Weed Technology. 2001. Volume 15:170–176

Weed Seed Bank Dynamics During a Five-Year Crop Rotation[1]

DOUGLAS D. BUHLER, KEITH A. KOHLER, and RICHARD L. THOMPSON[2]

Abstract: Cultural practices used for crop production influence the composition of the weed seed bank in the soil. This paper reports the results of a 5-yr experiment to characterize the weed seed bank conducted on a farmer-managed field in central Iowa. The number of weed seeds in the soil and their vertical distribution were examined each October. At the initial sampling in October 1994, the field had been in hay production and about 80% of the weed seeds were common waterhemp and foxtail species. The cropping sequence over the next 3 yr was corn/soybean/corn using a ridge tillage system. Over this period, the density of common waterhemp seeds declined each year. The density of foxtail seeds declined by almost 90% during the first year of corn and did not change during the following years of soybean and corn production. Prior to moldboard plowing of the hay sward in 1994, weed seeds were concentrated in the upper 10 cm of soil. Moldboard plowing resulted in a more uniform distribution of the weed seeds over the upper 20 cm of soil, and the distribution across depths remained relatively constant during the 3 yr of corn and soybean production. During the final year of the experiment, the field was rotated to oat and reseeded with hay species. The number of common waterhemp and foxtail seeds in the soil greatly increased following oat/hay production and seeds were concentrated in the upper 10 cm of the soil profile. Results indicated that the processes affecting the weed seed bank in production fields are complex and will vary greatly based on the production practices used and the timing of their application.

Nomenclature: Common waterhemp, *Amaranthus rudis* Sauer #[3] AMATA; corn, *Zea mays* L.; foxtail species, *Setaria* spp.; oat, *Avena sativa* L.; soybean, *Glycine max* (L.) Merr.

Additional index words: Cropping systems, ridge tillage, seed bank, seed distribution.

INTRODUCTION

The compositions of weed communities of agricultural lands vary greatly and are closely linked to cropping history. Species composition and density are influenced by farming practices and vary from field to field and among areas within fields (Buhler et al. 1997a; Fenner 1985; Mortensen et al. 1993). Seed densities in agricultural soils have been reported from near 0 to as much as 1 million seeds/m^2 (Fenner 1985). Although seed banks and the resulting weed populations are composed of many species, a few dominant species generally comprise 70 to 90% of the total seed bank (Wilson 1988). These dominant species are the primary pests because they are resistant to control measures or are adapted to the cropping system.

Populations of annual weed species are perpetuated by seeds that comprise the seed bank. Seeds enter the soil through many sources, but the major source is plants that escape control and produce seeds within the field (Cavers 1983). Buhler (1999a) found that weed seed bank response to differing weed control practices during a 4-yr experiment depended on the initial weed density. In general, weed seed numbers and crop yields were less sensitive to weed control practices when initial weed densities were low than when they were high. Keeping plots free of weeds for 4 yr greatly reduced seed numbers, but enough weed seeds remained in the soil to generate weed densities capable of reducing soybean (*Glycine max*) yields by 20 to 50% in the fifth year (Buhler 1999b). The number of seeds in the seed bank in continuous corn (*Zea mays*) dropped by approximately 70% after 3 yr of herbicide plus interrow cultivation (Schweizer and Zimdahl 1984). When herbicide use was discontinued for 3 yr and weeds were controlled by cultivation only, the seed bank was approximately 25 times greater than where herbicide use and cultivation were

[1] Received for publication May 5, 2000, and in revised form November 16, 2000.

[2] Former Research Agronomist and Research Technician, U.S. Department of Agriculture, Agricultural Research Service, National Soil Tilth Laboratory, Ames, IA 50011; Farmer/Researcher, Thompson On-Farm Research, Boone, IA 50036. Current address of senior author: Michigan State University, Department of Crop and Soil Sciences, East Lansing, MI 48824-1325. Corresponding author's E-mail: buhler@msu.edu.

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

Table 1. Cropping practices used for the field on the Thompson farm near Boone, IA, from 1993 through 1998.

Year	Crop	Tillage and cultural practices	Manure application
1993	Oat	Disk twice in spring, plant oat and legume mix.	Liquid from manure bunker in April and October.
1994	Hay	Moldboard plow in autumn, plant rye cover crop.	18 Mg/ha dry matter prior to moldboard plowing.
1995	Corn	Disk twice in spring, plant corn, rotary hoe twice, two interrow cultivations for weed control and ridge building, plant rye cover crop on ridges after corn harvest.	None
1996	Soybean	Truncate ridges during soybean planting, rotary hoe twice, two interrow cultivations for weed control and ridge building, broadcast oat cover crop in standing crop.	Liquid from manure bunker in April.
1997	Corn	Truncate ridges during corn planting, rotary hoe twice, two interrow cultivations for weed control and ridge building.	Liquid from manure bunker and 9 Mg/ha dry matter in April. Liquid from bunker in October.
1998	Oat	Disk twice in spring, plant oat and legume mix.	Liquid from manure bunker in April.

continued. In a similar study (Burnside et al. 1986), seed density in the soil declined by 95% after a 5-yr weed-free period. During the sixth year, herbicides were not used, and seed density increased to 90% of the original level at two of five locations.

While crop rotation is often cited as having a major influence on weed populations, few have characterized the effects of crop rotation on the weed seed bank. In ridge tillage (Forcella and Lindstrom 1988), soils harbored at least twice as many weed seeds under continuous corn than a corn/soybean rotation. Schreiber (1992) found that growing corn in a soybean/corn or soybean/wheat (*Triticum aestivum* L.)/corn rotation greatly reduced giant foxtail (*Setaria faberi* Herrm. # SETFA) seeds in the soil compared with corn grown continuously. The effects of crop rotation and environmental conditions associated with years and locations were larger than tillage effects on weed species composition and abundance in two separate studies in Canada (Derksen et al. 1993; Thomas and Frick 1993). Similarly, Ball (1992) reported that cropping sequence was the most dominant factor influencing species composition in weed seed banks.

Tillage is a major mechanism for vertical movement of weed seeds in agricultural soils. Spheres, with similar size and density of weed seeds, were found to depths of 12 cm following chisel plowing and 32 cm following moldboard plowing (Staricka et al. 1990). In chisel-plowed plots, 48% of the spheres were found within 4 cm of the soil surface compared with 4% in moldboard-plowed plots. Moldboard-plowed plots had fewer weed seeds in the upper 20 cm of soil than in chisel plow or no-tillage plots after 5 yr (Yenish et al. 1992). Moldboard plowing resulted in the most uniform distribution of seeds over soil depths. In the no-tillage system, more than 60% of all weed seeds were found in the upper 1 cm of soil and few seeds were found below 10 cm.

Under field conditions, many factors interact to regulate the character of the weed seed bank. The objective of this experiment was to document the density and vertical distribution of weed seeds in the soil during the course of a diverse 5-yr crop rotation in a farmer-managed field. Our goal was to better understand the effect of crop rotation on the weed seed bank and to determine whether weed seed bank responses to management practices observed in small plot studies could be substantiated under farmer-managed conditions.

MATERIALS AND METHODS

A field experiment was conducted from October 1994 through October 1998 in a 16-ha field on the farm of Richard and Sharon Thompson near Boone, IA, on a Clarion–Nicollet–Webster soil association. The management practices in the field used in this experiment included a 5-yr crop rotation (since 1967) of legume/grass hay, corn, soybean, corn, and oat (*Avena sativa*) underseeded with a legume/grass forage mixture (Karlen and Colvin 1992). Since 1980, the corn and soybean were produced using a ridge tillage system, and disking was conducted prior to planting oat. In the autumn prior to the first year of corn, a sweep plow was operated about 5 cm deep to sever plant roots and kill the forage sward. The species in the forage mixture included alfalfa (*Medicago sativa* L.), alsike clover (*Trifolium hybridum* L.), red clover (*Trifolium pratense* Sibth.), orchardgrass (*Dactylis glomerata* L.), and timothy (*Phleum pratense* L.). During the course of this experiment, tillage and fertility practices varied by year and crop (Table 1). No synthetic fertilizers or pesticides were used in the field

Table 2. Density of viable weed seeds of the upper 20 cm of a Nicollet loam soil near Boone, IA. Samples were collected in October of each year.

		Weed seed density[a]			
Year	Crop	Common waterhemp	Foxtail species	Other species[b]	All species
1994	Hay	27,880 b	4,840 b	8,650 a	41,370 b
1995	Corn	13,750 c	510 c	1,780 b	16,040 c
1996	Soybean	7,260 d	130 c	630 c	8,020 d
1997	Corn	1,910 e	500 c	400 cd	2,810 d
1998	Oat	64,160 a	6,490 a	130 d	70,780 a

[a] Means within a column followed by the same letter are not significantly different according to Fisher's LSD ($\alpha = 0.05$).

[b] Included common lambsquarters, Pennsylvania smartweed, and velvetleaf.

during the course of the experiment. Weeds were controlled in the corn and soybean with two or three passes with a rotary hoe and two interrow cultivations.

At initiation of the experiment, four representative sampling sites in areas of Nicollet loam soil (fine-loamy, mixed mesic, Aquic Hapludolls) were selected throughout the 16-ha field. Each sampling site was approximately 100 m^2 and was divided into three subsampling areas. The locations of these areas were recorded, and sampling was conducted in the same area each year. In October of each year, the weed seed content of the soil was assessed by collecting six soil cores (5 cm diam by 20 cm deep) in an M-shaped pattern from each of the three adjacent subsampling areas within each of the four sampling sites. Each core was sectioned by depth segments of 0 to 5 cm, 5 to 10 cm, 10 to 15 cm, and 15 to 20 cm during the field sampling process, and the six cores within each sampling area were composited by depth segment. Samples were thoroughly mixed and bagged by subsampling area/depth combination. Samples were transported to the National Soil Tilth Laboratory in Ames, IA, within 4 hr of sampling and stored at −5 C until analysis.

Six 100-g subsamples were removed from each composite sample and seeds were extracted using a flotation/centrifugation method (Buhler and Maxwell 1993). Seed viability was assessed using a pressure test (Rothrock et al. 1993), seeds were enumerated by species, and values were converted to viable seeds per square meter surface area for each 5-cm depth segment. Following extraction and enumeration, data for the three subsamples were combined to determine the sampling site (replication) means, and all data were reported as viable seeds.

The major weed species were common waterhemp (*Amaranthus rudis*) and foxtail species [giant foxtail and yellow foxtail, *Setaria glauca* (L.) Beauv. # SETLU]. These species comprised nearly 80% of the seed bank at the initial sampling (Table 2). The presence of common waterhemp was determined by identification of plants in the field and verified by growing out recovered seeds in the greenhouse. We determined that the *Amaranthus* population was more than 95% common waterhemp. Other species were primarily common lambsquarters (*Chenopodium album* L # CHEAL.), Pennsylvania smartweed (*Polygonum pensylvanicum* L. # POLPE), and velvetleaf (*Abutilon theophrasti* Medikus # ABUTH). None of these species accounted for more than 5% of the seeds recovered in any year and were pooled with common waterhemp and foxtail species and expressed as total weed seeds.

Weeds were counted prior to crop harvest each year and categorized in the same manner as weed seeds. Because of low weed densities in 1995, 1996, and 1997, weeds in the entire 100-m^2 sampling site were counted. In 1994 and 1998, weeds were counted in 10, 1-m^2 areas in each sampling site.

The design of the experiment was a split plot randomized complete block with four replications (sampling sites), with year treated as whole plots and sampling depths as subplots for each weed species. We realize that not having all crops in all years confounds some of our results. However, our objective was to evaluate the general effects of the rotational system on weed seed bank dynamics, rather than examining the effects of individual crops in the rotation. This design was also necessary to allow us to evaluate seed bank responses to management practices under farmer-managed conditions. All data were subjected to ANOVA. Main effects and interactions were tested for significance. Data were tested for nonadditivity and homogeneity of variance. Soil depth means within 1 yr and species were separated by Fisher's protected LSD test at $\alpha = 0.05$. Paired *t* tests were used to compare weed species/sampling depth means among years.

RESULTS AND DISCUSSION

Seed densities of common waterhemp, foxtail species, other species, and all species were affected by year, soil depth, and the year by soil depth interaction. To examine general trends in seed densities over years, data were pooled over soil depths within years. Because of the soil depth by year interaction, data for each species are presented by soil depth for each individual year.

Total Seeds. More than 41,000 weed seeds/m^2 were recovered from the upper 20 cm of soil prior to moldboard plowing of the hay sward in October 1994 (Table 2). Common waterhemp and foxtail species accounted for

Table 3. Weed density prior to crop harvest near Boone, IA.

Year	Crop	Weed density: Common waterhemp	Foxtail species	Other species[a]
		Plants/10 m^2		
1994	Hay	350	410	280
1995	Corn	6	2	4
1996	Soybean	1	0	0
1997	Corn	1	4	1
1998	Oat	750	510	80

[a] Included common lambsquarters, Pennsylvania smartweed, and velvetleaf.

67 and 12% of the seeds recovered, respectively. Following a year of corn production (October 1995), weed seed density declined to about 16,000 seeds/m^2, of which 86% was common waterhemp. During the soybean production year of 1996, total seed density declined 50% compared to 1995, and 90% of the seeds were common waterhemp. By October 1997, following another year of corn, seed density had dropped to less than 3,000 seeds/m^2, of which 68% was common waterhemp and 18% foxtail species. During 1998 when oat was produced and forage established, total seed density increased to more than 70,000 seeds/m^2, which was a 25-fold increase over the previous year. This increase in seed density over the previous year was completely accounted for by common waterhemp and foxtail species, which comprised 90 and 9% of the seed bank, respectively, at this time.

The classes of weed species behaved differently over years (Table 2). Common waterhemp seed density declined by 51, 47, and 74% compared to the previous year in 1995, 1996, and 1997, respectively. Following the 3 yr of decline, common waterhemp seed density increased 33-fold between 1997 and 1998. For foxtail species, there was an 89% decline in seed density between 1994 and 1995, but density did not change further until 1998 when seed density increased 13-fold compared with the previous year. The other species showed a steady decline over the course of the experiment, but did not increase in 1998. When all species were combined, seed density declined in 1995 and 1996, was unchanged between 1996 and 1997, and markedly increased in 1998.

The behavior of the seed bank over years suggested that there was large variation in weed seed production. Although seed production was not measured, weed densities at harvest support this conclusion (Table 3). Weed numbers during the years of corn and soybean production (1995 to 1997) were very low, and the patterns of decline of common waterhemp and foxtail species during this period were similar to those observed in controlled field experiments with no annual seed deposition. Buhler and Hartzler (2001) found that only 7% of the giant foxtail seeds added to the soil were viable 1 yr after burial, whereas more than 50% of the common waterhemp survived under the same conditions. None of the giant foxtail seed survived for more than 2 yr, but 12% of the common waterhemp remained viable after 4 yr of burial.

Although the seed bank was reduced to a low level during the 3 yr of corn and soybean, sufficient seed remained to generate a large weed population in 1998 (Table 3). These plants resulted in a rapid increase in weed seed density as plants matured and produced seeds in autumn 1998. Although top growth was removed from the field twice (harvest of oat for forage in July and for hay harvest in September), common waterhemp and foxtail species were able to produce enough seeds to greatly increase seed density in the soil. This rapid increase is similar to that observed by Burnside et al. (1986), when following a seed density decline of 95% after a 5-yr weed-free period, seed density increased to 90% of the original level in a single year when the remaining weeds were not controlled. Buhler (1999b) found that after keeping plots free of weeds for 4 yr, enough weed seeds remained in the soil to generate weed densities capable of reducing soybean yields by 20 to 50% in the fifth year.

The manure applied over the course of the experiment (Table 1) may have also contributed weed seeds to the soil. The majority of seeds are killed when passing through the digestive tracts of animals, but a small percentage typically survive (Harmon and Keim 1934). The manure used on this farm was composted prior to application, further reducing the weed seed content (Wiese et al. 1998). A study of 20 New York dairy farms found that, on average, spreading manure introduced 350 weed seeds/m^2 (Mt. Pleasant and Schlather 1994).

The seeds that increased the seed bank in 1998 were generated by regrowth of common waterhemp and foxtail plants following oat harvest and plants that emerged after oat harvest. Deposition came from early-maturing seeds that were shed prior to hay harvest and plants that were shorter than the clipping height. It is interesting to note that seeds of the other species present in the field (common lambsquarters, Pennsylvania smartweed, and velvetleaf) did not show an increase similar to common waterhemp and foxtail species. The reason for this is not readily apparent. However, most of the species that comprised the other category have been characterized as early-emerging species (Buhler et al. 1997b) and may have been more effectively controlled by clipping than common waterhemp and foxtail, species capable of emerging later into the growing season. Because of their low den-

Table 4. Vertical distribution of viable common waterhemp seeds in the upper 20 cm of a Nicollet loam soil near Boone, IA. Samples were collected in October of each year.

	Common waterhemp seed density[a]				
Depth	1994 Hay	1995 Corn	1996 Soybean	1997 Corn	1998 Oat
cm	Seeds/m²				
0–5	11,460 aB	3,820 aCD	4,330 aCD	1,020 aD	48,370 aA
5–10	8,910 aA	3,820 aB	1,150 bC	115 bC	9,550 bA
10–15	3,820 bAB	3,310 abB	890 bC	255 bC	4,200 cA
15–20	2,550 bAB	2,800 bA	890 bC	255 bC	1,910 dB

[a] Means within a column followed by the same lowercase letter are not significantly different according to Fisher's LSD ($\alpha = 0.05$). Means within a row followed by the same uppercase letter are not significantly different using a paired *t* test ($\alpha = 0.05$).

Table 5. Vertical distribution of viable foxtail seeds in the upper 20 cm of Nicollet loam soil near Boone, IA. Samples were collected in October of each year.

	Foxtail seed density[a]				
Depth	1994 Hay	1995 Corn	1996 Soybean	1997 Corn	1998 Oat
cm	Seeds/m²				
0–5	2,550 aB	130 aC	50 aC	370 aC	4,330 aA
5–10	1,270 bA	130 aB	50 aB	100 bB	1,530 bA
10–15	510 bA	130 aB	50 aB	50 bB	500 cA
15–20	510 bA	50 bB	0 aC	10 bC	250 cB

[a] Means within a column followed by the same lowercase letter are not significantly different according to Fisher's LSD ($\alpha = 0.05$). Means within a row followed by the same uppercase letter are not significantly different using a paired *t* test ($\alpha = 0.05$).

sities, common lambsquarters, Pennsylvania smartweed, and velvetleaf also may have been unable to tolerate competition from the high densities of common waterhemp and foxtail and from the forage sward.

Common waterhemp and foxtail species are among the most common weed species in corn and soybean in the north-central United States. Their dominance of the seed bank is not surprising, but the magnitude of the common waterhemp population is noteworthy. Common waterhemp is native to the central United States and is increasing in the region (Hagar et al. 1997). Common waterhemp biotypes resistant to acetolactate synthase–inhibiting herbicides have been identified (Hinz and Owen 1997), and the rapid increase of common waterhemp has been attributed to repeated use of these herbicides. However, no herbicides were used in this field during the course of this experiment, suggesting that other characteristics of common waterhemp were responsible for its increase. These characteristics may include high seed production potential (Battles et al. 1999) and ability to emerge late in the growing season (Buhler et al. 1997b).

Vertical Distribution. At the initial sampling in October 1994, weed seeds were concentrated near the soil surface (Tables 4–6). Common waterhemp densities were similar at depths of 0 to 5 cm and 5 to 10 cm, which were about threefold greater than at 10 to 15 cm and 15 to 20 cm deep (Table 4). Foxtail species density was greatest at 0 to 5 cm deep, with other depths being similar (Table 5). When all species were combined, the upper 5 cm had the greatest seed density, followed by the 5- to 10-cm segment, with the two deepest segments having the lowest seed densities (Table 6). This general distribution of weed seeds is similar to that observed in long-term no-tillage plots (Hoffman et al. 1998; Yenish et al. 1992) and reflects the tillage history of this field. The last tillage prior to initiation of the experiment was disking in spring 1993 (Table 1); the last time the field had been moldboard plowed was 1967.

Moldboard plowing in autumn 1994 and the following year of corn production reduced weed seed densities and altered vertical distribution. In October 1995, there were no differences in common waterhemp densities among the upper three depth segments, and the 15- to 20-cm depth was similar to 10- to 15-cm depth (Table 4). Seed densities in the upper two depth segments were lower in 1995 than 1994, but densities at greater depths did not change over the year. Foxtail densities in the upper three depth segments were similar to each other and greater than the 15- to 20-cm segment (Table 5). Foxtail density declines between 1994 and 1995 ranged from 75% in the 10- to 15-cm segment to 95% in the upper 5 cm. When seeds of all species were combined, the upper three depth segments had similar densities, as did the lower three depth segments (Table 6). With the exception of the 15- to 20-cm depth, density declined between 1994 and 1995.

The two major factors that regulated the changes in the seed bank between 1994 and 1995 were moldboard

Table 6. Vertical distribution of viable seeds of all species in the upper 20 cm of Nicollet loam soil near Boone, IA. Samples were collected in October of each year.

	Total weed seed density[a]				
Depth	1994 Hay	1995 Corn	1996 Soybean	1997 Corn	1998 Oat
cm	Seeds/m²				
0–5	17,820 aB	4,460 aC	4,840 aC	1,400 aC	52,830 aA
5–10	12,730 bA	4,330 abC	1,270 bD	640 bD	11,080 bB
10–15	5,090 cA	3,820 abB	1,020 bC	510 bcC	4,710 cAB
15–20	3,820 cA	3,440 bA	890 bC	250 cC	2,160 cB

[a] Means within a column followed by the same lowercase letter are not significantly different according to Fisher's LSD ($\alpha = 0.05$). Means within a row followed by the same uppercase letter are not significantly different using a paired *t* test ($\alpha = 0.05$).

plowing in the autumn of 1994 and low weed densities in corn in 1995 (Table 3). Inversion and mixing of the soil during tillage eliminated the stratification of weed seeds near the soil surface that had developed during the years with little tillage (Staricka et al. 1990; Yenish et al. 1992). The low weed densities in the field (Table 3) resulted in little seed deposition and seed bank decline similar to that observed without seed deposition to the soil (Buhler and Hartzler 2001).

By October of 1996, common waterhemp seed density was again greater in the surface 5 cm than in the other depth segments (Table 4). Common waterhemp seed density in the upper 5 cm was not different from the previous year, whereas seed density declined over the year in the other depth segments. Foxtail species declined to 50 seeds/m^2 or less, and there was little change from the previous year (Table 5). Because of dominance of common waterhemp, relative distribution of total seeds was the same as common waterhemp (Table 6). Weed counts at harvest in 1996 (Table 3) indicated that common waterhemp was the only species present in significant numbers. Given the high seed production capability of common waterhemp (Battles et al. 1998), a low density of escaping plants can significantly increase the seed bank and because there was no tillage following seed deposition, these seeds remained concentrated near the soil surface.

The second year of corn (1997) resulted in no significant changes in the character of the weed seed bank compared with 1996 (Tables 4–6). This was again because of the lack of surviving plants to deposit new seeds to the soil (Table 3).

Common waterhemp seed density increased in all depth segments between 1997 and 1998 (Table 4). The highest density of common waterhemp seeds was found in the upper 5 cm, with seed density decreasing as soil depth increased. Foxtail species densities also increased in all depth segments between 1997 and 1998 (Table 5). Foxtail density was greatest in the surface 5 cm, followed by the 5- to 10-cm segment. The 10- to 15-cm and 15- to 20-cm segments had lower densities than the shallower depths and were similar to each other. The relative vertical distribution of all seeds (Table 6) was the same as the foxtail species.

The vertical distribution of seeds was similar to that observed in systems with little or no tillage (Hoffman et al. 1998; Yenish et al. 1992). However, the increases in seed densities below the surface layer of soil were surprising given that there was no tillage following seed deposition in 1998 (Table 1). Although tillage in the spring of 1998 may have buried some of the seeds that were in the upper soil layer in 1997, these data indicate that there were processes other than tillage that moved weed seeds below the soil surface. The action of rain water, along with soil macropores such as root cavities and earthworm burrows (Harper 1977), soil cracks (Thompson et al. 1993), and earthworms and other soil fauna (Willems and Huijsmans 1994) may have provided natural mechanisms for downward movement of seed. The small seed size of common waterhemp and foxtail species also may have facilitated its penetration into the soil (Thompson et al. 1993). This rapid downward movement of seeds may be very important in the dynamics of weed populations in no-tillage systems, protection of seeds from predators, and maintenance of a seed bank.

The results of this on-farm study are in reasonable agreement with our expectations on weed seed densities in the soil (Buhler 1999a; Buhler et al. 1997a; Fenner 1985) and the effects of tillage on the weed seed bank (Staricka et al. 1990; Yenish et al. 1992). The downward movement of seeds in 1998 was somewhat surprising but seems reasonable given the weed species present in the field and the possible mechanisms of entry into the soil (Harper 1977; Thompson et al. 1993; Willems and Huijsmans 1994). However, the behavior of the weed seed bank during the course of the rotation was surprising. We expected the densities of the summer annual species to increase during the corn and soybean years and decline during oat and hay production (Jordan et al. 1995; Liebman and Ohno 1998). However, the high level of weed control during corn and soybean production resulted in a decline in weed seed numbers followed by a large increase during the year of oat production and hay establishment. It was expected that rotating to oat/hay would create an environment less favorable for the summer annual species because of the different planting and harvesting timings compared with corn and soybean (Liebman and Ohno 1998). However, following removal of the oat in July, common waterhemp and foxtail species grew rapidly and produced mature seeds prior to harvest of the hay in late September. Although the cultural practices in the field were altered, the timing of crop removal allowed these annual weed species to produce seeds and greatly increase the size of the weed seed bank. This shows the importance of resource availability and timing of management practices on weeds, even in the context of a rotation (Jordan et al. 1995). In the case of this experiment, the rotation included summer annual crops and tillage in 4 of 5 yr. Thus, it may be unrealistic to expect a shift away from summer annual species in this cropping system. We concluded that the processes affecting the weed seed bank in production fields are complex and will vary greatly based on the management practices used and the timing of their application. In addition, it may take several years for a change in crop life cycles to change the character of the weed community. The biological properties of the weeds and the timing and effectiveness of management practices will combine to regulate the response of the weed community.

LITERATURE CITED

Ball, D. A. 1992. Weed seedbank response to tillage, herbicides, and crop rotation sequence. Weed Sci. 40:654–659.

Battles, B., B. Hartzler, and D. Buhler. 1998. Effect of common waterhemp emergence date in soybeans on growth and competitiveness. Proc. North Cent. Weed Sci. Soc. 53:145–146.

Buhler, D. D. 1999a. Weed population responses to weed control practices. I. Seed bank, weed populations, and crop yields. Weed Sci. 47:416–422.

Buhler, D. D. 1999b. Weed population responses to weed control practices. II. Residual effects on weed populations, control, and soybean yield. Weed Sci. 47:423–426.

Buhler, D. D. and R. G. Hartzler. 2001. Emergence and persistence of seed of velvetleaf, common waterhemp, woolly cupgrass, and giant foxtail. Weed Sci. In press.

Buhler, D. D. and B. D. Maxwell. 1993. Seed separation and enumeration from soil using K_2CO_3-centrifugation and image analysis. Weed Sci. 41: 298–302.

Buhler, D. D., R. G. Hartzler, and F. Forcella. 1997a. Implications of weed seed bank dynamics to weed management. Weed Sci. 45:329–336.

Buhler, D. D., R. G. Hartzler, F. Forcella, and J. L. Gunsolus. 1997b. Relative Emergence of Weeds of Corn and Soybean. Ames, IA: Iowa State University Extension Publ. SA-11. 4 p.

Burnside, O. C., R. S. Moomaw, F. W. Roeth, G. A. Wicks, and R. G. Wilson. 1986. Weed seed demise in soil in weed-free corn (*Zea mays*) production across Nebraska. Weed Sci. 34:248–251.

Cavers, P. B. 1983. Seed demography. Can. J. Bot. 61:3678–3690.

Derksen, D. A., G. P. Lafond, A. G. Thomas, H. A. Loeppky, and C. J. Swanton. 1993. Impact of agronomic practices on weed communities: tillage systems. Weed Sci. 41:409–417.

Fenner, M. 1985. Seed bank dynamics. *In* Seed Ecology. New York: Chapman Hall. pp. 82–96.

Forcella, F. and M. J. Lindstrom. 1988. Movement and germination of weeds in ridge-till crop production systems. Weed Sci. 36:56–59.

Hager, A. G., L. M. Wax, F. W. Simmons, and E. W. Stoller. 1997. Waterhemp Management in Agronomic Crops. Champaign, IL: University of Illinois Bull. X855. p. 12.

Harmon, G. W. and F. D. Keim. 1934. The percentage and viability of weed seeds recovered in the feces of farm animals and their longevity when buried in manure. J. Am. Soc. Agron. 26:762–767.

Harper, J. L. 1977. The seed bank. *In* Population Biology of Plants. New York: Academic Press. pp. 61–82.

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.

Hoffman, M. L., M.D.K. Owen, and D. D. Buhler. 1998. Effects of crop and weed management on density and vertical distribution of weed seeds in soil. Agron. J. 90:793–799.

Jordan, N., D. A. Mortensen, D. M. Prenzlow, and K. Curtis Cox. 1995. Simulation analysis of crop rotation effects on weed seedbanks. Am. J. Bot. 82:390–398.

Karlen, D. L. and T. S. Colvin. 1992. Alternative farming system effects on profile nitrogen concentration on two Iowa farms. Soil Sci. Soc. Am. J. 56:1249–1256.

Liebman, M. and T. Ohno. 1998. Crop rotation and legume residue effects on weed emergence and growth: applications to management. *In* J. L. Hatfield, D. D. Buhler, and B. A. Stewart, eds. Integrated Weed and Soil Management. Chelsea, MI: Ann Arbor Press. pp. 181–221.

Mortensen, D. A., G. A. Johnson, and L. J. Young. 1993. Weed distribution in agricultural fields. *In* P. C. Robert, R. H. Rust, and W. E. Larson, eds. Soil Specific Crop Management. Madison, WI: American Society of Agronomists. pp. 113–123.

Mt. Pleasant, J. and K. J. Schlather. 1994. Incidence of weed seed in cow (*Bos* sp.) manure and its importance as a weed source for cropland. Weed Technol. 8:304–310.

Rothrock, P. E., E. R. Squiers, and S. Sheeley. 1993. Heterogeneity and size of persistent seedbank of *Ambrosia artemisiifolia* and *Seteria faberi* Herm. Bull. Torrey Bot. Club 120:417–422.

Schreiber, M. M. 1992. Influence of tillage, crop rotation, and weed management on giant foxtail (*Setaria faberi*) population dynamics and corn yield. Weed Sci. 40:645–653.

Schweizer, E. E. and R. L. Zimdahl. 1984. Weed seed decline in irrigated soil after six years of continuous corn (*Zea mays*) and herbicides. Weed Sci. 32:76–83.

Staricka, J. A., P. M. Burford, R. R. Allmaras, and W. W. Nelson. 1990. Tracing the vertical distribution of simulated shattered seeds as related to tillage. Agron. J. 82:1131–1134.

Thomas, A. G. and B. L. Frick. 1993. Influence of tillage systems on weed abundance in southwestern Ontario. Weed Technol. 7:699–705.

Thompson, K., S. R. Band, and J. G. Hodgson. 1993. Seed size and shape predict persistence in soil. Funct. Ecol. 7:236–241.

Wiese, A. F., J. M. Sweeten, B. W. Bean, C. D. Salisbury, and E. W. Chenault. 1998. High temperature composting of cattle feedlot manure kills weed seed. Appl. Eng. Agric. 14:377–380.

Willems, J. H. and K.G.A. Huijsmans. 1994. Vertical seed dispersal by earthworms: a quantitative approach. Ecography 17:124–130.

Wilson, R. G. 1988. Biology of weed seeds in the soil. *In* M. A. Altieri and M. Liebman, eds. Weed Management in Agroecosystems: Ecological Approaches. Boca Raton, FL: CRC Press. pp. 25–39.

Yenish, J. P., J. D. Doll, and D. D. Buhler. 1992. Effects of tillage on vertical distribution and viability of weed seed in soil. Weed Sci. 40:429–433.