaining year, yellow foxtail panicle length was increased with late sowing (28%) (Table 2).

Lastly, tillage regime significantly influenced panicle lengths of both species in 1996 but not in 1997. In the former year the shortest panicles were produced by both species in NT, whereas the longest panicles were produced in CP by green foxtail and in MP by yellow foxtail. According to Nadeau and Morrison (1986), green foxtail exhibits more plasticity in vegetative development than yellow foxtail in response to soil moisture stress. This response may explain why panicles of green foxtail, but not of yellow foxtail, tended to be shorter in 1996 than in 1997 (Table 2). Relatively dry conditions prevailed during the period of panicle initiation (June to July) during 1996, whereas abundant rain fell during that same period in 1997 (Table 1).

Foxtail Seed Production at Wheat Harvest. Fenoxaprop application and sowing date, but not tillage system, had significant effects on foxtail seed production (Table 3). Early sowing, by itself, kept seed production of green foxtail to < 100 seeds/m² and that of yellow foxtail to

Table 3. Main effects of sowing date and postemergence herbicide on green and yellow foxtail plant height and seed production at spring wheat harvest at Morris, MN, in 1996 and 1997.

		Green foxtail			Yellow foxtail		
			Seed production			Seed production	
Sowing date[a]	Postemergence herbicide[b]	Plant height[c]	1996	1997	Plant height	1996	1997
		cm	seeds/m^2		cm	seeds/m^2	
Early	Fenoxaprop + MCPA + 2,4-D	59	25	0	69	493	201
	2,4-D alone	84	103	42	94	867	891
Mid	Fenoxaprop + MCPA + 2,4-D	65	170	0	77	2,174	1,033
	2,4-D alone	88	601	156	98	6,166	3,251
Late	Fenoxaprop + MCPA + 2,4-D	60	102	247	72	880	1,994
	2,4-D alone	65	913	1,309	89	5,250	4,079
LSD (0.05)		10	293	456	14	1,083	759

[a] Early, mid, and late spring wheat sowing dates were April 28, May 13, and May 20, 1996, respectively; and April 29, May 6, and May 15, 1997, respectively.

[b] 2,4-D ester was applied at 0.5 kg ae/ha; Fenoxaprop + MCPA ester + 2,4-D ester were applied at 0.05 kg ai + 0.25 kg ae + 0.08 kg ae/ha.

[c] Pooled across years.

< 1,000 seeds/m^2. Early sowing combined with fenoxaprop nearly eliminated production of green foxtail seed at the time of crop harvest (Table 3).

Foxtail seed production increases as densities of plants and panicles increase (Forcella et al. 2000) and inflorescence size correlates well with seed production in several grasses (Forcella et al. 2000; Norris 1992; Schreiber 1965). Most foxtail seeds were produced by plants growing in mid and late sowings (Table 4), which emphasizes the importance of early sowing of spring wheat for reducing current season (Khan et al. 1996) as well as future crop–weed interactions.

Table 4. Main effects of tillage system, postemergence herbicide, and spring wheat sowing date on portion of green and yellow foxtail seeds that were produced before spring wheat harvest at Morris, MN, in 1996 and 1997.

	Seed production at spring wheat harvest[a]			
	Green foxtail		Yellow foxtail	
Experimental variable	1996	1997	1996	1997
	%			
Tillage regime				
No-till	45	7	44	17
Chisel plow	52	20	48	23
Moldboard plow	57	9	48	14
LSD (0.05)	NS[b]	NS	NS	8
Postemergence herbicide[c]				
Fenoxaprop + MCPA + 2,4-D	44	6	54	12
2,4-D	59	19	38	24
LSD (0.05)	11	NS	6	7
Spring wheat sowing date[d]				
Early	23	1	18	5
Mid	63	8	61	23
Late	68	27	61	26
LSD (0.05)	13	18	8	8

[a] The reciprocal value (100 − seed production at spring wheat harvest) will give percentage of foxtail seeds produced after spring wheat harvest.

[b] Abbreviation: NS, not significant.

[c] 2,4-D ester was applied at 0.5 kg ae/ha; Fenoxaprop + MCPA ester + 2,4-D ester were applied at a rate of 0.05 kg ai + 0.25 kg ae + 0.08 kg ae/ha.

[d] Early, mid, and late spring wheat sowing dates were April 28, May 13, and May 20 in 1996, respectively; and April 29, May 6, and May 15 in 1997, respectively.

Foxtail Seed Production after Wheat Harvest. Management treatments administered early in the growing season had little to no effect on foxtail seed production after spring wheat harvest, which mimics the results reported earlier (Kegode et al. 1999). There are two interesting features regarding postharvest seed production. First, very large quantities of seeds were produced after wheat harvest. In 1996, for instance, approximately 40% of the total seed production of each foxtail species occurred after wheat harvest, and foxtail seeds produced after harvest in 1997 often exceeded 60% of total seed production (Table 4). The differences in postharvest seed production between years were most likely due to higher precipitation and GDD from August to October in 1997, compared with 1996 (Table 1), which supported continued growth of foxtail after crop harvest.

The second interesting aspect of postharvest production of foxtail seeds is that some compensation seems to occur for low numbers of seeds at harvest. For example, in early-sown treatments, both green foxtail and yellow foxtail yielded very few seeds at harvest in both years, but numbers of seeds produced after harvest were 5 to 20 times greater than those at harvest. In contrast, treatments that resulted in a high percentage of seeds at harvest had a relatively low percentage of seeds produced after harvest (Table 4).

Despite the benefits of early sowing of spring wheat and the use of postemergence herbicide (e.g., fenoxaprop) to limit future foxtail infestations, reducing seed production by foxtail that continue to grow after wheat harvest is necessary. For example, Kegode et al. (1999) found that either tillage or glyphosate application within 10 d after wheat harvest lowered foxtail seed production considerably. Even though tillage after wheat harvest can result in burial of weed seeds, it also minimizes foxtail regeneration and consequently lowers the overall foxtail seedbank (Eyherabide and Calvino 2000).

Norris (1992) suggested that allowing even a single weed to produce seed is detrimental to long-term profits. However desirable this might seem, other factors such as weed seed dormancy, increased costs associated with attempts to eliminate a weed species, herbicide resistance, and environmental damage are but a few reasons why such an approach may be unattainable (Buhler et al. 1997) and perhaps not even desirable from the point of view of wildlife food resources (Watkinson et al. 2000). Others suggest that more permanent solutions to weed problems may be achieved by understanding the ways in which weed propagules are dispersed (Ghersa and Roush 1993). In our study, foxtail seeds were dispersed twice: during spring wheat harvest; and later, after wheat harvest, when seeds were shed from late-growing plants. With this information, management strategies that are geared toward minimizing the number of weed seeds that are dispersed can be implemented, for example, using tillage or glyphosate after wheat harvest (Kegode et al. 1999).

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