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Common Waterhemp Growth and Fecundity as Influenced by Emergence Date and Competing Crop

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ABSTRACT

Common waterhemp (*Amarathus rudis* Sauer) is a frequent weed in glyphosate-resistant (GR) crops in the midwestern USA due, in part, to the delayed emergence of its seedlings. Variable waterhemp emergence was simulated by transplanting seedlings into both corn (*Zea mays* L.) and soybean [*Glycine max* (L.) Merr.] and bare plot areas at differing crop growth stages during two growing seasons in western Minnesota. Growth and fecundity were measured. As expected, late planted weeds produced little dry matter and few seeds, and competition from corn or soybean reduced waterhemp dry weight and fecundity by ≥ 90% compared with isolated plants. Interestingly, common waterhemp was affected differently by crop and transplanting date. Common waterhemp grown with corn was always shaded by the crop canopy but produced seeds even when transplanted as late as the V10 growth stage. In soybean, weeds transplanted before the V4 growth stage were taller than soybean and produced more seeds than those transplanted into corn at a comparable growth stage; however, those transplanted after V5 produced no seeds. Consequently, control of late-emerging common waterhemp plants in soybean may not be needed, whereas control of late-emerging plants in corn may be justified because of relatively high levels of seed production.

MOST WEED MANAGEMENT APPROACHES deal only with the existing weed problem and fail to address the reasons for persistent weed infestations (Buhler et al., 2000; Horak and Loughin, 2000). Increasing knowledge of weed biology and ecology provides a better understanding of the interference mechanisms of undesirable plants, expands crop loss prevention techniques, and leads to better long-term management strategies. For example, knowing the potential of seed production provides an opportunity for predicting the nature of forthcoming weed populations (Swinton and King, 1994; Wiles et al., 1996; Buhler et al., 1997). In addition, information on seed production of weeds that escape control can add a new dimension to decisions of when to control weeds and which weeds need to be controlled (Berti et al., 1996; Nordby and Hartzler, 2004). Lastly, understanding seed production, especially of late-emerging species, may allow prediction of species that have high probabilities of escaping control in systems that rely only on postemergence herbicides.

Minimum tillage coupled with the use of GR cultivars changes weed diversity in fields because the weed species (i) may either be tolerant or have developed resistance to glyphosate; (ii) may be too large to be controlled effectively by either chemical or mechanical control techniques; or (iii) emerge after the season's final weed control method (chemical or mechanical) has been completed (Scursoni et al., 2006, 2007). Common waterhemp was not recognized as a problem in crop fields before 1990 (Hager et al., 1997; Pratt and Clark, 2001). However, it was one of the first weeds recorded to escape control in GR soybean crops throughout the midwestern United States (Horak and Peterson, 1995; Wax, 1995; Hinz and Owen, 1997; Buhler et al., 2001; Hager et al., 2002; Hartzler, 2003).

Common waterhemp has been described as the perfect weed (Hartzler, 2003) because of season-long emergence patterns (Forcella et al., 1997; Hartzler et al., 1999; Buhler et al., 2001), a fast growth rate (Hartzler, 2003), prolific seed production potential with >2 million seeds produced per plant (Hartzler et al., 2004), and populations that can be resistant to many herbicides with diverse modes of action (Wax, 1995; Anderson et al., 1996; Hinz and Owen, 1997; Sprague et al., 1997a, 1997b; Foes et al., 1998; Patzoldt et al., 2002). In addition, common waterhemp plants often escape control and survive under the crop canopy in GR crops either because early emerged plants are often too large to be controlled by a postemergence application (Norsworthy et al., 2001) or plants emerge after the final postemergence application of a nonresidual herbicide (Scursoni et al., 2007). Uncontrolled weeds can produce viable seeds that continue the infestation.

While the potential seed production of a plant population may be very high, seed production of an individual can be influenced by factors such as time of emergence, plant size, and the amount of interference or competition exerted by surrounding plants (Murphy et al., 1996; Knezevic and Horak, 1998; Clay et al., 2005). In general, plant fecundity decreases when plants emerge late in the growing season (Knezevic and Horak, 1998; Clay et al., 2005), although even a few viable seeds can be enough to reinfest an area or further spread an infestation. The crop species with which the weed is competing also can influence plant growth and, ultimately, seed production. For example, redroot pigweed (*Amaranthus retroflexus* L.) plants that emerged after the V2 stage of soybean growth (Ritchie et al., 1994) produced no seed, whereas plants that emerged in corn after the V2 stage of corn growth (Ritchie et al., 1996) produced an average of 55 seed plant^{-1} (Clay et al., 2005).

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Abbreviations: GDD, growing degree days; GR, glyphosate-resistant; LAI, leaf area index; VE, crop emergence.

Continued replenishment of the soil weed seed bank is one of the reasons given for control decisions of late-emerging weeds (Boerboom, 2002). The objective of this study was to determine the seed production potential of common waterhemp at four simulated emergence dates when grown alone or with corn or soybean. These data can be used to help guide decisions and recommendations about the extent of control needed for late-emerging plants based on their seed production potential.

MATERIALS AND METHODS

The 2001 and 2002 field study was conducted at the Swan Lake Research Farm of the USDA-ARS facility in Morris, MN. The soil type was a Barnes loam (fine-silty, mixed, superactive, frigid Calcic Hapludoll) with a pH of 7.3; sand, silt, and clay content of 41, 33, and 25%, respectively; and organic matter content of 60 g kg^{-1}. The plot area was moldboard plowed in the fall and field cultivated in spring of the growing season. The previous crop in the corn plot area in 2001 was wheat (*Triticum aestivum* L.), whereas the previous crop in the soybean plot area was corn. In 2002, the plots of corn and soybean were interchanged.

Planting of GR corn (‘Cropland 212’) and GR soybean (‘Pioneer 90B72’) occurred on 29 May in both 2001 and 2002. Individual plots were four rows wide with a 76-cm row spacing and 4 m long. Seeding rates were 79,000 corn seed ha^{-1} and 445,000 soybean seed ha^{-1}. At planting, corn was fertilized with 150–35–35 kg ha^{-1} of N–P–K and soybean was fertilized with 7–35–35 kg ha^{-1} of N–P–K. Both crops emerged on 6 June in 2001 and on 5 June in 2002.

Common waterhemp seed for the 2001 study were collected from plants in agricultural fields near Morris, MN, in the fall of 2000, and seed for the 2002 study were collected from plants at the Swan Lake Research Farm in the fall of 2001. Seed were stored at 4°C from the time of harvest until use the following spring. Seeds were placed in a circulating water bath at 35°C for 48 h to stimulate germination just before planting in peat pots. The pots were placed in a greenhouse and watered to keep near field-capacity. Common waterhemp plants that were at the first-true-leaf growth stage were transplanted into field plots at four crop growth stages each year (Table 1). To have the common waterhemp plants at this growth stage, seeds were planted in the greenhouse several times during the season, about 8 d before each transplanting date. When the crop was at the desired growth stage, 64 peat pots that each contained one common waterhemp plant were transplanted into the center two interrow areas of each crop at equidistant spacing for a density of 5.2 waterhemp plants m^{-2}. In addition, common waterhemp was transplanted into bare plot areas that had been fertilized similarly to corn (high fertility) or soybean (low fertility) in the same pattern at each time to determine maximum growth and seed production potential. Treatments (i.e., timing of common waterhemp transplanting) were replicated four times in a randomized complete block design.

To keep plots free of extraneous weeds, glyphosate [isopropylamine salt (50.2% a.i.)] was applied to plots not containing transplants using a backpack sprayer at a rate of 1.15 kg a.i. ha^{-1} 4 d before each transplanting date. Weeds that emerged after transplanting were removed by hand, whenever necessary, throughout the rest of the growing season.

During the season, the height of four common waterhemp plants per plot was measured from the soil surface to the tip of the tallest plant part. In addition at these sampling times, canopy diameters from the same plants were estimated using the main stem as the center point and measuring the widest plant span. After flowering, seedheads of four randomly selected common waterhemp plants for each replication were enclosed in nylon mesh bags that allowed air movement and penetration of sunlight but avoided seed loss. After the first frost, bagged plants were harvested by clipping them at ground level. Plants were divided into vegetative and reproductive structures. Vegetative structures were separated into main stem, branch, and leaf components, dried at 72°C for at least 1 wk, and weighed. Reproductive structures were air-dried in the greenhouse. Seeds were separated mechanically from bracts, cleaned, and weighed. One hundred seeds per plant for each treatment and replication were counted and weighed. These measurements were used to estimate the total number of seeds produced per plant by treatment from the total seed weight per plant.

Air temperatures were collected on site at a 2-m height. Growing degree days (GDD), used to calculate cumulative thermal time to compare biomass and seed production of the plants at different transplanting times, were calculated as

$$\mathrm{GDD} = \Sigma[(\mathrm{T}_{\mathrm{max}} - \mathrm{T}_{\mathrm{min}})/2]$$

where $\mathrm{T}_{\mathrm{max}}$ is the maximum temperature, and $\mathrm{T}_{\mathrm{min}}$ is the minimum temperature for each day from crop planting through the first fall frost. Temperatures < 10°C were set at 10°C (base temperature), and temperatures above 30°C were set at 30°C (ceiling temperature).

Data were not pooled across years because common waterhemp was transplanted at slightly different growth stages of the crop each year. Data were not distributed normally and did not have constant variance; therefore, data were $\log_{10}$ transformed before ANOVA (SAS Institute, 1997). Mean comparisons were made using Duncan’s Multiple Range Test ($P = 0.05$) (SAS Institute, 1997). Equations were developed for each crop to describe the relationship between cumulative GDD exposure for each transplant treatment before first fall frost and dry matter production or seed production. Although common waterhemp transplanting dates differed between years, a single curve described the 2 yr of data for each parameter by crop.

Table 1. Common waterhemp transplanting date, crop phenological stage and height, and total number of growing degree days (GDD) to which common waterhemp plants from each transplant group were exposed to by the end of the growing season at Morris, MN, in 2001 and 2002. The GDD base and ceiling temperatures were 10 and 30°C, respectively.

2001						2002					
Transplanting date	Corn phenological stage	Corn height	Soybean phenological stage	Soybean height	Total GDD	Transplanting date	Corn phenological stage	Corn height	Soybean phenological stage	Soybean height	Total GDD
		cm		cm				cm		cm	
June 6	VE	1	VE	1	2120	June 12	V1	5	V1	5	2100
June 20	V2	10	V3	10	1878	June 26	V4	25	V4	17	1824
July 5	V5	27	V5	27	1596	July 10	V8	120	V6	40	1740
July 18	V9	150	V8	50	1270	July 26	V10	200	V11	83	1169

RESULTS AND DISCUSSION

Total GDD for 2001 and 2002 growing seasons (from crop planting to first frost) averaged about 2100. Crops had similar growth patterns in both years. Common waterhemp plants transplanted at crop emergence (VE) were exposed to this maximum GDD, whereas those transplanted last (V9 corn/V8 soybean) were exposed to only about 1200 GDD, or 40 to 44% less than maximum cumulative heat units (Table 1).

Common Waterhemp Growth and Vegetative Dry Matter Production

The earliest transplanted common waterhemp plants were generally the tallest, had the greatest canopy diameter, and had the greatest vegetative dry weight at the end of the season when compared with later transplants (Table 2). Branch biomass was reduced to a greater extent than main stem and leaf biomass when vegetative biomass of early and late transplants was compared within any treatment (data published in Uscanga-Mortera, 2004).

Common waterhemp plants grown alone but at the same fertility level as the crop were taller, had greater canopy diameters, and had dry weights that were up to 10 times greater than plants grown in competition with either crop (Table 2). In high-fertility plots (i.e., corn), late transplanted common waterhemp produced 19 to 21% of the biomass of the early transplants. In the low-fertility plots, late transplanted common waterhemp produced 9 to 11% of the biomass of early transplants.

Common waterhemp transplanted into corn always was below the corn canopy. For each year at the end of the season, average maximum corn height was 250 cm whereas common waterhemp height ranged from 235 cm (VE) to about 20 cm (V9, 2001 and V10, 2002) (Table 2). Maximum soybean height was about 90 cm each year and common waterhemp was taller than soybean when transplanted at VE and V3 (2001) and V1 (2002), but shorter than soybean when transplanted at later soybean growth stages (Table 2).

Common waterhemp transplanted into soybean at VE (2001) had about 2.2 times greater vegetative biomass and at V1 (2002) had nine times greater vegetative biomass than when transplanted in corn at the same growth stages in the same years (Table 2). When transplanted into either crop at V5 or later in 2001, or V4 or later in 2002, the amount of vegetative biomass produced was very low (<2 g plant^{-1}). While common waterhemp survived very late transplanting (V8−V11) in corn, all transplants in soybean died when planted at or after V8.

Dry weights of common waterhemp transplanted into corn at VE were greater than dry weights reported from common waterhemp that emerged early in corn under Iowa conditions. Nordby and Hartzler (2004) reported that common waterhemp that emerged with corn produced about 28 g of biomass plant^{-1}, whereas in this study, biomass of the early transplants averaged 85 g plant^{-1}. The difference between this study and the Iowa study may be due to the transplants having an advantage over those that emerged with the crop; that is, at *emergence* in this study, transplants were at the first-true-leaf stage rather than the cotyledon stage of true seedlings. Biomass of common waterhemp that was either transplanted into V8 corn in Minnesota or emerged at the V8 corn growth stage in Iowa (Nordby and Hartzler, 2004) had similar low weights (<1 g plant^{-1}). Common waterhemp biomass from plants grown in soybean in this study had similar biomass as plants grown in Iowa soybean (Hartzler et al., 2001, 2004).

Common Waterhemp Seed Production

Common waterhemp seed production from plants grown alone ranged from 33,500 to over 1 million seeds

Table 2. Common waterhemp height, canopy diameter, vegetative dry weight, and seed production per plant at physiological maturity in 2001 and 2002 at Morris, MN, when grown with corn, soybean, and alone at similar fertility levels as the respective crop.

	2001					2002				
Crop	**Crop phenology**	**Height**	**Canopy diam.**	**Dry wt.**	**Seed no.**	**Crop phenology**	**Height**	**Canopy diam.**	**Dry wt.**	**Seed no.**
		cm	cm	g plant^{-1}	no. plant^{-1}		cm	cm	g plant^{-1}	no. plant^{-1}
Corn	VE	235a†	41a	85.0a	43,000a	V1	115a	27a	17.8a	21,200a
	V2	103b	28b	6.0b	3,200b	V4	51b	16b	3.4b	2,950b
	V5	35c	12c	1.3c	1,500c	V8	33bc	11c	0.2c	200c
	V9	24c	10c	0.2d	150d	V10	20c	6c	0.5c	100c
No corn	VE	264a	165a	765a	476,000a	V1	162b	68b	627a	593,000a
	V2	204b	97b	263b	198,900b	V4	187a	90a	716a	669,300a
	V5	213b	159a	532a	244,400b	V8	102c	53b	–‡	–
	V9	161c	92b	166b	76,900c	V10	100c	55b	121b	94,400b
Soybean	VE	212a	81a	187a	180,700a	V1	160a	41a	163a	128,000a
	V3	154b	43b	54.7b	22,700b	V4	70b	19b	2.14b	1,200b
	V5	38c	13c	1.1c	30c	V6	9c	4c	0.05c	6c
	V8	0d	0d	0d	0c	V11	0d	0d	0c	0c
No soybean	VE	200a	105a	626a	547,800a	V1	172a	75b	920a	832,000a
	V3	177b	105a	374ab	334,500ab	V4	166a	117a	966a	1,053,000a
	V5	166b	106a	243b	180,300b	V6	114b	91ab	348b	264,900b
	V8	112c	76b	66c	33,500c	V11	88b	72b	86c	67,700c

† Numbers followed by the same letter within a crop and year indicate no differences between treatments at $P \leq 0.05$.
‡ Missing values.

plant^{-1} depending on transplanting date and soil fertility conditions (Table 2). Compared with common waterhemp grown alone, corn competition reduced seed production by 90% or more, whereas soybean competition had less effect at VE (about 33% seed reduction) and more effect (no seeds produced) when transplanted at V8 or V11.

The seed production in corn reported here is higher than numbers reported in an Illinois study (Steckel and Sprague, 2004b) but similar to numbers reported in an Iowa study (Nordby and Hartzler, 2004). For example, common waterhemp transplanted in corn at VE in this study averaged 43,000 seeds plant^{-1}, whereas seed numbers from common waterhemp plants transplanted into corn at VE in Illinois averaged 16,000 seeds plant^{-1} (Steckel and Sprague, 2004b). The differences in seed production potential between the studies may have been due to the high planting densities in Illinois (490 plants m^{-2}) versus low densities in Minnesota (5 plants m^{-2}), corn growth, or environmental differences.

Common waterhemp in Iowa (Nordby and Hartzler, 2004) at 3 plants m^{-2} that emerged in corn at either the VE or V5 stage produced 48,400 and 1,300 seeds plant^{-1}, respectively, similar to seed numbers in Minnesota. However, in contrast with the Iowa data that reported no seed production when the weed emerged at the V8 corn stage, plants in this study survived and produced 100 to 150 seeds plant^{-1} even when transplanted at the V9 to V10 corn growth stages. These data indicate that even very late-emerging common waterhemp plants possibly can survive in corn and produce seeds to maintain or increase infestations. About 1 to 5% of the common waterhemp seeds from the soil seedbank germinate annually (Leon and Owen, 2004). Thus, fecundity rates as low as 100 to 150 seeds plant^{-1} conceivably could maintain viable replacement populations of waterhemp.

Common waterhemp plants that were transplanted into soybean from VE to V3 had a greater seed production potential than comparable plants grown in corn (Table 2), with values ranging from 180,700 (VE, 2001) to 128,000 (V1, 2002) seeds plant^{-1}. These seed production potentials are similar to the 200,000 seeds plant^{-1} reported for waterhemp emerging early in soybean in Illinois (Steckel and Sprague, 2004a). Seed production of waterhemp in soybean was reduced to 30, 6, and 0 seeds plant^{-1} when transplanted at V5 (2001), V6 (2002), and V8 or later soybean stages in both years, respectively (Table 2). These seed numbers are considerably lower than those reported in Iowa, where common waterhemp plants produced 64,000, 17,000, and 3,000 seeds plant^{-1} when they emerged at the V2, V4, and V6 soybean stages, respectively (Hartzler et al., 2004).

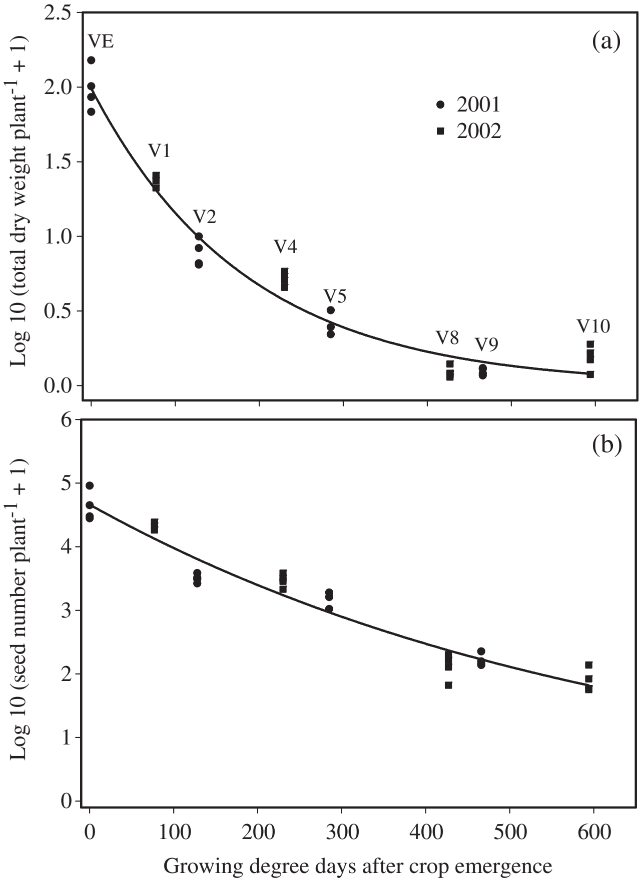

Fig. 1. Effect of delayed transplantation on (a) total dry weight and (b) seed number produced by common waterhemp plants transplanted into corn at growth stages VE, V2, V5, and V9 (2001) and V1, V4, V8, and V10 (2002). The equation for each of the lines for (a) total dry weight and (b) seed number is: Log$_{10}$ $Y = a^{(-bx)}$. Coefficients for total dry weight are $a = 2.0$ (0.05) and $b = 0.005$ (0.0003) ($R^2 = 0.97$), and for seed number are $a = 4.7$ (0.09) and $b = 0.0016$ (0.0001) ($R^2 = 0.94$). Numbers in parentheses are standard errors of the parameter values.

Equations that fit total common waterhemp dry weight and seed production (Fig. 1 and 2) to GDD based on time of transplanting indicated that the two crops had different effects on common waterhemp. Total dry weight and seed production of plants transplanted into corn fitted exponential decay curves when plotted against cumulative GDD exposure after transplanting (Fig. 1). In contrast, equations that fit GDD vs. total dry weight or seed production of plants transplanted into soybean were sigmoidal curves (Fig. 2). These data indicate that corn competition had a larger effect on common waterhemp than that of soybean during the first stages of crop growth. Soybean was a weak competitor during these initial stages, allowing common waterhemp to grow taller than the crop (Table 2). Light intensity differences between crop canopies most likely influenced common waterhemp growth and seed production patterns. For example, in prior studies at the Morris location, maximum corn leaf area index (LAI) of 3.75 was attained at about 450 GDD after planting (Westgate et al., 1997), whereas soybean did not reach 3.75 LAI until about 550 GDD (≈1 wk later) (Reicosky et al., 1985). Moreover, final maximum soybean LAI of about 7 was 86% greater than corn LAI and attained at about 700 GDD after planting (about 2 wk after corn maximum LAI) (Reicosky et al., 1985). These canopy closure and maximum LAI differences between crops would result in light intensity penetration differences in the crop canopy. Seed production in common waterhemp has been reported to be associated closely and negatively with shading (Steckel et al., 2003). Linear

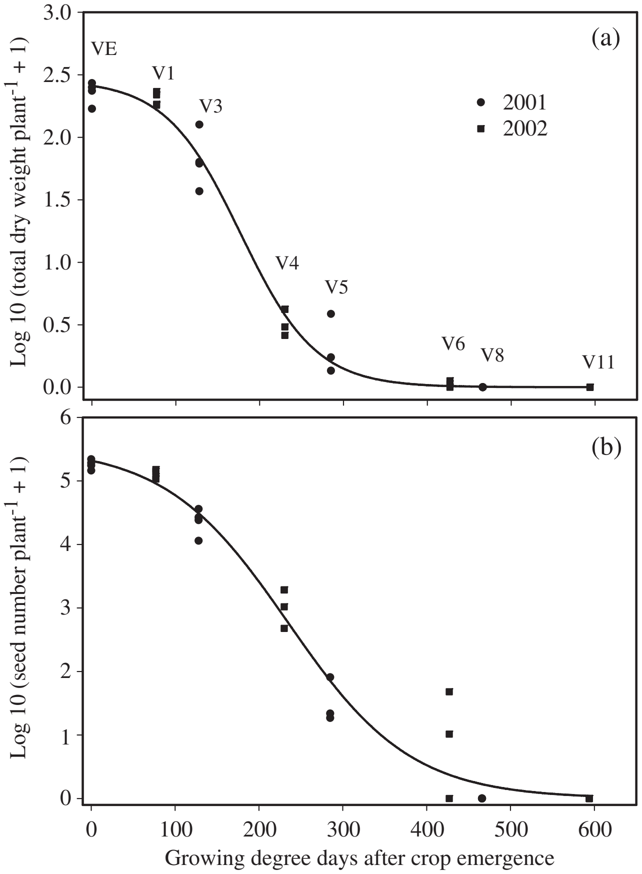

Fig. 2. Effect of delayed transplantation on (a) total dry weight and (b) seed number produced by common waterhemp plants transplanted into soybean at growth stages VE, V3, V5, and V8 (2001) and V1, V4, V6, and V11 (2002). The equation for each of the lines is $\mathrm{Log}_{10}\, Y = a/\{1 + e^{[-1(x-x_o)/b]}\}$. Coefficients for total dry weight are $a = 2.5$ (0.07), $b = -44.9$ (3.9), $x_o = 177.3$ (5.9) ($R^2 = 0.99$); and for seed number are $a = 5.5$ (0.26), $b = -73.2$ (10), and $x_o = 235$ (12) ($R^2 = 0.97$). Numbers in parentheses are standard errors of the parameter values.

regressions of shading percentage and waterhemp seed production for seedlings transplanted into corn in Illinois (Table 1 in Steckel et al., 2003) indicated that 100% shading was required to eliminate seed production of early (May 23) transplanted seedlings, but only 90% shading was needed to inhibit seed production of late (June 23) transplanted seedlings. By analogy, late-emerging waterhemp seedlings would be expected to be more sensitive to shading than early-emerging plants. Differential sensitivity to shading and early- and late-emerging plants may help explain differences in seed production among crops and locations.

In addition, although dry matter was not divided by strata in this study, we observed that most dry matter primarily was in the upper parts of the common waterhemp plant and above the soybean canopy when transplanted at the VE, V1, and V3 soybean growth stages. The vertical distribution of dry weight of redroot pigweed, a closely related species, within the crop canopy has been reported to be altered by differences in crop competition (McLachlan et al., 1993; Knezevic et al., 1994; Hartzler et al., 2004). The stratification of common waterhemp in soybean allowed the top of the plant to grow without light competition and also without obstructions for pollen movement in these dioecious plants. Ready access to light and pollen may explain why common waterhemp plants that grew above the soybean canopy produced greater amounts of seed compared with common waterhemp plants grown within either the corn or soybean canopy.

CONCLUSIONS

The results from this research indicated that common waterhemp could survive late transplanting (simulated late emergence) into crop canopies and have the potential to produce seeds. Corn and soybean affected common waterhemp growth and seed production differently. Soybean was a weak competitor up to the V4 stage of soybean growth, and control of common waterhemp emerging before this growth stage would be critical to prevent future infestations. However, transplants into soybean after the V5 stage of soybean produced few seeds, and those transplanted after V6 did not survive. These data indicated that control of very late-emerging seedlings may not be necessary because of the competition exerted by soybean. In contrast, late-emerging common waterhemp plants growing in corn produced many more seeds. An effective control method for these late but fecund plants would be recommended. Such control could be accomplished easily by supplementing (glyphosate-based) postemergence weed management with any of a wide range of soil-applied herbicides commonly used in corn.

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REFERENCES

Anderson, D.D., F.W. Roeth, and A.R. Martin. 1996. Occurrence and control of triazine-resistant common waterhemp (*Amaranthus rudis*) in field corn (*Zea mays*). Weed Technol. 10:570–575.

Berti, A., C. Dunan, M. Sattin, G. Zanin, and P. Westra. 1996. A new approach to determine when to control weeds. Weed Sci. 44:496–503.

Boerboom, C. 2002. Time of weed emergence and economic impact on crops. www.soils.wisc.edu/extension/FAPM/2002proceedings/Boerboom-Conf-2002.pdf [cited Jan. 2007; verified 31 May 2007]. Univ. of Wisconsin Ext., Madison.

Buhler, D.D., K.A. Kohler, and R.L. Thompson. 2001. Weed seed bank dynamics during a five-year crop rotation. Weed Technol. 15: 170–176.

Buhler, D.D., M. Liebman, and J.J. Obrycky. 2000. Theoretical and practical challenges to an IPM approach to weed management. Weed Sci. 48:274–280.

Buhler, D.D., R.G. Hartzler, F. Forcella, and J.L. Gunsolus. 1997. Relative emergence of weeds of corn and soybean. Publ. SA-11. Iowa State Univ. Ext., Ames.

Clay, S.A., J. Kleinjan, D.E. Clay, F. Forcella, and W. Batchelor. 2005. Growth and fecundity of several weed species in corn and soybean. Agron. J. 97:294–302.

Foes, M.J., L. Liu, P.J. Tranel, L.M. Wax, and E.W. Stoller. 1998. A biotype of common waterhemp (*Amaranthus rudis*) resistant to triazine and ALS herbicides. Weed Sci. 46:514–520.

Forcella, F., R.G. Wilson, J. Dekker, R.J. Kremer, J. Cardina, R.L. Anderson, D. Alm, K.A. Renner, R.G. Harvey, S. Clay, and D.D. Buhler. 1997. Weed seed bank emergence across the Corn Belt. Weed Sci. 45:67–76.

Hager, A.G., L.M. Wax, R.W. Simmins, and E.W. Stoller. 1997. Waterhemp management in agronomic crops. Bull. X855. Univ. of Illinois, Urbana.

Hager, A.G., L.M. Wax, E.W. Stoller, and G.A. Bollero. 2002. Common waterhemp interference in soybean. Weed Sci. 50:607–610.

Hartzler, R. 2003. Waterhemp—The perfect weed? Available at www.weeds.iastate.edu/mgmt/2003/symposium.shtml [cited Feb. 2007; verified 31 May 2007]. Iowa State Univ., Ames.

Hartzler, R.G., B.A. Battles, and D. Nordby. 2004. Effect of waterhemp (*Amaranthus rudis*) emergence date on growth and fecundity in soybean. Weed Sci. 52:242–245.

Hartzler, R., B. Battles, and D. Refsell. 2001. Effect of delayed waterhemp emergence on waterhemp growth and fecundity. Available at www.weeds.iastate.edu/mgmt/2001/ncwssposter.htm [cited Feb. 2007; verified 31 May 2007]. Iowa State Univ., Ames.

Hartzler, R.G., D.D. Buhler, and D.E. Stoltenberg. 1999. Emergence characteristics of four annual weed species. Weed Sci. 47:578–584.

Hinz, J.R.R., and M.D.K. Owen. 1997. Acetolactate synthase resistance in a common waterhemp (*Amaranthus rudis*) population. Weed Technol. 11:13–18.

Horak, M.J., and T.M. Loughin. 2000. Growth analysis of four *Amaranthus* species. Weed Sci. 48:347–355.

Horak, M.J., and D.E. Peterson. 1995. Biotypes of Palmer amaranth (*Amaranthus palmeri*) and common waterhemp (*Amaranthus rudis*) are resistant to imazethapyr and thifensulfuron. Weed Technol. 9:192–195.

Knezevic, S.Z., and M.J. Horak. 1998. Influence of emergence time and density on redroot pigweed (*Amaranthus retroflexus*). Weed Sci. 46:665–672.

Knezevic, S.Z., S.F. Weise, and C.J. Swanton. 1994. Interference of redroot pigweed (*Amaranthus retroflexus*) in corn (*Zea mays*). Weed Sci. 42:568–573.

Leon, R.G., and M.D.K. Owen. 2004. Artificial and natural seedbanks differ in seedling emergence patterns. Weed Sci. 52:531–537.

McLachlan, S.M., M. Tollenaar, C.J. Swanton, and S.F. Weise. 1993. Effect of corn-induced shading on dry matter accumulation, distribution, and architecture of redroot pigweed (*Amaranthus retroflexus*). Weed Sci. 41:568–573.

Murphy, S.D., Y. Yussif, S.F. Weise, C.J. Swanton, and Y. Yakubu. 1996. Effect of planting patterns and inter-row cultivation on competition between corn (*Zea mays*) and late emerging weeds. Weed Sci. 44: 865–870.

Nordby, D.E., and R.G. Hartzler. 2004. Influence of corn on common waterhemp (*Amaranthus rudis*) growth and fecundity. Weed Sci. 52:255–259.

Norsworthy, J.K., N. Burgos, and L.R. Oliver. 2001. Differences in weed tolerance to glyphosate involve different mechanisms. Weed Technol. 15:725–735.

Patzoldt, W.L., A.G. Hager, and P.J. Tranel. 2002. An Illinois waterhemp biotype with resistance to PPO-, ALS-, and PSII-inhibitors. Proc. North Cent. Weed Sci. Soc. 57:161.

Pratt, D.B., and L.G. Clark. 2001. *Amaranthus rudis* and *A. tuberculatus*—One species or two? J. Torrey Bot. Soc. 128:282–296.

Reicosky, D.C., D.D. Warnes, and S.D. Evans. 1985. Soybean evapotranspiration, leaf water potential and foliage temperature as affected by row spacing and irrigation. Field Crops Res. 10: 37–48.

Ritchie, S.W., J.J. Hanway, H.E. Thompson, and G.O. Benson. 1994. How a soybean plant develops. Spec. Rep. 53. Rev. ed. Iowa State Univ. Coop. Ext. Serv., Ames.

Ritchie, S.W., J.J. Hanway, H.E. Thompson, and G.O. Benson. 1996. How a corn plant develops. Spec. Rep. 48. Rev. ed. Iowa State Univ. Coop. Ext. Serv., Ames.

SAS Institute. 1997. User's manual. v. 6.2. SAS Inst., Cary, NC.

Scursoni, J., F. Forcella, J. Gunsolus, M. Owen, R. Oliver, R. Smeda, and R. Vidrine. 2006. Weed diversity and soybean yield with glyphosate management from the north–south transect in the USA. Weed Sci. 54:713–719.

Scursoni, J., F. Forcella, and J. Gunsolus. 2007. Weed escapes and delayed weed emergence in glyphosate-resistant soybean. Crop Prot. 26:212–218.

Sprague, C.L., E.W. Stoller, and L.M. Wax. 1997a. Response of an acetolactate synthase (ALS)-resistant biotype of *Amaranthus rudis* to selected ALS-inhibiting and alternative herbicides. Weed Res. 37:93–101.

Sprague, C.L., E.W. Stoller, L.M. Wax, and M.J. Horak. 1997b. Palmer amaranth (*Amaranthus palmeri*) and common waterhemp (*Amaranthus rudis*) resistance to selected ALS-inhibiting herbicides. Weed Sci. 45:192–197.

Steckel, L.E., and C.L. Sprague. 2004a. Late season common waterhemp (*Amaranthus rudis*) interference in soybean. Weed Sci. Soc. Am. Abstr. 43:18.

Steckel, L.E., and C.L. Sprague. 2004b. Common waterhemp (*Amaranthus rudis*) interference in corn. Weed Sci. 52:359–364.

Steckel, L.E., C.L. Sprague, A.G. Hager, F.W. Simmons, and G.A. Bollero. 2003. Effects of shading on common waterhemp (*Amaranthus rudis*) growth and development. Weed Sci. 51:898–903.

Swinton, S.M., and R.P. King. 1994. A bioeconomic model for weed management in corn and soybean. Agric. Syst. 44:313–335.

Uscanga-Mortera, E. 2004. Effect of simulated emergence date on growth and seed production of *Amaranthus rudis* and *A retroflexus*. Ph.D. diss. South Dakota State Univ., Brookings. (Diss. Abstr. Int. 66B:3).

Wax, L.M. 1995. Pigweeds of the Midwest—Distribution, Importance and Management. Proc. of Iowa Integr. Crop Manag. Conf. 7:239–242.

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.

Wiles, L.R., R.P. King, E.E. Schweizer, D.W. Lybecker, and S.M. Swinton. 1996. GWM: General weed management model. Agric. Syst. 50:355–376.