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Tillage, Cropping System, and Soil Depth Effects on Common Waterhemp (*Amaranthus rudis*) Seed-Bank Persistence

Lawrence E. Steckel, Christy L. Sprague, Edward W. Stoller, Loyd M. Wax, and F. William Simmons*

A field experiment was conducted in Urbana, IL, from 1997 to 2000 to evaluate the effect that crop, tillage, and soil depth have on common waterhemp seed-bank persistence. A heavy field infestation of common waterhemp (approximately 410 plants m^{-2}) was allowed to set seed in 1996 and was not allowed to go to seed after 1996. In 1997, 1998, 1999, and 2000, the percentage of the original common waterhemp seed bank that remained was 39, 28, 10, and 0.004%, respectively, averaged over tillage treatments. Initially, germination and emergence of common waterhemp was greater in no-till systems. Consequently, the number of remaining seeds was greater in the till treatments compared with no-till in the top 0 to 6 cm of the soil profile. This reduction was in part explained by the higher germination and emergence of common waterhemp in the no-tillage treatments. Tillage increased the seed-bank persistence of common waterhemp in the top 0 to 2 cm of the soil profile in 1997 and the top 0 to 6 cm in 1998. Crop had no effect on common waterhemp emergence or seed-bank persistence. In 2001, > 10% of the seed germinated that was buried 6 to 20 cm deep compared with 3% for seed 0 to 2 cm deep.

Nomenclature: Common waterhemp, *Amaranthus rudis* Sauer AMATA.
Key words: Seed bank, tillage, crop.

Common waterhemp is capable of producing over 400,000 seeds per female plant under reduced light and in excess of 1 million seeds per female plant under full-light (Steckel et al. 2003). With common waterhemp being a prolific seed producer, information regarding the immediate and long-term viability of its soil seed bank would be helpful in constructing an integrated approach for control. Seed longevity in the soil depends upon the interaction of many factors, such as intrinsic dormancy characteristics of the seed, environmental conditions, and biological interactions (Fenner 1994). The fate of the soil weed seed bank is determined by the amount of germination or decay, predation, and the species' intrinsic germination characteristics.

Seed depth in the soil profile has an impact on soil environmental conditions that influence secondary dormancy because some weed seeds require exposure to light, specific temperature regimes, or oxygen to germinate. Seed in the upper 2 cm of the soil profile are the most exposed to a 24-h diurnal temperature regimen (Alm et al. 1993). Stoller and Wax (1974) reported enhanced germination of weed seeds under a slow-varying diurnal temperature regimen. Steckel et al. (2004) reported that a diurnal temperature fluctuation around an average temperature of 15, 20, and 25 C enhanced germination in 8 out of 9 *Amaranthus* spp. studied. Weed seed on the surface are also exposed to light, which promotes germination. Sauer and Struik (1964) reported that a flash of light encouraged germination of some *Amaranthus* spp. Gallagher and Cardina (1998a) reported that *Amaranthus* spp. needed as little as 3 μmol m^{-2} of red light in buried seed and 1,000 μmol m^{-2} in unburied seed to initiate germination. Taylorson and Hendricks (1977) discovered a water-soluble germination inhibitor in some cocklebur (*Xanthium strumarium* L.) that only breaks down and allows germination if the seed is exposed to oxygen. The deeper in the soil profile seed is buried, the less available are environmental stimuli, such as light and oxygen, which promote germination. Ballare et al. (1988) reported that seed survival of large thornapple (*Datura ferox* L.) (Solanaceae) was 30% when seed were left on the soil surface but between 40 to 90% when buried 7 to 15 cm deep. Tillage also has an effect upon the soil environment that influences germination.

Tillage and crop can play a role in creating or removing environmental stimuli that regulate germination of many weed seeds. Cardina et al. (2002) reported greater weed seed-bank numbers in no-till compared with till treatments. They also reported that the density of weed seed in the top 5 cm of the soil profile was four times greater than at 5 to 10 cm depth and six times greater than at 10 to 15 cm depth in no-till treatments. Seed density did not vary in the moldboard-plow treatment by depth. Oryokot and Swanton (1997) reported that *Amaranthus* seedling densities were much higher in no-till environments compared with till environments. Roberts and Feast (1972) reported that after 5 yr of weed seed being placed in the soil at 2.5, 7.5, and 15 cm that total emergence was 75, 65, and 54%, respectively, where the soil was cultivated, and 58, 36, and 21%, where it was left undisturbed. The depth of the seed-burial disposition in the soil also plays a role in persistence of seeds with burial less than 5 cm showing less than 6% viability, whereas burial of 15 cm exceeded 10% for many annual weed species after 5 yr (Roberts and Feast 1972). Crop rotation also has an effect on the seed-bank dynamics of weeds. Cardina et al. (2002) reported that greater weed-seed numbers could be found in a corn (*Zea mays* L.)–oat (*Avena sativa* L.)–hay rotation compared with continuous corn rotation or a corn–soybean [*Glycine max* (L.) Merr] rotation.

Predation by insects and small vertebrae is another fate of the soil weed seed bank. Seed predation appears to change density and relative abundance of dominant species that have annual life histories (Gashwiler 1967). Ghersa (1997) observed that nearly all of a current year's seed rain of barnyardgrass [*Echinochloa crus-galli* (L.) Beauv.], redroot pigweed (*Amaranthus retroflexus* L.), and common lambsquarters (*Chenopodium album* L.) was eliminated under

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*Author affiliations. First author: Department of Plant Sciences, West Tennessee Research and Education Center, University of Tennessee, 605 Airways Blvd, Jackson, TN 38301; second author: Department of Crop and Soil Sciences, Michigan State University, East Lansing, MI 48824-1325; third and fourth authors: United States Department of Agriculture, Agricultural Research Service, University of Illinois, Urbana, IL 61801; fifth author: Department of Natural Resources and Environmental Sciences, University of Illinois, Urbana, IL 61801. Corresponding author's E-mail: mailto:lsteckel@utk.edu

a canopy of alfalfa (*Medicago sativa* L.) by a small field mouse (*Peromyscus sp.*). Field cricket (*Gryllus pennsylvanicus* Burmeister) was found to be able to consume 90 redroot pigweed seeds in 1 hr (Carmona et al. 1999).

The persistence of seed in the soil is also dependent upon the plant species. In the Beal (Kivilaan and Bandurski 1973) and Duvel (Toole and Brown 1946) experiments, where seed and soil were placed in glass bottles and buried, it was shown that at least one redroot pigweed seed could germinate after being buried from 10 to 40 yr, but other species including curly dock (*Rumex crispus* L.) and moth mullein (*Verbascum blattaria* L.) could germinate after being buried for 90 yr. Though some redroot pigweed has the ability to survive and germinate after many years within buried glass bottles, in studies of soil seed banks under an agricultural environment, no viable redroot pigweed seed could be found after 3 yr in one study (Schweizer and Zimdahl 1984) and no different than zero after 3 yr in another (Egley and Williams 1990). Egley and Williams (1990) reported that the seed bank of several *Amaranthus* species was reduced to 0 seeds m^{-2} within 3 yr, whereas several grass species still had 174 seeds m^{-2}.

The persistence of the soil seed bank is a complex system regulated by the interaction of environmental conditions, the depth of the seed, and the state of physiological readiness of the seed (Baskin and Baskin 1989). Information on the dynamics of common waterhemp seed in the soil seed bank is important to the development of improved weed management strategies. Our objective was to investigate the soil seed-bank persistence of common waterhemp as affected by time, depth, till, and crop.

Materials and Methods

In 1996, a severe natural infestation of common waterhemp (approximately 410 plants m^{-2}) was allowed to produce seed in a field at the University of Illinois' Crop Sciences Research and Extension Center at Urbana, IL, on an Elburn silt loam (fine-silty, mixed, mesic Aquic Argiudolls) with 4.5% organic matter and a soil pH of 6.8. In 1997, a long-term field experiment was established to examine common waterhemp emergence, seed distribution in the soil profile, and seed depletion in a corn–soybean rotation under conventional till and no-till systems. Blocks of either till or no-till were randomly assigned in the first year of the experiment and were permanent throughout the 4 yr of the study. Corn or soybean were then randomly assigned to the till blocks. Crop was alternated in each subsequent year. Common waterhemp emergence was recorded weekly in two 1-m^2 quadrats from the date of first observed seedling emergence (April 20 to April 27) until emergence ceased in early July. Emerged waterhemp seedlings were removed either by glyphosate at 0.84 kg ae ha^{-1}, by glufosinate at 0.5 kg ai ha^{-1}, or by hand-weeding. Common waterhemp plants were not allowed to grow or go to seed for the duration of this experiment. Measurements of photosynthetic active radiation (PAR) were taken throughout the growing season at three places between the middle two rows of each plot using a SunScan Canopy Analysis System[1] at each corn and soybean growth stage.

Tillage consisted of a fall chisel-plow, followed in the spring by a field cultivator and a disk harrow before planting. Corn and soybean seeds were planted with a four-row John Deere[2] 7200 vacuum planter. Row width was 76.2 cm. Plots were 6.1 m wide by 20.4 m long with 8 rows. 'Asgrow 3701' variety Roundup Ready soybeans[3] planted at 400,000 seeds ha^{-1} were used throughout the duration of this experiment. 'Pioneer Liberty Link 33G28' hybrid[4] was used the first 3 yr and 'Asgrow 730' Roundup Ready hybrid was used the 4th year at a planting rate of 75,000 seeds ha-1. Corn and soybeans were planted on April 21, 1997, April 16, 1998, April 12, 1999, and May 6, 2000. Corn plots were side-dressed with 168 kg ha^{-1} of a 82% nitrogen product, anhydrous ammonium. Common waterhemp soil seed bank was evaluated each fall by taking soil from a 20 by 20 cm square in six locations in each plot at depths of 0 to 2, 2 to 6, 6 to 12, and 12 to 20 cm. One hundred grams of soil from each sample was then run through a No. 40–mesh screen. The material collected in the 40–mesh screen was put into a solution of 200 ml deionized water. Common waterhemp seed floated to the top and was collected with a flask filter. Seed was then air-dried and counted. The count was performed on a weight basis. The average weight of 5 samples of 100 seeds each was used to determine the number of common waterhemp seeds. To assess the long-term viability of common waterhemp, seed-germination tests were run on seed collected in March of 2001. Germination tests were based on those performed by Mulugeta and Stoltenberg (1998) and Gallagher and Cardina (1998b) with modification. Seeds were scarified with concentrated sulfuric acid as suggested by Rojas-Garciduenas and Kommedahl (1960). One hundred seeds from each treatment were treated with concentrated sulfuric acid for 60 s, then rinsed and dried. The treated seeds were then placed on filter paper in a petri dish in a darkened growth chamber and subjected to a diurnal sinusoidal temperature regimen. The basis for the temperature regimen is based on Steckel et al. (2004), who suggest that maximum germination of common waterhemp can be acquired by varying the temperatures in a sinusoidal fashion from 18 to 35 C every 12 h. After 14 d, percentage of common waterhemp germination was calculated by counting those with a protruded radical of seed length or greater.

The statistical design was a randomized complete block with a factorial arrangement of tillage and crop with five replications. The data were analyzed using the MIXED procedure of SAS (SAS 2000). Main effects and all possible interactions were tested using the appropriate expected mean square values as recommended by McIntosh (1983). Individual treatment differences were determined using Fisher's Protected LSD test at the α = 0.05 level. Single degree-of-freedom contrasts were used to compare the effect within each year of tillage and crop on the common waterhemp emergence and seed bank. The univariate procedure of SAS (SAS 2000) showed that the common waterhemp emergence data was normal.

Results and Discussion

Initial 1996 Common Waterhemp Soil Seed Bank. The initial common waterhemp seed in the soil seed bank in the fall of 1996 was significantly affected by depth in the soil profile (P = 0.0001) (data not shown). The average number of seeds in the 2 to 6, 6 to 12, and 12 to 20 cm of the soil profile averaged 730,000 seeds m^{-2} and was 2.7 times that found in the top 0 to 2 cm of the soil profile (270,000). This is similar to what Roberts and Feast (1972) found who

Table 1. Common waterhemp cumulative emergence in 1997, 1998, 1999, and 2000 as affected by tillage and crop. Common waterhemp emergence was recorded weekly in two 1-m^2 quadrats from the date of first observed seedling emergence until emergence ceased in early July. Data are the average of five replications.

Year	Tillage			Crop		
	Till	No-till	$P > F$	Corn	Soybean	$P > F$
	Plants m^{-2}			Plants m^{-2}		
1997	2,110	3,940	0.0064	2,980	3,050	0.1586
1998	610	810	0.0579	620	810	0.0608
1999	50	60	0.6664	50	50	0.9172
2000	40	90	0.5688	50	80	0.5136
$LSD_{0.05}$	210	210		90	90	

reported increased loss of seeds at shallow soil depths compared with deeper in the soil profile. However, this is inconsistent with Cardina et al. (2002) who reported that weed seed bank in the top 5 cm of the soil profile was four times greater than the seed found 5 to 10 cm deep.

Common Waterhemp Emergence. Common waterhemp emergence began when the average weekly soil temperature was 12 C, which agrees with a study that found common waterhemp emergence begins at 10 C (Steckel et al. 2004). Common waterhemp emergence in 1997 was very high (> 2,000 seedlings m^{-2}). In 1997, common waterhemp emerged 1.8 times greater in no-till compared with till (Table 1). The magnitude in the number of plants that emerged in 1998 was dramatically less compared with 1997 (Table 1). Another dramatic decrease in plant emergence was recorded in 1999 compared with 1998. Common waterhemp emergence in 2000 was similar to 1999. Consistent across all yr was the cessation of common waterhemp emergence in late June to early July. The ending of emergence in early July was a surprise as personal observations have often seen this weed emerging well into August. However, these observations occurred in fields where soybeans were planted late June or early July following a wheat harvest, and the soybean canopy had not fully developed to shade the soil. The reduction in emergence of common waterhemp occurred when > 98% of the light at the top of the canopy did not reach the soil surface (data not shown). The cessation of common waterhemp emergence under those conditions would agree with work by many researchers who found that red light exposure will trigger germination (Gallagher and Cardina 1998b; Scopel et al. 1991). Crop had no effect on emergence.

Effect of Year and Tillage on Seed-Bank Dissipation. There was a significant main effect of year on the common waterhemp soil seed bank. In each year of the study, there was a significant reduction in the percentage of the original seed bank. Regardless of tillage, the common waterhemp soil seed bank, averaged over the 0 to 20 cm depth of the soil profile, deteriorated in 4 yr to less than 1% of the original seed bank in 1996 (Table 2). These data would suggest that the common waterhemp seed bank is not as persistent compared with other weed species in literature (Kivilaan and Bandurski 1973). These results would agree with research on the seed-bank persistence of another *Amaranthus* species, redroot pigweed, (Schweizer and Zimdahl 1984), where less than 1% of the original seed bank was accounted for after 3 yr. It would also concur with Egley and Williams (1990), who reported that pigweed species soil seed bank was reduced to 0 within 3 yr, whereas several grass species still had 174 seeds m^{-2}.

Table 2. Single degree-of-freedom contrasts on the main effect of year, tillage, and crop on common waterhemp seed bank, showing the percentage of the original seed bank.

Year	All years	Tillage			Crop		
		Till	No-till	$P > F$	Corn	Soybean	$P > F$
	%				%		
1997	39	40	37	0.0065	38	40	0.1399
1998	28	31	27	0.0001	29	30	0.6463
1999	10	10	9	0.2577	9	12	0.2694
2000	0.004	0.004	0.004	0.9963	0.004	0.004	0.9964
$LSD_{0.05}$	4						

There was also a significant year-by-tillage effect (Table 2). Common waterhemp seed bank was reduced to 40 and 37% of the original 1996 seed bank for the till and no-till treatment, respectively, in the first year of the study. Similar to 1997, common waterhemp soil seed bank in 1998 also showed a significantly higher percentage of the original seed bank remaining from the till, compared with no-till, treatments (31 to 27%). These results are supported by greater common waterhemp emergence in no-till compared with till (Table 1). Other factors, such as predation reported by Gashwiler (1967) and Carmona et al. (1999), also likely played a significant role in the difference in soil seed-bank persistence between the tilled and no-till treatments. These results are supported by other research (Buhler 1992; Oryokot and Swanton 1997). Tillage did not have an effect upon the common waterhemp seed bank in 1999 or 2000. Egley and Williams (1990) also reported that tillage only affected weed seed germination in the first year of a 5-yr study.

Effect of Crop on Seed-Bank Dissipation. Crop did not have an effect upon common waterhemp seed bank in any year of the study (Table 2).

Tillage by Soil-Depth Effect on Seed-Bank Distribution. Because there was a significant tillage effect in 1997 and 1998, those years were examined for a depth-by-tillage interaction ($P = 0.0001$) (Table 3). Common waterhemp seed bank compared with the original seed bank was reduced to 30 and 24%, respectively, for the till and no-till treatments in 1997 at the 0 to 2 cm profile depth (Table 3). Tillage did not have an effect in the 2 to 20 cm of the soil profile in 1997 and ranged from 42 to 44% of the original common waterhemp soil seed bank. In 1998, the seed bank in the top 0 to 2 cm depth contained 27% and 22% of the original seed,

Table 3. Effect of year, tillage and depth on common waterhemp seed bank in 1997 and 1998. Data are averaged across crops, showing the percentage of the original seed bank.

Depth	1997		1998	
	Till	No-till	Till	No-till
cm	%			
0 to 2	30	24	27	22
2 to 6	43	43	34	28
6 to 12	44	43	34	28
12 to 20	44	42	31	28
$LSD_{0.05}$	3		4	

Table 4. Common waterhemp germination percentage from various soil depths from seed collected in 2001. Data are averaged over tillage and crops.

Depth	Germination
cm	%
0 to 2	3
2 to 6	6
6 to 12	10
12 to 20	11
$LSD_{0.05}$	3

respectively, for the till and no-till treatments. Additionally, in 1998, the 2 to 6 and 6 to 12 cm depths of the soil profile with the till treatment had more remaining seed (34%) compared with the no-till (28%). There were no differences due to tillage for the 12 to 20 cm depth of the soil profile. Other researchers have reported similar results (Roberts and Feast 1972). Cardina et al. (2002) reported a depth-by-tillage interaction where the density of seed from 0 to 5 cm was four times that found in 5 to 10 cm and six times that at 15 to 20 cm in no-till, but seed density did not differ with depth when soil was tilled with a moldboard plow. There were no differences because of till in 1999 or 2000.

Common Waterhemp Seed-Bank Germination Spring of 2001. Tillage had no effect on germination regardless of depth (Table 4). In addition, crop had no effect on the viability of common waterhemp seed at any depth. However, the main effect of depth averaged over crop and tillage was significant ($P = 0.0001$). The seed exhumed from the 0 to 2 cm and 2 to 6 cm depth had lower germination than seed from 6 to 12 and 12 to 20 cm in the soil profile (Table 4). Other researchers have reported similar increases in viable seed from several weed species due to depth in the soil profile (Gallagher and Cardina 1998a). Gutterman (1992) also reported that in several plant species, variations in the magnitude of germination among seed sources were attributable to environmental and biological factors. Environmental and biological factors may influence the permeability of seed coats, the amount of endogenous inhibitory chemicals within seeds, and the proportion of active and inactive forms of phytochrome within seeds.

The results of this study indicate that common waterhemp seed banks are not as stable as some other weed species and will, in many environments, last no longer than 4 yr. It also confirms that, because of enhanced germination in no-till, shallow-buried common waterhemp is less persistent in no-till than till system. Crop does not affect the persistence of the common waterhemp soil seed bank. Cardina et al. (2002) suggested that management practices filter in or out plant characteristics to determine the weed community in a given field. Our study would suggest that continuous no-till practices can promote common waterhemp to become more of a problem because of enhanced germination. However, if common waterhemp does not replenish new seed to the soil bank each fall, no-till may aid in the depletion of the soil seed bank. Unfortunately, common waterhemp is a very prolific seed producer (Steckel et al. 2003), and a few escapes can potentially replenish germination losses. Therefore, management practices that can eliminate common waterhemp from producing seed over a 2 to 3 yr period could possibly deplete the soil seed bank of common waterhemp.

Sources of Materials

[1] SunScan Canopy Analysis System, Model SS1-TM-1.05, Delta-T Devices Ltd. 128 Low Road Burwell Cambridge, CB5 0EJ, U.K.

[2] John Deere 7200 Vacuum planter, Deere & Company. One John Deere Place. Moline, IL 61265-8098.

[3] Asgrow 3701 Roundup Ready variety and 730 Roundup Ready corn hybrid. Monsanto Company. 800 North Lindbergh Boulevard. St. Louis, MO 63167.

[4] Pioneer 33G28 Liberty Link hybrid. Pioneer Hi-Bred International, Inc. 400 Locust St. P.O. Box 14454. Des Moines, IA 50306-3454.

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