Effects of Initial Seed-Bank Density on Weed Seedling Emergence during the Transition to an Organic Feed-Grain Crop Rotation

Author(s): Richard G. Smith, Randa Jabbour, Andrew G. Hulting, Mary E. Barbercheck, and David A. Mortensen
Source: Weed Science, 57(5):533-540.
Published By: Weed Science Society of America
https://doi.org/10.1614/WS-09-031.1
URL: http://www.bioone.org/doi/full/10.1614/WS-09-031.1

Weed Science 2009 57:533–540

Effects of Initial Seed-Bank Density on Weed Seedling Emergence during the Transition to an Organic Feed-Grain Crop Rotation

Richard G. Smith, Randa Jabbour, Andrew G. Hulting, Mary E. Barbercheck, and David A. Mortensen*

The transition period to certified organic production can present a significant weed management challenge for growers. Organic certification requires that prohibited fertilizers and pesticides must not have been used for 36 mo before harvest of the first organic crop. Understanding how organic management practices and initial weed seed-bank densities affect weed population dynamics during the transition period may improve weed management efficacy and adoption of organic practices. We examined how tillage systems (full or reduced) and cover crop species planted during the first transition year (rye or a mixture of timothy and red clover) affect the seedling densities of three common annual weed species, common lambsquarters, velvetleaf, and foxtail spp., during the 3-yr transition period. Weed seeds were applied in a one-time pulse at the beginning of the study at three densities, low, medium, and high (60, 460, and 2,100 seeds m^{-2}, respectively), and cumulative seedling densities of each species were assessed annually. Treatment factors had variable and species-specific effects on weed seedling densities. In general, the full-tillage system, with an initial cover crop of timothy and red clover, resulted in the lowest density of weed seedlings following seed-bank augmentation. There was little consistent association between the initial densities of applied weed seeds in the weed seed bank at the start of the transition and weed seedling densities at the end of the transition period. This suggests that when multiple crop and weed cultural management practices are employed during the organic transition period, initial failures in weed management may not necessarily lead to persistent and intractable annual weed species management problems following organic certification.

Nomenclature: Common lambsquarters, *Chenopodium album* L. CHEAL; giant foxtail, *Setaria faberi* Herrm. SETFA; velvetleaf, *Abutilon theophrasti* Medik. ABUTH; yellow foxtail, *Setaria glauca* (L.) Beauv. SETLU; red clover, *Trifolium pretense* L.; rye, *Secale cereal* L.; timothy, *Phleum pratense* L.

Key words: Cover crops, pulse-chase, seed bank, tillage.

The number of cropland acres certified organic in the United States has increased from 850,173 acres in 1997 to 1,723,271 acres in 2005 (USDA ERS 2008). For cropland managed conventionally to become certified organic, growers can not use any prohibited practices or materials, including synthetic fertilizers and pesticides, for 36 mo preceding certification. This 3-yr transition period can present a significant weed management challenge. Growers considering the transition to an organic system report that potential problems with weed management are a significant concern affecting their decision to transition from conventional practices (Barberi 2002; Bond and Grundy 2001; Ngouajio and McGiffen 2002; Walz 1999). Problems with weed management during the transition period are often a result of a high density of weeds present following conventional management and a lack of experience with nonchemical weed management techniques (Martini et al. 2004).

There have been few studies explicitly designed to quantify the response of weed populations during the transition period or the role that different transition strategies may play in mediating future weed management challenges following organic certification (Maxwell et al. 2007). Previous research on weed population dynamics in organic transition systems has produced various results, showing that weed populations can increase (Archer et al. 2007; Riemens et al. 2007) or decrease (Liebman and Davis 2000; Ngouajio and McGiffen 2002) following conversion to organic management. These inconsistencies suggest that it may be difficult to generalize regarding how weed populations are likely to respond to a shift from conventional to organic weed management strategies.

Are there general weed management principles that might guide grower management decisions during the transition period? An important principle underlying weed ecology and long-term weed management is that weed seed banks maintain emergent populations, and therefore, seed banks must be managed at low densities to reduce the potential for a buildup of intractably high weed populations (Gallandt 2006; Jones and Medd 2000; Norris 1999; Swanton and Booth 2004). This principle suggests that fields with low weed seed-bank densities at the start of the transition period should be better candidates for transition than fields with high initial weed seed-bank densities. Consequently, growers are often advised to begin the transition in fields that meet this criteria and are further encouraged to reduce the soil weed seed-bank density in fields that do not by using conventional weed management practices before initiating the transition (Menalled et al. 2009). However, the influence of seed-bank density on weed population dynamics is not well understood (Swanton and Booth 2004), and there have been few studies designed specifically to examine the dynamics of pest populations during this transition period. Maxwell et al. (2007) examined the response of wild oat (*Avena fatua* L.) seed banks to experimental seed additions in eight organically managed, small-grain cropping systems in Montana and found that although augmentation of the seed bank resulted in increased wild oat soil seed densities in the following two growing seasons, no residual effects were apparent in subsequent growing seasons in any of the management systems. However, because the study focused only on changes occurring within the seed bank (i.e., assessed seed densities), the importance of different organic management strategies in driving the dynamics of emergent weed populations during the transition period remains unknown.

DOI: 10.1614/WS-09-031.1

* First, third, and fifth authors: Department of Crop and Soil Sciences, The Pennsylvania State University, University Park, PA 16802; second and fourth authors: Department of Entomology, The Pennsylvania State University, University Park, PA 16802. Current address of second author: Department of Entomology, Washington State University, Pullman, WA 99164. Current address of third author: Department of Crop and Soil Science, Oregon State University, Corvallis, OR 97331. Corresponding author's E-mail: rgs14@psu.edu

There are no specific management strategies designed to maximize the success of the transition phase; however, mechanical weed management, crop rotation, and use of cover crops are important components of organic management systems that could be integrated with one another to increase the potential for weed suppression during the transition period (Barberi 2002; Bond and Grundy 2001; Liebman and Gallandt 1997). Mechanical management is often the primary weed management method in organic systems (Bond and Grundy 2001). However, intensive soil disturbance in agricultural systems can decrease soil organic matter and reduce soil quality (Franzluebbers et al. 1999; Reeves 2004), and there is increasing interest among organic growers in reducing the need for tillage (Peigné et al. 2007). Cover crops can improve soil quality (Dabney et al. 2001), and when planted at the beginning of the transition phase, may provide essential soil-building properties and improve weed suppression (Barberi 2002; Martini et al. 2004); however, soil quality effects and ability of cover crops to suppress weed species varies among cover crop species (Melander et al. 2005; Snapp et al. 2005). If initial weed seed-bank density is an important determinant of future weed management challenges in organic systems, then management practices that are effective in both ameliorating the effects of initially high seed-bank densities during the transition phase and improving soil quality during the short-term may allow more growers to successfully transition.

Despite the increasing acreage being transitioned to organic production, few recommendations exist for managing weeds during the transition period. The objectives of this study were (1) to assess how weed seed-bank density and organic management systems aimed at improving soil quality and weed management affect the seedling densities of three common summer annual weed species during the transitional period, and (2) to determine how the initial density of the weed seed bank might affect weed populations at the start of certified organic production.

Materials and Methods

Site Description. The field experiment was conducted at the Russell E. Larson Agricultural Research Center near Rock Springs, PA (40°43′N, 77°55′W, 350 m elevation). The climate of central Pennsylvania is continental, with 975 mm of mean annual precipitation and mean monthly temperatures ranging from 3 C (January) to 21.6 C (July). Soils at the site are shallow, well drained, lithic Hapludalfs, formed from limestone residuum (Braker 1981). The dominant soil type at this location is a Hagerstown silt loam (fine, mixed, semiactive, mesic, Typic Hapludalf). Soil texture in our experimental field was predominantly clay loam with spatial variability in silt (range, 39.9 to 54.7%) and sand (range, 14.0 to 27.0%) content across the field. Previous to the establishment of the current study, the site had been in a conventional tomato (*Solanum lycopersicum* L) and wheat (*Triticum aestivum* L.) crop rotation; tomato had been planted at the site the year before the initiation of the transition treatments.

Agronomic Treatments. The field experiment was established twice, first in the fall of 2003, and again in fall of 2004 in an adjacent field (the two experiments are hereafter referred to as S1 and S2), in a split-split plot, randomized complete-block design, with four replications per treatment. The approximate total combined area of the field experiment was 4 ha and was surrounded by a minimum of 7 m of routinely mown, grassy border on all sides. To ensure relevance to organic feed-grain cropping systems typical of the mid-Atlantic region, we relied on a farmer advisory board composed of local growers to guide the crop sequence and management decisions throughout the experiment. The 3-yr crop sequence in the experiment consisted of a cover crop in the first year, followed by soybean [*Glycine max* (L.) Merr], and finally, by maize. All management practices followed U.S. Department of Agriculture National Organic Program guidelines (www.ams.usda.gov/NOP).

The main plot treatment was tillage system, and included full tillage (FT, moldboard plow based) and reduced tillage (RT, chisel plow and field cultivator based). Subplot treatments were perennial forage and cereal grain cover crops planted in the first year of the 3-yr rotation. The perennial forage and cereal grain cover crops were chosen because they are crops potentially capable of providing the benefits of traditional cover crops (e.g., improved soil quality, erosion control, weed suppression), as well as immediate financial returns during the economically challenging transition period. The cover-crop treatments were initiated in fall 2003 in S1 and managed through the spring and summer of 2004 (Table 1). Each subplot was 0.067 ha in size (24 m by 27 m). The two cover crop treatments were rye, managed for grain and straw production, followed by hairy vetch (*Vicia villosa* Roth), hereafter called *rye*, and a mixture of timothy and red clover, hereafter called *timothy*, managed for sod and forage production. The timothy was established with an oat (*Avena sativa* L.) nurse crop that suffered winter-kill and oat was subsequently replanted in the spring of 2004. Cover crops in S1 and S2 were managed in a similar fashion, but treatments were offset in time by 1 yr in S2, relative to S1 (Table 1). S2 was managed with timothy, oat, and red clover cover crops for the year before start of the second experiment.

Tillage differences between the FT and RT treatments in S1 first occurred following the rye harvest in September 2004 (Table 1). Hairy vetch served as a winter cover crop in the rye treatment. In the spring, the vetch was killed either by moldboard plow (FT treatment) or by mechanical roller-crimper (RT treatment). The timothy/clover treatment was tilled in the spring, before planting soybean. Through the remainder of the experiment, primary tillage in the FT system was accomplished with a moldboard plow, in contrast to a chisel plow used in the RT system. Feed-grade soybean (late group III maturity, 'Pioneer 93B87') was planted in all cover crop/tillage treatments in 2005 at a row spacing of 76 cm. In 2006, maize (*Zea mays* L., 'Pioneer 36B08') was planted at a row spacing of 76 cm. Rotary hoe and cultivator use was the same in both tillage treatments. These implements were typically set to disturb the soil to a depth of 2 to 6 cm (rotary hoe) and 7 to 10 cm (cultivator).

In general, the same management practices implemented in S1 were implemented 1 yr later in S2 (Table 1); however, there were several minor deviations. When the experiment began in S2, in fall 2004, plots to be planted to rye were moldboard plowed and planted. Plots receiving the timothy/clover treatment were mowed, but not plowed. Also, an additional cultivation occurred in maize in S2 in the RT system to improve perennial weed control.

Table 1. Schedule of tillage, planting, and harvest operations for each treatment.[a] Dates for specific operations correspond to the first start of the experiment (S1). Operations conducted in the second start (S2) were identical; however, the timing of each S2 operation was offset from S1 by 1 yr.

			Treatment			
Year	Month	Operation	FT-Rye	RT-Rye	FT-Tim	RT-Tim
2003	October	Planted rye	X	X		
	October	Planted timothy and oats			X	X
2004	March	Added weed seeds to sub-subplots (S1)	X	X	X	X
	April	Planted red clover			X	X
	August	Moldboard plowed	X			
	August	Chisel plowed		X		
	October	Planted hairy vetch	X	X		
	November	Added weed seeds to sub-subplots (S2)	X	X	X	X
2005	May	Rotary hoed vetch	X			
	May	Moldboard plowed	X		X	
	May	Chisel plowed				X
	May	Disked	X		X	X
	June	Disked and cultimulched	X		X	X
	June	Rolled vetch		X		
	June	Planted soybean	X		X	X
	June	Planted soybean		X		
	June	Rotary hoed	X		X	X
	July	S-tined			X	X
	July	Replanted soybean			X	X
	July	Cultivated	X	X	X	X
	October	Harvested soybean	X	X	X	X
2006	April	Disked	X	X	X	X
	April	Moldboard plowed	X		X	
	April	Disked		X		X
	April	Disked	X	X	X	X
	May	S-tined	X	X	X	X
	May	Planted corn	X	X	X	X
	May	Rotary hoed	X	X	X	X
	May	Rotary hoed	X	X	X	X
	June	Cultivated	X	X	X	X
	December	Harvested corn	X	X	X	X

[a] Abbreviations: FT-Rye, full tillage with a rye cover crop; RT-Rye, reduced tillage with a rye cover crop; FT-Tim, full tillage with a timothy cover crop; RT-Tim, reduced tillage with a timothy cover crop.

Seed-Bank Densities. We established three weed seed-bank density treatments (sub-subplot treatment) to determine the effect of initial weed seed-bank density and cover crop and tillage treatment on the seedling densities of three common weed species during the 3-yr transition period. The three weed species were common lambsquarters, velvetleaf, and a mix of giant and yellow foxtail, hereafter *foxtail*. Weed seed pools containing a mixture of the three species were added to permanently marked individual 2-m^2 sub-subplots within each cover crop subplot at three densities: low (60 seeds m^{-2}), medium (450 seeds m^{-2}), and high (2,100 seeds m^{-2}). Weed seeds were collected from local weed populations within a 2-km radius of the study site. Seed pools were added to the plots on March 24, 2004 (S1), and November 16, 2004 (S2). Logistical constraints prevented us from applying the seed pools in the fall of 2003 in S1, as originally planned. Weed seed densities were selected to represent the range in naturally occurring seed densities found in the northeast (Cavers and Benoit 1989). The weed seeds were mixed with 250 g of sand and applied by hand to the soil that had been disturbed with a rake to ensure even distribution of the weed seed within the subplot. The location of the subplots was permanently marked. We quantified cumulative weed seedling densities nondestructively in both the augmented weed sub-subplots and within the larger subplots (to determine background weed seedling densities) before and after management disturbances. Emerged seedlings were quantified throughout each growing season in 0.25-m^2 quadrats. Seedlings were not marked or removed after counting; however, because we counted seedlings immediately before and after each management disturbance, we were able to accurately distinguish between different seedling cohorts. Background (ambient) densities of seedlings of the three weed species were assessed in each subplot from five quadrats placed randomly but outside of the density sub-subplots; these were used to correct seedling density estimates from the sub-subplots to which seeds were added. In general, background seedling densities of common lambsquarter and velvetleaf were low; mean seedling densities in the first year of S1 and S2 were 18.7 and 5.2 seedlings m^{-2}, and 0.7 and 0.0 seedlings m^{-2}, respectively. Mean background densities of foxtail in the first year of S1 and S2 were 201.9 and 0.0 seedlings m^{-2}, respectively.

Statistical Analyses. We used a repeated-measures, split-plot, mixed model (PROC MIXED, SAS)[1] to determine how tillage intensity (main plot), initial cover crop (subplot), weed density (sub-subplot), and rotation phase affected the numbers of foxtail, velvetleaf, and common lambsquarters present in the sub-subplots. Because of a significant effect of *start*, data from S1 and S2 were analyzed separately. Experimental block was included as a random factor. All predictors were classified as categorical variables. The response variables (cumulative weed seedling densities) were log-transformed and corrected for background seedling densities. We used an autoregressive covariance matrix to account for sampling in the same density sub-subplots repeatedly

Table 2. Results of mixed-model ANOVA of the effects of tillage system, cover crop, weed seed pool density, and rotation phase on the density of seedlings of three common annual weed species.[a]

Factor	Common lambsquarters		Velvetleaf		Foxtail spp.	
	S1	S2	S1	S2	S1	S2
T	NS	NS	NS	NS	NS	NS
CC	NS	NS	**	NS	*	**
T × CC	NS	NS	NS	*	NS	NS
D	NS	**	****	**	*	****
T × D	NS	NS	NS	NS	NS	*
CC × D	NS	NS	NS	NS	NS	NS
T × CC × D	NS	NS	NS	NS	NS	NS
RP	**	****	****	****	NS	**
RP × T	**	NS	NS	NS	*	*
RP × CC	****	**	***	NS	***	**
RP × T × CC	NS	*	NS	NS	NS	NS
RP × D	NS	**	****	NS	*	NS
RP × T × D	NS	NS	NS	NS	***	NS
RP × CC × D	NS	NS	*	NS	NS	NS
RP × T × CC × D	NS	NS	NS	NS	*	NS

[a] Abbreviations: T, tillage; NS, not significant at the < 0.05 probability level; S1, field experiment established in the fall of 2003; S2, field experiment established in fall of 2004 in an adjacent field; CC, cover crop; D, density; RP, rotation phase.

* Significant at the 0.05 probability level.

** Significant at the 0.01 probability level.

*** Significant at the 0.001 probability level.

**** Significant at the 0.0001 probability level.

throughout the experiment (Littell et al. 1998). To determine whether the density treatments resulted in increased seedling abundance at the end of the 3-yr transition, single-sample *t* tests were used to determine whether populations were significantly greater ($P < 0.05$) than ambient populations for each of the three density levels in 2006 (S1) and 2007 (S2) in each of the four cover crop-tillage system treatment combinations. The *t* tests were conducted in SYSTAT.[2]

Results and Discussion

Organic Transition Treatment Effects on Cumulative Annual Seedling Recruitment. Each of the three weed species differed in their response to the four management systems (two tillage systems and two initial cover-crop treatments) (Table 2). In general, seedling densities of common lambsquarters were highly variable during the 3-yr study period (Figure 1) and were affected by seed-bank augmentation in S2 only ($F_{2,36} = 6.48$, $P = 0.004$). Rotation phase and an interaction between rotation phase and cover-crop treatment in both experimental starts (interaction: S1, $F_{2,67} = 12.33$, $P < 0.0001$; S2, $F_{2,64} = 5.19$, $P = 0.008$) affected common lambsquarters seedling densities and resulted in an increase from year 1 to 2 in seedling densities in the rye cover-crop systems in S1 and in the timothy cover-crop systems in S2. Interactions between rotation phase and other treatment factors had differential effects on common lambsquarters seedling densities depending on the experimental start (S1 or S2, Table 2).

Velvetleaf seedling densities in each of the four management systems also varied during the study period; however seedling population dynamics were more consistent among management systems and within experimental starts compared with common lambsquarters (Figures 1 and 2). Augmentation of the velvetleaf seed bank and rotation phase affected velvetleaf seedling densities during the study period in both S1 (density: $F_{2,25} = 22.39$, $P < 0.0001$; rotation: $F_{2,63} = 56.35$, $P < 0.0001$) and S2 (density: $F_{2,31} = 6.63$, $P = 0.004$; rotation: $F_{2,77} = 63.9$, $P < 0.0001$). The impact of other experimental factors varied between S1 and S2. In S1, seed-bank augmentation resulted in greater seedling densities in 2004, particularly at the highest augmentation level and in the two tillage treatments with the rye cover crop treatment (3-way interaction: $F_{4,66} = 2.53$, $P = 0.049$). Despite the enhancement of velvetleaf seedling densities due to augmentation in 2004, densities in all treatments declined to ambient levels by 2006. Similar to S1, augmentation of the velvetleaf seed bank in S2 resulted in higher seedling densities, particularly at the highest augmentation level; however, this was particularly apparent in the second season following augmentation (soybean phase) in the FT-rye and RT-timothy treatments (tillage × cover crop interaction, $F_{1,5} = 7.11$, $P = 0.042$). Also similar to observations in S1, velvetleaf seedling densities in S2 returned to ambient levels by 2007, despite initial seed-bank augmentation in the fall of 2004.

Foxtail responded most consistently to the tillage and cover-crop management systems (Table 2). Foxtail seedling densities in S1 and S2 were affected by both augmentation (density: S1, $F_{2,28} = 3.40$, $P = 0.048$; S2, $F_{2,34} = 12.59$, $P < 0.0001$) and cover-crop treatments (S1, $F_{1,6} = 8.00$, $P = 0.029$; S2, $F_{1,6} = 22.03$, $P = 0.003$), and by the interactions between rotation phase and tillage (S1: $F_{2,66} = 3.28$, $P = 0.44$; S2: $F_{2,69} = 3.29$, $P = 0.043$) and rotation phase and cover crops (S1: $F_{2,66} = 8.84$, $P = 0.0004$; S2: $F_{2,69} = 5.23$, $P = 0.008$). In general, augmentation of the seed bank resulted in higher cumulative foxtail seedling densities in the rye compared with the timothy cover crop (Figure 3). The effect of other treatment factors differed between S1 and S2.

The variability in weed seedling densities from year to year and between the two starts (S1 and S2) was striking and may have been due to year-to-year environmental variation, coupled with seeds being added in different seasons in starts 1 (spring) and 2 (fall). Previous research has shown that factors such as postdispersal weed seed predation, which can affect seed survival and germination, can vary with season (O'Rourke et al. 2006). Total precipitation during April and May was higher in 2004 than 2005 (Figure 4). Soil moisture

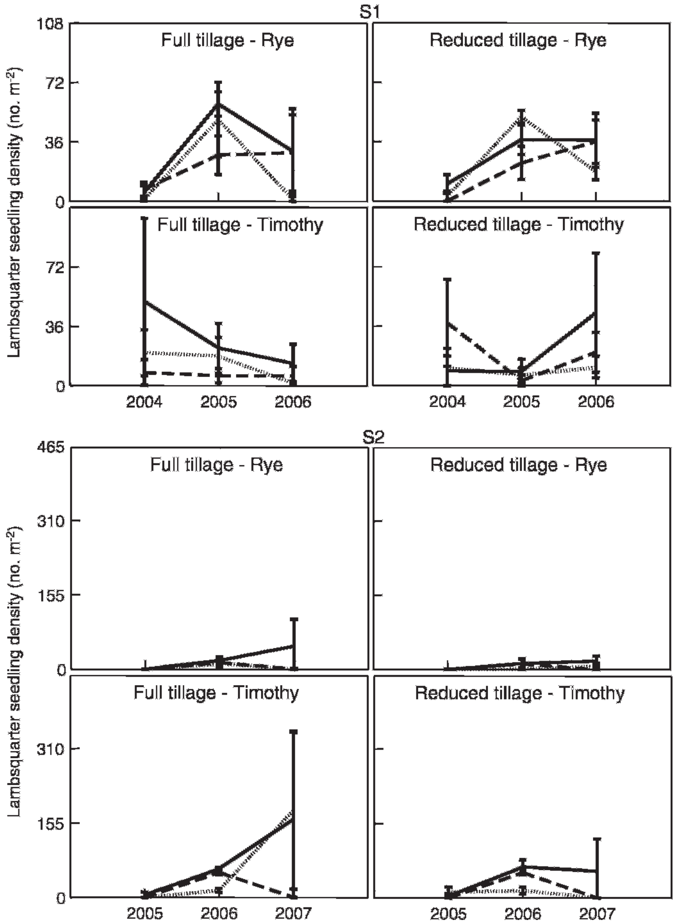

Figure 1. Emergence of common lambsquarters (*Chenopodium album*) during 3 yr following a one-time seed addition in spring (S1) or fall (S2) 2004. Seeds were added at three densities, high (solid line), medium (broken line), and low (dotted line). Data are means ± SE; $n = 4$.

can influence weed seed germination (Roman et al. 1999; Weaver et al. 1988) and may have resulted in higher germination rates in the first rotation phase of the study in S1 compared with S2, and this could have affected seedling densities in subsequent phases of the rotation. Because all phases of the rotation were not present each year, we cannot separate individual crop effects from other sources of environmental variation. Despite this constraint, however, it is reasonable to assume that individual crop rotation phases in some years exerted strong influences on weed seedling densities in this experiment, as has been observed in other studies (Buhler et al. 2001; Smith and Gross 2006; Teasdale et al. 2004). Changes in management from one crop to another in a rotation can result in rapid shifts in the composition and abundance of the germinable fraction of the weed seed bank from year to year (Smith and Gross 2006). Buhler et al. (2001) observed substantial variation in weed seed-bank densities across individual phases of a 5-yr rotation in Iowa resulting in twofold to 33-fold differences in foxtail seed-bank abundance between years.

Reduction of soil disturbance often results in increases in the density of weeds, particularly perennial weeds, in systems managed without herbicides (Barberi 2002). That reduced tillage did not result in substantially greater summer annual seedling densities in this study was surprising. O'Donovan and McAndrew (2000) found that densities of common lambsquarters and green foxtail [*Setaria viridis* (L.) Beauv] in a system managed with herbicides were lower in no-tillage compared with conventional-tillage, and they attributed this, in part, to greater levels of surface residue and lower soil surface temperatures in the no-tillage system (Gauer et al. 1982; Hayhoe et al. 1993). None of the three weed species in this study were perennials, which may have contributed to the lack of response to the tillage treatments (Barberi 2002). Changes in soil residue associated with the reduction in tillage levels may also have contributed to higher rates of weed seed loss from seed predators or other sources of mortality in the RT compared with the FT (Li and Kremer 2000; Ngouajio and McGiffen 2002). Lundgren et al. (2006) reported that seed predator abundances and seed removal rates were higher in organic transition systems that had reduced levels of tillage and management compared with systems with higher tillage intensities.

Effects of Seed-Bank Augmentation on Weed Seedling Densities at the End of the Transition. A primary objective of this study was to determine how the density of the weed seed bank at the beginning of the transition period would affect the potential for successful management once the transition period ended and systems were certified organic. We used a single-sample t test to assess whether we could detect an enhancement of the weed seedling population in the last year of the study because of the initial pulse of seeds that was added 3 yr prior, at the beginning of the study. That is, we examined whether seedling densities in the augmented subplots in final year of the study were significantly different from background (ambient) levels given initial differences in seed-bank densities. The results of the analysis indicated that the effects of initial weed seed-bank density on the abundance of weeds present at the end of the transition period depended upon the weed species and the specific crop management practices that were employed during that period (Table 3). Augmentation of the common lambsquarters seed bank resulted in seedling densities that were significantly greater than ambient densities in the RT rye system (S1 and S2) and, in one case, in the RT timothy system (medium pulse, S1). Augmentation of the velvetleaf seed bank did not result in any enhancement of velvetleaf seedling densities in the final transition year in any of the treatments or start years (S1 or S2). Effects of seed-bank augmentation on foxtail seedling densities in the final transition year were variable and depended on start (S1 or S2). Seed-bank augmentation resulted in enhanced foxtail seedling densities in the RT timothy system (S1 only) and the FT and RT rye systems (S2 only; Table 3).

These results have at least two important implications for growers considering transitioning to organic crop production. First, some organic transition management systems are more consistently weed-suppressive than others are. The full-tillage system with a timothy/clover cover crop planted at the beginning of the transition period was the only system that consistently dampened initial differences in weed seedling densities in this experiment (all densities not significantly different from zero; Table 3). Moldboard plow tillage may have contributed to this observation because it results in burial and redistribution of emerged weeds, weed seeds, and crop residues and has been shown to lead to reduced emerged weed populations relative to less-intensive forms of tillage (Buhler 1995; Buhler and Daniel 1988; Clements et al. 1996; Mohler 1993). The consistency of this system in terms of ameliorating

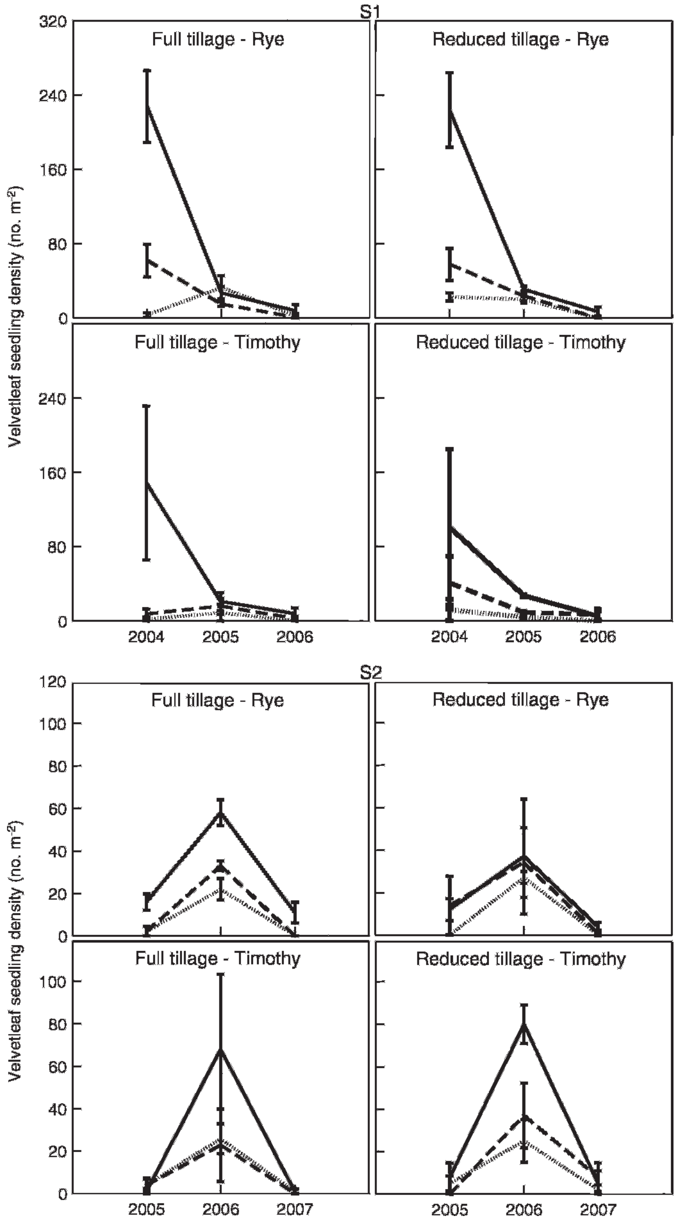

Figure 2. Emergence of velvetleaf (*Abutilon theophrasti*) during 3 yr following a one-time seed addition in spring (S1) or fall (S2) 2004. Seeds were added at three densities, high (solid line), medium (broken line), and low (dotted line). Data are means ± SE; n = 4.

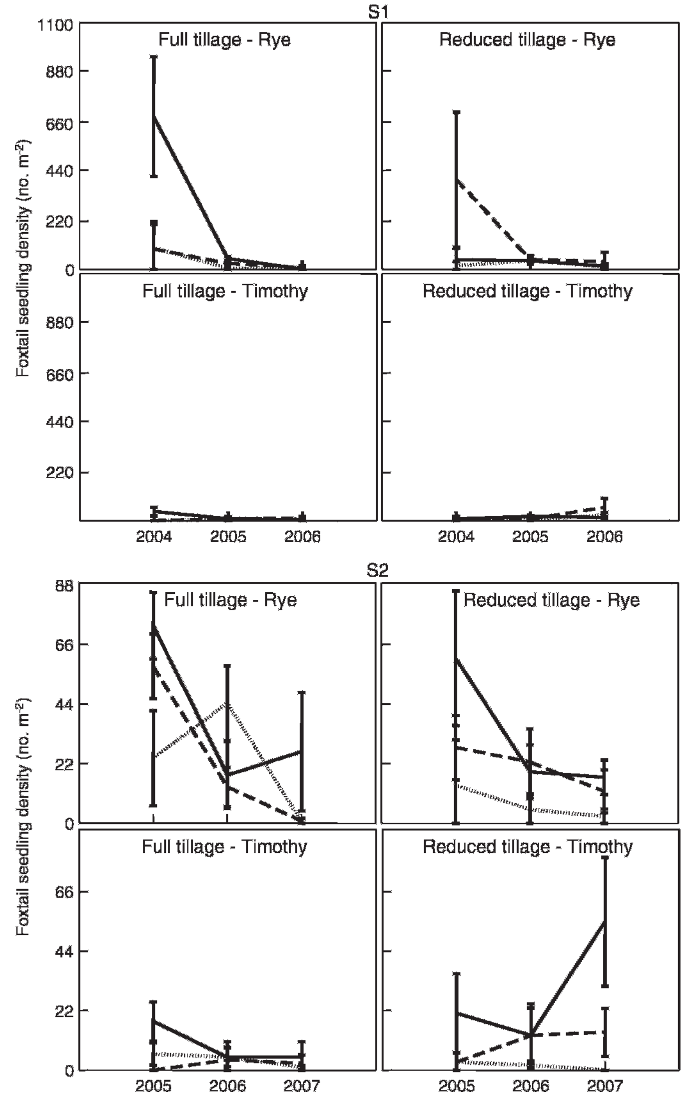

Figure 3. Emergence of foxtail spp. (*Setaria faberi* and *S. glauca*) during 3 yr following a one-time seed addition in spring (S1) or fall (S2) 2004. Seeds were added at three densities, high (solid line), medium (broken line), and low (dotted line). Data are means ± SE; n = 4.

initially high density weed populations may also have been due to weed suppression through direct competition from the timothy and red clover cover crop or interactions between tillage, cover crops, and other biologically based sources of weed mortality (Teasdale et al. 2005). In addition to direct suppression of weeds, the red clover grown with the timothy is known to be allelopathic to a wide range of weed species, including those examined in this study (Davis and Liebman 2003; Liebman and Sundberg 2006). These data suggest that growers in the mid-Atlantic region, who are considering transitioning fields with high initial weed densities to organic feed-grain production, may realize different probabilities of success depending on the particular transition strategy they employ, and that a full-tillage strategy that uses timothy/clover cover crops may be successful. However, there may be potential trade-offs associated with reduced soil quality with this system because of the relatively high intensity of tillage (Franzluebbers et al. 1999; Reeves 2004). Effects of the four management systems on select soil quality parameters in this study are reported in Jabbour (2009).

The second implication of these data for growers considering transitioning to organic production is related to the observation that there was little consistent association between the initial density of seeds of these three commonly occurring annual weeds added to the soil seed bank at the start of the transition and the seedling densities of these three species at the end of the transition period. Although the seed-bank manipulations conducted in this study may not necessarily be representative of the seed banks occurring on real farms, they may reasonably approximate a situation where a grower has initially low seed-bank densities but then experiences a sudden, new input of weed seeds because of a season of poor weed control, such as could occur during the initial year of the transition period. These results are similar to those of Maxwell et al. (2007) who found few residual effects

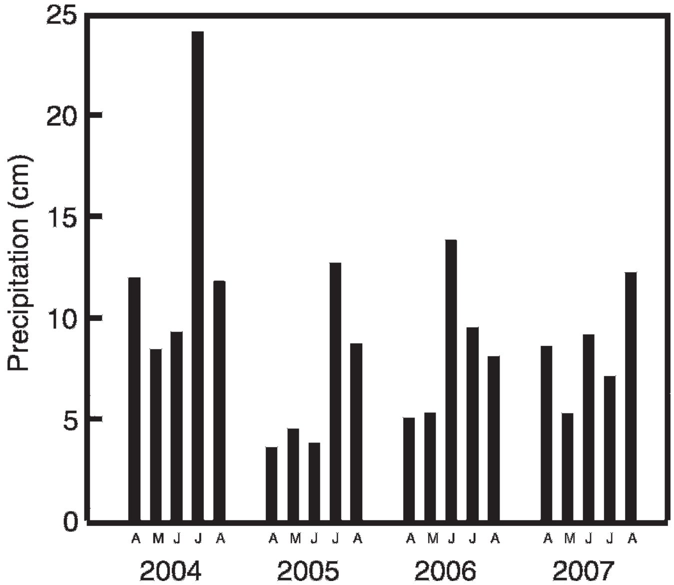

Figure 4. Monthly precipitation during the growing season (April through August) from 2004 to 2007 at the Russell E. Larson Agricultural Research Center near Rock Springs, PA.

of a one-time pulse of wild oat seeds to the soil seed bank at the beginning of the organic transition period in small-grain cropping systems in the Northern Great Plains. Although we observed short-term (i.e., 1 to 2 yr) responses of weed seedling densities to the experimental management systems that appeared to be fairly species specific (Figures 1–3), all three species showed similar longer-term (i.e., 3 yr) responses that were largely independent of management systems. Initially, elevated densities of these three species returned to ambient densities (Table 3). It is possible that skilled management contributed to reduced weed population densities or prevented weed seed return to the soil across all management treatments, despite the initial pulse of weed seeds (Martini et al. 2004; Riemens et al. 2007). Weed seeds that we added to the plots may also have been dispersed via the movement of farm equipment during the tillage and planting operations (Davis and Luschei 2009). Although we cannot discount either of these explanations, it is important to note that weed management intensity was constant across all subplots differing in weed seed densities in this study. Therefore, the reductions in seedling density that occurred at all augmentation levels during the 3-yr study period were not due to select treatments being managed for weeds more aggressively than others because all plots were managed consistently, regardless of the observed weed pressure.

That individual weed species respond differently to management is well known (Booth and Swanton 2002; Cardina et al. 2002; Shrestha et al. 2002), and short-term observations may not provide a realistic indication of longer-term weed management success under a given management system (Firbank 1993; Smith and Gross 2006). Also, this study examined the effect of a single seed addition, which may not represent the behavior of a typical weed seed bank, which would include seeds of different ages and dormancy status mixed in soil over time. Thus, responses observed in this study should be interpreted with an element of caution. However, if these data are representative of typical organic transition systems, then initial failures in weed management (and subsequent weed seed return to the soil)—such as those that may occur early in the transition period to organic production—may not necessarily doom growers to persistent and intractable weed management problems (Maxwell et al. 2007). Additional research aimed at assessing the generality of these results will be necessary to determine how weed management challenges occurring during the transition period to organic production can be further minimized to encourage greater adoption of reduced-input cropping systems.

Sources of Materials

[1] SAS, Version 9.1, SAS Institute Inc., Cary, NC 27513.

[2] SYSTAT software, Version 8.0, Systat Software Inc., San Jose, CA 95110.

Table 3. Significance of *t* tests to assess whether seedling densities in the third year of the study in the first (2006) and second (2007) start were significantly different from ambient densities. Single-sample *t* test, $df = 3$.[a,b]

	S1 (2006)				S2 (2007)			
Seed density	FT-Rye[2]	RT-Rye	FT-Tim	RT-Tim	FT-Rye	RT-Rye	FT-Tim	RT-Tim
Lambsquarters								
Low	NS	**	NS	NS	NS	NS	NS	NS
Medium	NS	**	NS	*	NS	NS	NS	NS
High	NS	*	NS	NS	NS	*	NS	NS
Velvetleaf								
Low	NS	NS	NS	NS	NS	NS	NS	NS
Medium	NS	NS	NS	NS	NS	NS	NS	NS
High	NS	NS	NS	NS	NS	NS	NS	NS
Foxtail								
Low	NS	NS	NS	*	NS	NS	NS	NS
Medium	NS	NS	NS	*	NS	NS	NS	NS
High	NS	NS	NS	NS	*	**	NS	NS

[a] Seed additions were made in March (S1) and November (S2) 2004.
[b] Abbreviations: FT-Rye, full tillage with cereal rye cover crop; RT-Rye, reduced tillage with cereal rye cover crop; FT-Tim, full tillage with timothy cover crop; RT-Tim, reduced tillage with timothy cover crop; NS, not significant at the < 0.05 probability level.
* Significant at the 0.05 probability level.
** Significant at the 0.01 probability level.

Acknowledgments

We are grateful for the technical assistance provided by S. Harkcom, D. Heggenstaller, V. Houck, B. Jones, S. Kinneer, C. Mullen, C. Nardozzo, D. Sandy, and S. Smiles. We would also like to acknowledge the invaluable advice provided by our advisory board: C. Altemose, L. Garling, J. Moyer, B. Snyder, K. Yoder, P. Yoder, A. Ziegler, and L. Zuck. We thank the associate editor and two anonymous reviewers who provided helpful comments on a previous draft of this manuscript. Funding for this research was provided by the U.S. Department of Agriculture Initiative for Renewable Energy and the Environment (USDA–IREE) Competitive Grants Program IPM-ORG-112.E.

Literature Cited

Archer, D. W., A. A. Jaradat, J.M.F. Johnson, S. L. Weyers, R. W. Gesch, F. Forcella, and H. K. Kludze. 2007. Crop productivity and economics during the transition to alternative cropping systems. Agron. J. 99:1538–1547.

Barberi, P. 2002. Weed management in organic agriculture: are we addressing the right issues? Weed Res. 42:177–193.

Bond, W. and A. C. Grundy. 2001. Non-chemical weed management in organic farming systems. Weed Res. 41:383–405.

Booth, B. D. and C. J. Swanton. 2002. Assembly theory applied to weed communities. Weed Sci. 50:2–13.

Braker, W. L. 1981. Soil Survey of Centre County, Pennsylvania. Washington, DC: U.S. Department of Agriculture–Soil Conservation Service. 162 p.

Buhler, D. D. 1995. Influence of tillage systems on weed population-dynamics and management in corn and soybean in the central USA. Crop Sci. 35:1247–1258.

Buhler, D. D. and T. C. Daniel. 1988. Influence of tillage systems on giant foxtail, *Setaria faberi*, and velvetleaf, *Abutilon theophrasti*, density and control in corn, *Zea mays*. Weed Sci. 36:642–647.

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

Cardina, J., C. P. Herms, and D. J. Doohan. 2002. Crop rotation and tillage system effects on weed seedbanks. Weed Sci. 50:448–460.

Cavers, P. B. and D. L. Benoit. 1989. Seed banks in arable land. Pages 309–328 *in* M. A. Leck, V. T. Parker, and R. L. Simpson, eds. Ecology of Soil Seed Banks. San Diego: Academic.

Clements, D. R., D. L. Benoit, S. D. Murphy, and C. J. Swanton. 1996. Tillage effects on weed seed return and seedbank composition. Weed Sci. 44:314–322.

Dabney, S. M., J. A. Delgado, and D. W. Reeves. 2001. Using winter cover crops to improve soil and water quality. Commun. Soil. Sci. Plant Anal. 32:1221–1250.

Davis, A. S. and E. C. Luschei. 2009. Living boundaries: tracking weed seed movement with nondormant seed. Weed Sci. 57:163–168.

Davis, A. S. and M. Liebman. 2003. Cropping system effects on giant foxtail (*Setaria faberi*) demography, I: green manure and tillage timing. Weed Sci. 51:919–929.

Firbank, L. G. 1993. Short-term variability of plant-populations within a regularly disturbed habitat. Oecologia 94:351–355.

Franzluebbers, A. J., G. W. Langdale, and H. H. Schomberg. 1999. Soil carbon, nitrogen, and aggregation in response to type and frequency of tillage. Soil Sci. Soc. Am. J. 63:349–355.

Gallandt, E. R. 2006. How can we target the weed seedbank? Weed Sci. 54:588–596.

Gauer, E., C. F. Shaykewich, and E. H. Stobbe. 1982. Soil–temperature and soil–water under zero tillage in Manitoba. Can J. Soil Sci. 62:311–325.

Hayhoe, H. N., L. M. Dwyer, D. Balchin, and J.L.B. Culley. 1993. Tillage effects on corn emergence rates. Soil Tillage Res. 26:45–53.

Jabbour, R. 2009. Management Effects on Epigeal Arthropods and Soil-Dwelling Communities during the Transition to Organic Agriculture. Ph.D dissertation. University Park, PA: The Pennsylvania State University. 175 p.

Jones, R. E. and R. W. Medd. 2000. Economic thresholds and the case for longer term approaches to population management of weeds. Weed Technol. 14:337–350.

Li, J. M. and R. J. Kremer. 2002. Rhizobacteria associated with weed seedlings in different cropping systems. Weed Sci. 48:734–741.

Liebman, M. and A. S. Davis. 2000. Integration of soil, crop and weed management in low-external-input farming systems. Weed Res. 40:27–47.

Liebman, M. and E. R. Gallandt. 1997. Many little hammers: ecological management of crop–weed interactions. Pages 291–343 *in* L. E. Jackson, ed. Ecology in Agriculture. San Diego: Academic.

Liebman, M. and D. N. Sundberg. 2006. Seed mass affects the susceptibility of weed and crop species to phytotoxins extracted from red clover shoots. Weed Sci. 54:340–345.

Littell, R. C., P. R. Henry, and C. B. Ammerman. 1998. Statistical analysis of repeated measures data using SAS procedures. J. Anim. Sci. 76:1216–1231.

Lundgren, J. G., J. T. Shaw, E. R. Zaborski, and C. E. Eastman. 2006. The influence of organic transition systems on beneficial ground-dwelling arthropods and predation of insects and weed seeds. Renew. Agric. Food Syst. 21:227–237.

Martini, E. A., J. S. Buyer, D. C. Bryant, T. K. Hartz, and R. F. Denison. 2004. Yield increases during the organic transition: improving soil quality or increasing experience? Field Crops Res. 86:255–266.

Maxwell, B. D., R. G. Smith, and M. Brelsford. 2007. Wild oat (*Avena fatua*) seed bank dynamics in transition to organic wheat production systems. Weed Sci. 55:212–217.

Melander, B., I. A. Rasmussen, and P. Barberi. 2005. Integrating physical and cultural methods of weed control—examples from European research. Weed Sci. 53:369–381.

Menalled, F., C. Jones, D. Buschena, and P. Miller. 2009. From Conventional to Organic Cropping: What to Expect during the Transition Years. Bozeman, MT: Montana State University Extension Service MontGuide MT200901AG.

Mohler, C. L. 1993. A model of the effects of tillage on emergence of weed seedlings. Ecol. Appl. 3:53–73.

Ngouajio, M. and M. E. McGiffen. 2002. Going organic changes weed population dynamics. Horttechnology 12:590–596.

Norris, R. F. 1999. Ecological implications of using thresholds for weed management. Pages 31–58 *in* D. D. Buhler, ed. Expanding the Context of Weed Management. New York: Haworth.

O'Donovan, J. T. and D. W. McAndrew. 2000. Effect of tillage on weed populations in continuous barley (*Hordeum vulgare*). Weed Technol. 14:726–733.

O'Rourke, M. E., A. H. Heggenstaller, M. Liebman, and M. E. Rice. 2006. Post-dispersal weed seed predation by invertebrates in conventional and low-external-input crop rotation systems. Agric. Ecosys. Environ. 116:280–288.

Peigne, J., B. C. Ball, J. Roger-Estrade, and C. David. 2007. Is conservation tillage suitable for organic farming? a review. Soil Use Manag. 23:129–144.

Reeves, D. W. 1997. The role of soil organic matter in maintaining soil quality in continuous cropping systems. Soil Tillage Res. 43:131–167.

Riemens, M. M., R.M.W. Groeneveld, L.A.P. Lotz, and M. J. Kropff. 2007. Effects of three management strategies on the seedbank, emergence and the need for hand weeding in an organic arable cropping system. Weed Res. 47:442–451.

Roman, E. S., A. G. Thomas, S. D. Murphy, and C. J. Swanton. 1999. Modeling germination and seedling elongation of common lambsquarters (*Chenopodium album*). Weed Sci. 47:149–155.

Shrestha, A., S. Z. Knezevic, R. C. Roy, B. R. Ball-Coelho, and C. J. Swanton. 2002. Effect of tillage, cover crop and crop rotation on the composition of weed flora in a sandy soil. Weed Res. 42:76–87.

Smith, R. G. and K. L. Gross. 2006. Rapid change in the germinable fraction of the weed seed bank in crop rotations. Weed Sci. 54:1094–1100.

Snapp, S. S., S. M. Swinton, R. Labarta, D. Mutch, J. R. Black, R. Leep, J. Nyiraneza, and K. O'Neil. 2005. Evaluating cover crops for benefits, costs and performance within cropping system niches. Agron. J. 97:322–332.

Swanton, C. J. and B. D. Booth. 2004. Management of weed seedbanks in the context of populations and communities. Weed Technol. 18(Suppl. 1):1496–1502.

Teasdale, J. R., R. W. Mangum, J. Radhakrishnan, and M. A. Cavigelli. 2004. Weed seedbank dynamics in three organic farming crop rotations. Agron. J. 96:1429–1435.

Teasdale, J. R., P. Pillai, and R. T. Collins. 2005. Synergism between cover crop residue and herbicide activity on emergence and early growth of weeds. Weed Sci. 53:521–527.

[USDA-ERS] U.S. Department of Agriculture–Economic Research Service. 2008. Data Sets: Organic Production. http://www.ers.usda.gov/Data/Organic/index.htm#tables. Accessed: November 6, 2008.

Walz, E. 1999. Final results of the third biennial national organic farmers' survey. Santa Cruz, CA: Organic Farming Research Foundation. http://ofrf.org/publications/pubs/3rdsurvey_results.pdf. Accessed: December 1, 2008.

Weaver, S. E., C. S. Tan, and P. Brain. 1988. Effect of temperature and soil moisture on time of emergence of tomatoes and four weed species. Can. J. Plant. Sci. 68:877–886.

Received February 13, 2009, and approved June 14, 2009.