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Impact of composted swine manure and tillage on common waterhemp (*Amaranthus rudis*) competition with soybean

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Use of composted swine manure produced in deep-bedded hoop structures is a promising approach for recycling farm waste products and improving soil fertility, but little is known about its effects on crop–weed interactions. A 2-yr study was conducted to evaluate the effect of compost amendments and tillage on soybean–common waterhemp competition. Experiments were conducted in no-tillage and chisel plow main plots with compost applied to one of two types of subplots. Common waterhemp and soybean growth was measured in sub-subplots accommodating weed-free soybean and soybean with common waterhemp sown at soybean planting, soybean emergence (VE), soybean second-node stage (V2), and soybean sixth-node stage (V6). Soybean heights were not influenced by compost or common waterhemp sowing time. Soybean stem diameters were influenced by year, tillage regime, and an interaction between compost and common waterhemp sowing time. In contrast, common waterhemp heights and basal diameters were greater when sown at planting and VE in compost-amended subplots than in compost-free subplots. Overall, there was a negative quadratic relationship between common waterhemp biomass and soybean yield ($r^2 = 0.746$). The extremely low common waterhemp emergence in V2 and V6 treatments suggested that early-season weed suppression was sufficient to protect soybean from common waterhemp competition. The sex determination of 2,557 common waterhemp plants showed a marginally higher male to female ratio in compost-amended treatments than in compost-free treatments ($P = 0.0611$). A linear-slope regression indicated that common waterhemp fecundity was positively related to individual plant biomass, with a change in slope occurring at 118.7 g. Under the conditions present in this experiment, compost did not enhance soybean yield but increased the competitive ability of waterhemp. Because composted swine manure can have a major influence on competition of common waterhemp with soybean, effective weed management practices should be in place when this soil amendment is used.

Nomenclature: Common waterhemp, *Amaranthus rudis* Sauer AMATA; soybean, *Glycine max* (L.) Merr.

Key words: Compost, crop–weed competition, fecundity, tillage regime.

Composted swine manure from deep-bedded hoop structures constitutes both an economically competitive production approach to recycling waste products and a means of improving soil fertility and quality (Richard and Smits 1999). Because compost can release phytotoxic compounds such as short-chain fatty acids, phenols, and ammonia, it can reduce weed germination and seedling growth (Ligneau and Watt 1995; Marambe and Ando 1992; Ozores-Hampton et al. 1999; Roe et al. 1993). In addition, compost may affect weed population dynamics through the modification of soil physical properties, such as soil water-holding capacity, bulk density, aggregate stability, and nutrient content (Bazzoffi et al. 1998; Gonzales and Cooperband 2002). The use of deep-bedded hoop structures is a newly introduced swine husbandry practice, and little is known about how compost produced from bedding–manure mixtures could affect plant growth, fecundity, and crop–weed interactions. Also, possible synergistic effects of compost and tillage practices on crop–weed interactions are not known.

In this study, we assessed the impact of composted swine manure on competition between soybean and common waterhemp. Common waterhemp is a dioecious, wind-pollinated, annual species indigenous to the Midwest region of the United States (Hager et al. 2002a). Over the last decade, common waterhemp has become a major concern to crop producers in the Corn Belt and Great Plains (Patzoldt et al. 2002). The increased occurrence of common waterhemp has been attributed to the adoption of no-till production systems, differential susceptibility to herbicides, development of herbicide-resistant biotypes, abundant seed production, seed persistence, late germination and extended emergence patterns, and rapid plant growth and establishment (Buhler and Hartzler 2001; Hager et al. 2002a, 2002b; Hartzler et al. 1999; Horak and Loughin 2000).

For dioecious plants, such as common waterhemp, the sex ratio and seed production rates represent fundamental population parameters (Delph 1999; Gauquelin et al. 2002). Thus, understanding how management practices could affect common waterhemp sex ratio and fecundity represents a necessary step in the development of mid- and long-term weed management programs. Zelaya and Owen (2000) reported that common waterhemp is differentially affected by glyphosate, with male individuals inheriting resistance. In a herbicide tolerance assay conducted in greenhouse conditions, they observed an increase in the relative abundance of male individuals. To our knowledge, no field study has evaluated changes in common waterhemp sex ratio and fecundity as a function of tillage regime and compost applications.

Increased understanding of common waterhemp biology and ecology is a necessary step to facilitate the development of farming systems that use composted manure as a source of organic matter. The objectives of this study were to determine (1) whether composted swine manure modifies competition between soybean and common waterhemp, (2) whether this competition changes as a function of tillage system, and (3) whether composted swine manure and tillage system alter common waterhemp growth and demographic parameters, including sex ratio and fecundity.

Materials and Methods

Site Description and Experimental Design

The study site was located at the Iowa State University Agronomy and Agricultural Engineering Research Center, Boone, IA. The site was in continuous corn (*Zea mays* L.) production since 1987 and was maintained in different tillage main plots (consisting of moldboard plow, chisel plow, and no till) since 1988. In 1997 the entire site was planted to soybean. In 1998, a corn–soybean–winter wheat (*Triticum aestivum* L.) rotation was initiated, with all crops represented each year in the three tillage systems.

This study was conducted during 2001 and 2002 in the soybean crop in the chisel plow and no-till plots (3.8 by 27.2 m, five 0.76-m-wide rows). Before soybean planting, chisel plow main plots were managed with fall chisel plowing, early-spring disking, and preplanting field cultivation. Chisel plow depth was 25 cm using twisted shanks. Main plots were replicated four times and were split in 1998 to accommodate applications of composted swine manure to one of two types of subplots (3.8 by 13.6 m). In October 1998, 1999, and 2000, subplots were amended with compost at the rate of 8,000 kg C ha^{-1} preceding the corn and soybean crops in the rotation sequence. In October 2001 the compost was applied at a rate of 4,000 kg C ha^{-1}. To maximize corn yield potential, synthetic N was added in the form of 32% urea–ammonium nitrate using a modified spoke-wheel fertilizer injector in compost-amended and compost-free corn plots, with a higher rate of synthetic N in subplots not receiving compost than in plots receiving compost. Synthetic P and K fertilizers were not applied at any time during the rotation sequence. Beginning in 2000, winter wheat was intercropped with red clover (*Trifolium pratense* L.) to provide N to the succeeding corn crop and to increase weed suppression. A detailed description of soil physical and chemical characteristics can be found in Singer et al. (2004).

Glyphosate-tolerant soybean ('Pioneer 92B84') was planted at a density of 444,600 seeds ha^{-1} in 76-cm rows on May 9, 2001, and May 20, 2002. A single application of 0.9 kg ae ha^{-1} of glyphosate was applied postemergence before common waterhemp emergence. Late-season weed escapes were controlled by spot spraying of glyphosate and periodic hand hoeing.

In each compost-amended or compost-free subplot, five sub-subplots (1.7 by 3.8 m) were established. Sub-subplots were randomly assigned to the following treatments: (1) common waterhemp sown at soybean planting (at-planting), (2) common waterhemp sown at soybean emergence (VE), (3) common waterhemp sown at soybean second-node stage (V2), (4) common waterhemp sown at soybean sixth-node stage (V6), and (5) season-long weed-free soybean (control). Locally collected common waterhemp seeds were suspended in a 2.5% solution of Laponite® RD (Southern Clay Products Inc., Gonzales, TX) for 24 h before planting. When soybean plants reached the targeted growth stage, suspended seeds were planted in appropriate sub-subplots 2.5 cm on the west side of soybean rows. Suspended common waterhemp seeds were planted with a 20-ml syringe. This approach to sowing common waterhemp allowed us to handle large quantities of imbibed seeds. Common waterhemp seedlings were thinned by hand to 10 plants m^{-1} of crop row when they were at the second- to fourth-leaf stage of development. Because of the low emergence and high mortality of common waterhemp in V2 and V6 treatments, no thinning was performed in these sub-subplots. Soybean density was measured in all sub-subplots on July 2, 2001, and June 29, 2002.

Daily rainfall and air temperature values were obtained from a meteorological station located at the study site. Growing degree day (GDD) values were calculated as the mean of the minimum and maximum temperatures minus a base temperature of 10 C. Accumulated GDDs from soybean planting to specific soybean growth stages were calculated and used to assess the effect of common waterhemp sowing time on common waterhemp biomass and soybean yield. The use of GDD presents several advantages over more traditional indicators such as crop stage or days after crop emergence. Among them are the close association of GDD with plant development, the ease of comparisons across years and locations, and the availability of a continuous and precise scale that facilitates the use of regression analysis (Knezevic et al. 2002).

Soybean and Common Waterhemp Measurements

When the targeted weed density was established, 15 soybean and 15 common waterhemp plants were selected in the center of each sub-subplot. Heights and stem diameters of the chosen plants were measured at a 2-wk interval between June 21 and August 29, 2001, and between June 26 and August 20, 2002. Soybean seed yield and common waterhemp biomass were determined at maturity by manually harvesting the 15 selected plants per species. All plants were oven-dried to constant weight. Soybean seed yield was adjusted to a moisture content of 130 g kg^{-1}.

In September 2001 and 2002, common waterhemp sex was determined for all plants growing at the study site. To assess variations in common waterhemp fecundity as a function of compost and tillage, a total of 165 female plants were selected in September 2002 to represent the range of size and shape observed in the experiment. Plants were harvested at ground level, oven-dried to constant weight, and threshed to remove seeds. Seed weight and nonreproductive dry weight were obtained for each plant. The relationship between common waterhemp seed weight and seed number was established for 10 samples (r^2 = 0.9621) and used to estimate individual plant fecundity. Seeds that may have shattered onto the ground before harvest were not collected. However, because common waterhemp shatters few seeds early in the growing season (F. D. Menalled, personal observation), underestimation of fecundity should have been negligible.

Statistical Analysis

The split–split-plot experiment had four replications and followed a randomized complete block design. Year and tillage regimes were analyzed as whole-plot factors, compost applications as the first split, and common waterhemp sowing date as the second split. For each treatment, soybean relative yield (RY) was defined as:

$$RY_i = \frac{\text{yield of treatment, } i}{\text{yield of season-long weed-free treatment}} \times 100.$$

Treatment effects on season-mean soybean height and diameter, soybean relative yield, season-mean common waterhemp height and diameter, and common waterhemp biomass were estimated with a split–split-plot analysis of variance (ANOVA) model (PROC MIXED, SAS 1998). Least square means tests were used to perform multiple comparisons among treatments. When first-order interactions were detected, least square means tests on simple effects were carried out through the slicing of data (Littell et al. 1996).

For each compost–tillage system combination, a nonlinear regression model was fitted to describe the effect of compost application, tillage regime, and common waterhemp sowing date on soybean relative yield or common waterhemp biomass (PROC NLIN, SAS 1998). For this analysis, common waterhemp sowing date was expressed in accumulated GDD units since soybean planting. Goodness of fit was assessed as 1 − (error sum of squares/total sum of squares) (Schabenberger and Pierce 2002). A Gompertz function was used to describe changes in soybean relative yield as a function of common waterhemp sowing time estimated by the number of GDD accumulated between soybean planting and common waterhemp sowing:

$$Y = a \exp(-\, b \exp(-\, k\text{GDD}))$$

where Y is the predicted relative yield, a is the relative yield asymptote, and b and k are constants. A negative linear-plateau function was used to predict common waterhemp biomass as a function of common waterhemp sowing time estimated by the number of GDD accumulated between soybean planting and common waterhemp sowing:

$$Y = (b_0 + b_1\text{GDD})I_1 + (b_0 + b_1a_1)I_2,$$

where Y represents the predicted common waterhemp biomass, b_0 is the intercept, b_1 is the slope, a_1 is the joint point, I_1 is an indicator that takes on a value of 1 if GDD $\leq a_1$ and 0 otherwise, and I_2 is an indicator that takes on a value of 1 if GDD $> a_1$ and 0 otherwise (Schabenberger and Pierce 2002).

A split-plot ANOVA model (PROC MIXED, SAS 1998) with year and tillage as whole-plot factors and compost application as the split factor was used to examine differences in regression parameters between compost and tillage treatments. Differences in the common waterhemp male to female ratio as a function of compost and tillage were assessed by means of a split-plot ANOVA model. Linear-slope regression was used to describe the relationship between common waterhemp biomass and fecundity:

$$Y = (b_0 + b_1X)I_1 + (b_0 + b_1a_1 + b_2(X - a_1))I_2,$$

where Y represents the predicted seed production, X the plant biomass, b_0 is the intercept, b_1 and b_2 represent the slopes, a_1 is the joint point, I_1 is an indicator that takes on a value of 1 if $X \leq a_1$ and 0 otherwise, and I_2 is an indicator that takes on a value of 1 if $X > a_1$ and 0 otherwise (Schabenberger and Pierce 2002).

Results and Discussion

General Patterns

Soybean density was greater in 2002 than in 2001 ($P < 0.0001$) (mean ± SE = 232,396 ± 4,992 plants ha^{-1} in 2001; 311,063 ± 3,618 plants ha^{-1} in 2002). Despite this difference, soybean density was not affected by tillage ($P = 0.5538$), compost ($P = 0.7947$), common waterhemp sowing time ($P = 0.8961$), or any second- or third-order interaction among these variables. Compost increased soil organic matter, P, and K concentration in both tillage systems (Table 1). In the no-till system, buffer pH was higher in the compost-amended subplots than in the compost-free subplots (Table 1). Mean air temperatures and precipitation were similar between years. Both years were drier than the long-term mean, and the early season in 2001 was drier than that in 2002 (Table 2). More GDD accumulated between soybean planting and VE in 2001 than in 2002 (164 and 66 GDD, respectively), but the number of GDDs accumulated between soybean planting and V2 was similar, with 529 GDD in 2001 and 526 GDD in 2002. At the V6 stage, 944 GDD accumulated in 2001 and 954 GDD accumulated in 2002. At soybean harvest, 2,933 GDD accumulated in 2001 and 3,087 GDD in 2002.

Overall, there was a negative quadratic relationship between common waterhemp biomass and soybean yield, confirming the competitive ability of this weed species (Figure 1). Previous studies also have reported reduced crop yields due to competition with *Amaranthus* species, including common waterhemp (Bensch et al. 2003; Dieleman et al. 1995; Hager et al. 2002b).

Common Waterhemp and Soybean Morphology

Soybean and common waterhemp had different height and stem diameter responses to compost, tillage, and common waterhemp sowing time (Figure 2). The split–split-plot ANOVA indicated that common waterhemp height was influenced by year ($P < 0.0001$), compost ($P = 0.0033$), common waterhemp sowing time ($P < 0.0001$), and several first-order interactions. In contrast, soybean heights differed between years ($P < 0.0001$) and tillage regimens ($P = 0.0006$). Soybean heights were marginally affected by compost ($P = 0.0853$) but were not influenced by common waterhemp sowing time ($P = 0.6768$).

The similar heights achieved by all soybean plants (Figure 2, top), regardless of when common waterhemp was sown, agree with Mulugeta and Boerboom (2000) that this species responds to competition by allocating resources to increase height at the expense of basal diameter growth. Common waterhemp showed a more flexible response to competition than did soybean, with heights varying as a function of compost treatment, tillage system, and planting date. Knezevic et al. (2001) and McLachlan et al. (1995) observed that redroot pigweed (*Amaranthus retroflexus* L.) dry matter par-

TABLE 1. Effects of compost on selected soil characteristics (0- to 20-cm depth) for samples collected on April 4, 2001, and April 10, 2002. Values are means (± 1SE).[a]

	Organic matter[b]			Buffer pH[c]			P[d]			K[e]		
	2001	2002	Mean	2001	2002	Mean	2001	2002	Mean	2001	2002	Mean
	$g\ kg^{-1}$			$-\log[H^+]$			$mg\ kg^{-1}$			$mg\ kg^{-1}$		
Chisel plow												
No compost	59 (8)	55 (8)	57 (5)	6.8 (0.2)	6.8 (0.1)	6.8 (0.1)	56 (5)	56 (11)	56 (6)	166 (17)	137 (11)	151 (11) a
Compost	66 (6)	66 (5)	66 (4)	6.8 (0.1)	7.2 (0.1)	7.0 (0.1)	155 (12)	208 (19)	182 (15)	276 (16)	316 (34)	296 (19) b
Notill												
No compost	57 (4) a	56 (6) a	57 (3) a	6.6 (0.3) a	6.7 (0.3) a	6.7 (0.2) a	54 (4) a	61 (3) a	58 (3) a	159 (15) a	137 (6) a	148 (9) a
Compost	60 (6) a	67 (6) b	64 (4) b	6.8 (0.1) a	7.0 (0.2) a	6.9 (0.1) b	195 (9) b	190 (20) b	192 (10) b	330 (23) b	313 (28) b	321 (17) b
Source of variation												
Yr		NS[f]			NS[f]			NS[f]			NS[f]	
Tlg		NS			NS			NS			NS	
Comp		*			*			**			**	
Tlg by Yr		NS			NS			NS			NS	
Comp by Yr		NS			NS			NS			NS	
Tlg by Comp		NS			NS			NS			NS	
Tlg by Comp by Yr		NS			NS			NS			NS	

[a] Abbreviations: Yr, year; Tlg, tillage; Comp, compost.
[b] Values determined using combustion method.
[c] Values determined using 1:1 soil–water slurry.
[d] Values determined using Bray-1 method.
[e] Values determined using ammonium acetate extraction and atomic absorption spectroscopy.
[f] Within columns, means followed by different letters are significantly different ($P < 0.05$), using analysis of variance.
*, $P < 0.01$; **, $P < 0.001$; NS, not significant ($P > 0.05$).

Table 2. Average air temperature and total precipitation in April through November at Boone, IA, in 2001 and 2002.

	Mean air temperature			Total precipitation		
Month	2001	2002	Long-term mean[a]	2001	2002	Long-term mean[a]
	C			cm		
April	11.7	9.1	9.4	8.8	8.6	8.7
May	15.9	14.2	16.2	16.4	11.2	11.2
June	20.9	22.5	21.2	4.7	7.1	12.8
July	24.1	24.3	23.2	4.2	13.4	10.0
August	22.5	21.3	21.9	6.7	12.4	10.3
September	16.3	18.7	17.5	13.5	3.2	8.1
October	10.1	7.2	11.3	5.4	7.0	6.0
November	8.8	1.7	2.6	3.5	0.4	4.2
Total	—	—	—	63.3	63.3	71.3

[a] Long-term mean between 1951 and 2001.

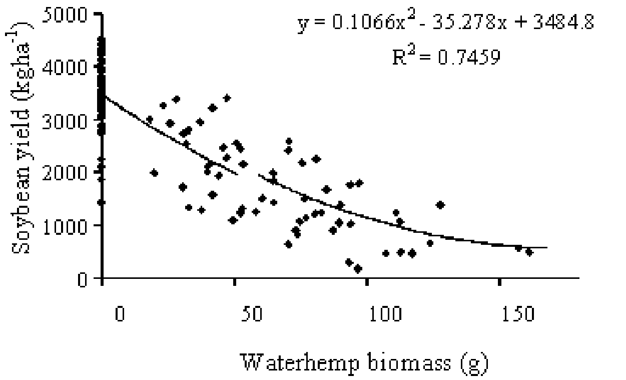

Figure 1. Quadratic regression of soybean yield relative to mean common waterhemp plant biomass. $Y = 0.1066x^2 - 35.278x + 3{,}484.8$, $r^2 = 0.7459$.

titioning and allometric relationships were affected by time of emergence and light conditions.

Common waterhemp stem diameters differed between compost treatments (P = 0.0009) and among sub-subplots where common waterhemp was sown at different times (P = 0.0001). Furthermore, common waterhemp diameter was modified by the first-order interaction between tillage and compost (P = 0.0383). Examination of this interaction sliced by compost application indicated that in the amended subplots, mean common waterhemp diameters were 18% larger in the chisel plow system than in the no-till system (P = 0.0243). However, in compost-free subplots common waterhemp diameter did not differ between tillage systems. In the at-planting sub-subplots, common waterhemp diameters were on average 15% larger in the chisel plow than in the no-till system (P = 0.0082).

Soybean diameter differed with year (P = 0.0002), tillage system (P = 0.0007), compost (P = 0.0017), common waterhemp sowing time (P < 0.0001), and the interaction between compost and common waterhemp sowing time (P = 0.0019). Compost treatment did not influence soybean diameters in the planting and emergence treatments. However, in the absence of common waterhemp competition, soybean diameters were larger in compost-amended subplots than in compost-free subplots (V2 treatment, P < 0.0001; V6 treatment, P = 0.0096; and season-long weed-free treatment, P = 0.0016).

Common Waterhemp Biomass

The responses of common waterhemp biomass to variations in compost, tillage system, and common waterhemp sowing time were consistent across years (Figure 3). Although mean common waterhemp biomass was enhanced 64% by compost (P = 0.0003) and reduced 64% by delaying common waterhemp sowing time from planting to emergence (P < 0.0001), there was an interaction between compost treatment and common waterhemp sowing time (P < 0.0001). The slicing of this interaction by common waterhemp sowing time showed that compost increased mean common waterhemp biomass by 57% in the at-planting and by 71% in the VE sub-subplots (P < 0.0001) but did not modify common waterhemp biomass in the V2 or V6 sub-subplots. When the compost by common waterhemp sow-

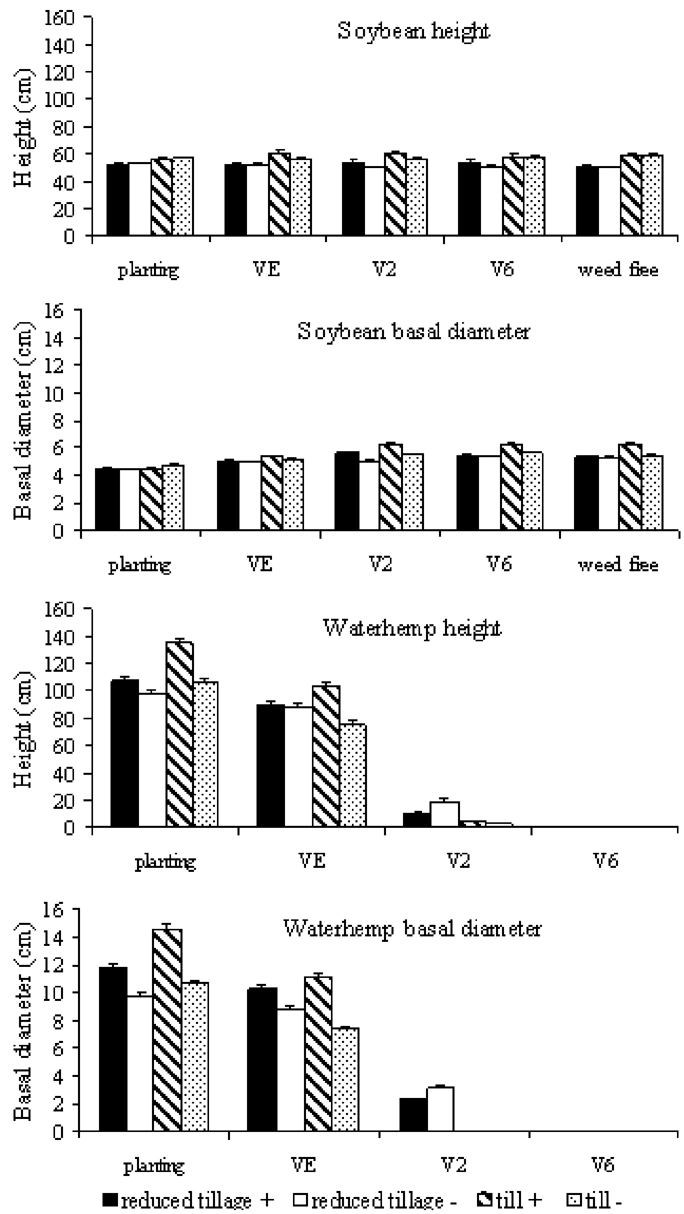

Figure 2. Mean soybean and common waterhemp height and diameter as functions of tillage regimen, compost, and common waterhemp sowing time. Error bars represent one standard error of the mean of four replicates.

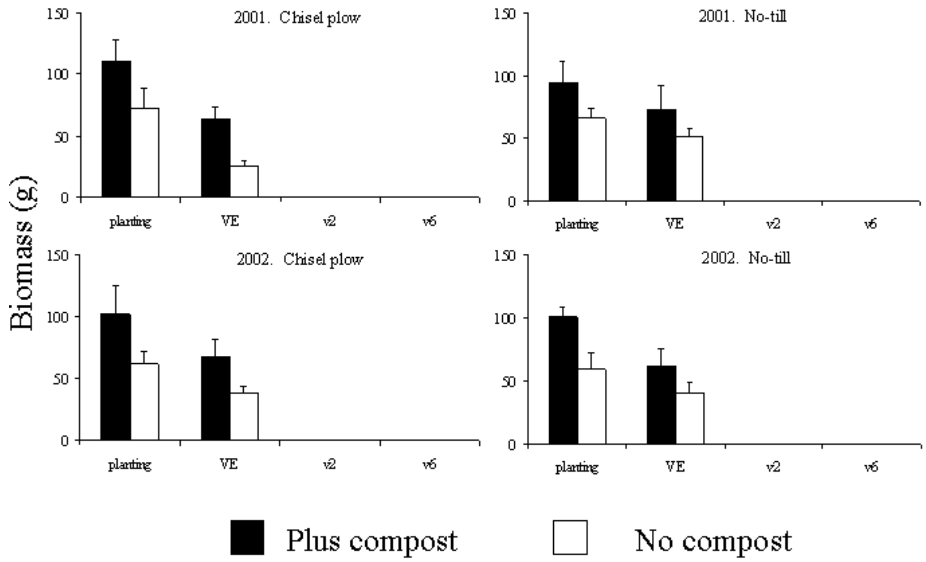

FIGURE 3. Mean common waterhemp biomass sampled in 2001 and 2002 at different tillage, compost, and time of common waterhemp sowing regimens. Error bars represent one standard error of the mean of four replicates.

ing time interaction was sliced by compost application, it was seen that in compost-amended subplots mean common waterhemp biomass was 56% greater when it was sown at soybean planting than at VE ($P < 0.0001$). The same analysis revealed that in compost-free subplots mean common waterhemp biomass was 68% greater at planting than at VE ($P < 0.0001$). Because waterhemp emergence in V2 and V6 treatments was very low, there were no differences between these treatments and the season-long weed-free treatment regardless of the presence or absence of compost.

For each compost–tillage combination, the relationship between common waterhemp biomass and accumulated GDD between soybean planting and common waterhemp sowing time was described by a linear-plateau function with negative slopes. A split-plot ANOVA on the parameter estimates showed that the slope of the regression functions was not modified by changes in tillage, year, compost, or the interaction between these variables. Intercept values were higher for equations obtained from composted-amended subplots than from compost-free subplots (Table 3). More GDD accumulated between soybean planting and VE in 2001 than in 2002. Therefore, the joint point of the linear-plateau function was higher in 2001 than in 2002, suggesting that soybean canopy is an important variable conditioning common waterhemp growth (Table 4).

Soybean Yield

The effects of common waterhemp sowing time, compost treatment, and tillage system on relative soybean seed yield were consistent between the 2 yr of this study (Figure 4). Although soybean relative yield differed with common waterhemp sowing time ($P < 0.0001$) and compost treatment ($P = 0.0221$), there was an interaction between these variables ($P = 0.0010$). Soybean yield was influenced by common waterhemp sowing time in compost-amended and compost-free subplots ($P < 0.0001$, both compost treatments). When common waterhemp was sown at planting, soybean relative yield was 87% higher in compost-free than in compost-amended subplots ($P < 0.0001$). At the VE treatment, soybean relative yield was 37% higher in compost-free than in compost-amended subplots ($P < 0.0001$). However, in the absence of competition (i.e., in the V2, V6, and weed-free treatments), compost did not modify soybean yield. These results indicate that compost did not enhance soybean yield and agree with the observation that compost enhanced common waterhemp growth and competitive ability.

For each year and tillage–compost combination, changes in soybean relative yield as a function of accumulated GDDs between soybean planting and common waterhemp sowing

TABLE 3. Parameter estimates and coefficients of determination of the negative linear-plateau functions that described the relationship between common waterhemp biomass and accumulated growing degree days (base 10 C) (GDD) from soybean planting to common waterhemp sowing in compost-amended and compost-free treatments. Within columns, means followed by different letters are significantly different ($P < 0.05$). Values are means (± 1SE).

	Parameter estimates[a]			
Compost amendment	b_0	b_1	a_1	r^2
Plus compost	96.96 (8.06) a	− 0.40 (0.22) a	245.38 (23.43)	0.84
Compost free	62.17 (7.78) b	− 0.31 (0.11) a	203.33 (23.41)	0.83

[a] $Y = (b_0 + b_1\ \mathrm{GDD})I_1 + (b_0 + b_1\ a_1)I_2$, where Y represents the predicted common waterhemp biomass, b_0 is the intercept, b_1 is the slope, a_1 is the joint point, I_1 is an indicator that takes on a value of 1 if GDD $\leq a_1$ and 0 otherwise, and I_2 is an indicator that takes on a value of 1 if GDD $> a_1$ and 0 otherwise.

Table 4. Parameter estimates and coefficients of determination of the negative linear-plateau functions that described the relationship between common waterhemp biomass and accumulated growing degree days (base 10 C) (GDD) from soybean planting to common waterhemp sowing during the first and second years of this study. Within columns, means followed by different letters are significantly different (P < 0.05). Values are means (± 1SE).

	Parameter estimates[a]			
Year	b_0	b_1	a_1	r^2
2001	85.49 (8.56) a	− 0.35 (0.11) a	241.38 (22.50) a	0.79
2002	81.08 (9.00) a	− 0.76 (0.12) a	106.81 (24.31) b	0.79

[a] $Y = (b_0 + b_1 \text{ GDD})I_1 + (b_0 + b_1\ a_1)I_2$, where Y represents the predicted common waterhemp biomass, b_0 is the intercept, b_1 is the slope, a_1 is the joint point, I_1 is an indicator that takes on a value of 1 if GDD $\leq a_1$ and 0 otherwise, and I_2 is an indicator that takes on a value of 1 if GDD $> a_1$ and 0 otherwise.

Table 5. Parameter estimates and coefficients of determination of the Gompertz functions that described the relationship between soybean relative yield as a function of the common waterhemp sowing time in compost-amended and compost-free treatments. Within columns, means followed by different letters are significantly different (P < 0.05). Values are means (± 1SE).

Compost amendment	Parameters estimates[a]			
	a	b	k	r^2
Plus compost	101.56 a	1.6645 a	0.01487	0.67
Compost free	101.70 a	0.9113 b	0.02044	0.70

[a] $Y = a \exp(-\ b \exp(-\ k\text{GDD}))$, where Y is the predicted relative soybean yield, a is the relative yield asymptote, b and k are constants, and GDD is the accumulated growing degree days (base 10 C) between soybean planting and common waterhemp sowing.

were described by Gompertz functions. A split-plot ANOVA of the equation parameters revealed that the asymptotic relative yield was not modified by year, tillage, compost, or the interaction between these variables. Similar results were observed for parameter k of the Gompertz function. However, parameter b of the Gompertz function was larger in the compost-amended subplots than in the compost-free subplots (Table 5). Parameter b represents the slope at which soybean relative yield varies in compost-amended and compost-free treatments as a function of common waterhemp sowing time. The difference in parameter b suggests that the relative change in soybean yield as a function of common waterhemp sowing time was larger in compost-amended subplots than in compost-free subplots. This pattern results from the fact that in at-planting and VE sub-subplots, soybean yields were lower in compost-treated subplots than in compost-free subplots, whereas there were no differences between compost treatments when common waterhemp was sown at V2, V6, and weed-free sub-subplots. In addition, there was a marginally significant interaction between tillage and compost (P = 0.0513) and a significant interaction between tillage and year (P = 0.0463) on the parameter b of the Gompertz function. In compost-treated subplots, parameter b was 29% larger in chisel plow systems than in no-till systems (P = 0.0368). In contrast, in compost-free subplots no differences in parameter b were observed between tillage systems (P = 0.9024). The analysis of the tillage by year interaction showed that in 2001 parameter b was 49% larger in chisel plow systems than in no-till systems (P = 0.0233), whereas there was no difference between tillage systems in 2002 (P = 0.6408).

Common Waterhemp Sex Ratio and Fecundity

A total of 2,557 common waterhemp plants were sexed during the 2 yr of this study. Sex ratio was not influenced by year of study, tillage, or first- and second-order interactions among years of study, tillage, and compost. A marginally higher male to female ratio was observed in compost-amended treatments than in compost-free treatments (compost-free subplots, mean ± SE = 1.10 ± 0.10; compost-amended subplots, mean ± SE = 1.36 ± 0.12) (P = 0.0611).

A linear-slope regression indicated that common waterhemp fecundity was positively related to individual plant biomass (Figure 5). The change in slope occurring at 118.7 g of common waterhemp biomass indicates that smaller plants produced proportionally more seeds per gram of non-

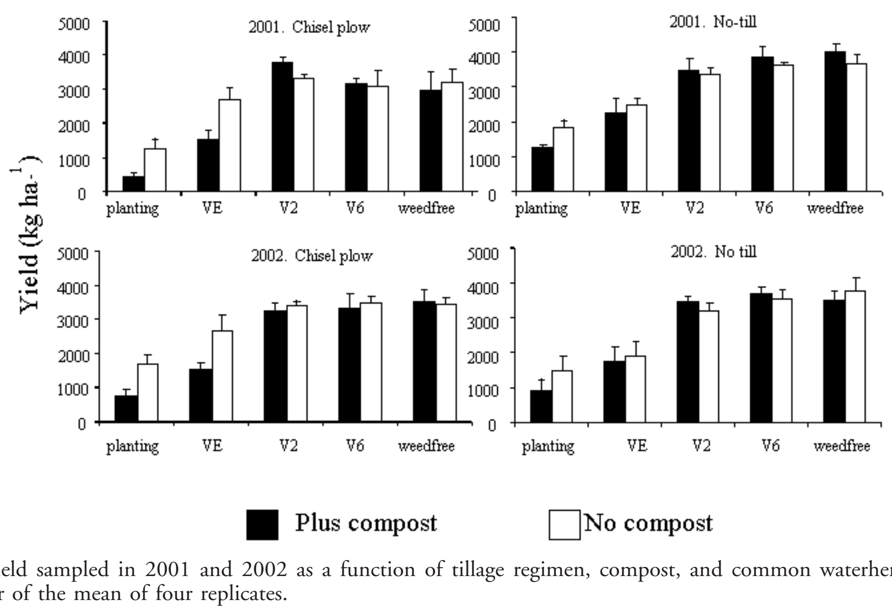

Figure 4. Mean soybean yield sampled in 2001 and 2002 as a function of tillage regimen, compost, and common waterhemp sowing time. Error bars represent one standard error of the mean of four replicates.

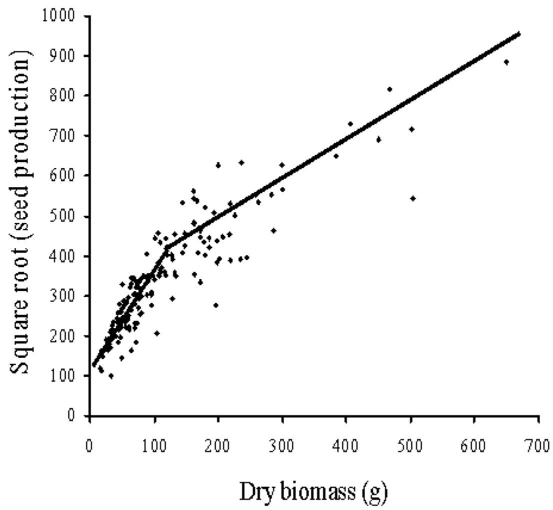

FIGURE 5. Common waterhemp seed production as a function of individual plant biomass. $Y = 121.1 + 2.33X$ ($X \leq 118.7$), $Y = 121.1 + 2.33 \times 118.7 + (0.86(X - 118.7))$ ($X > 118.7$), $r^2 = 0.84$.

reproductive tissue than did larger ones. Several studies have determined that agricultural weeds respond to variations in intraspecific competition by modifying seed production rates. When competition is low, seed production increases with increasing densities, but a plateau in seed production is usually reached as density and intraspecific competition increase to high levels (Bensch et al. 2003; Sartorato et al. 1996). Two hypotheses could explain the observed change in common waterhemp fecundity with plant size. First, it is possible that intraspecific competition among the large common waterhemp plants growing in compost-amended subplots was responsible for the observed decrease in relative fecundity. Alternatively, the high N, P, and K concentrations in compost-amended subplots may have stimulated common waterhemp vegetative growth and delayed maturity of fruits and seeds, as has been observed for certain vegetable crops (Thompson and Kelly 1957).

The soybean canopy was developed enough by the V2 stage to suppress common waterhemp establishment. Van Acker et al. (1993) observed that a period of weed control lasting up to the fourth-node stage (V4) prevented soybean yield losses of more than 2.5%. However, Eyherabide and Cendoya (2002) determined that weeds should be controlled up to the soybean full-bloom growth stage (R2) to prevent significant yield reductions. The wide range of results confirms the observation of Lindquist et al. (1996) that site-specific factors may determine when control practices need to be implemented to prevent yield loss to weed competition.

This research showed that composted swine manure differentially influenced soybean and common waterhemp growth. Compost applications did not enhance soybean yield but increased common waterhemp growth. Although it is unclear why soybean and common waterhemp responded differently to the presence of compost, we can speculate on the mechanisms responsible for the observed results. Seibert and Pearce (1993) determined that plant relative growth rate (RGR) is negatively correlated with seed size. Because of this correlation, small-seeded species, such as common waterhemp, are able to compensate for their initial size disadvantage through rapid growth and nutrient uptake. The nutrient rich environment in the compost-amended subplots could have allowed common waterhemp plants to reach higher RGR than in compost-free sites. Also, composted swine manure can modify the abundance and diversity of soilborne pathogens and mycorrhizal fungi (Douds et al. 1997). These changes could have increased growth rates of common waterhemp at the expense of soybean.

In conclusion, composted swine manure did not improve crop yield and, depending on timing, could result in larger weeds. Nevertheless, compost represents a viable source of nutrients and organic materials that allows farmers to recycle livestock waste products. Farmers who apply compost but fail to control common waterhemp during the early stages of soybean development could face a significant yield decrease. This study also showed that compost could modify common waterhemp sex ratio and fecundity. Future research should address the mechanisms responsible for common waterhemp sex determination, seed production, and competitive ability as well as the ecological significance of altering these parameters.

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