CROP ROTATIONS

Weed Seedbank Dynamics in Three Organic Farming Crop Rotations

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ABSTRACT

Weed management is a primary concern of organic farmers. Crop rotation is an important potential management approach for regulating weed seed populations in the soil of organic farming systems. This research was conducted to determine the effect of three organic crop rotations on the weed seedbank during the first 6 yr of a long-term cropping systems experiment at Beltsville, MD. The rotations consisted of (i) a 2-yr corn (*Zea mays* L.)–soybean [*Glycine max* (L.) Merr.] rotation, (ii) a 3-yr corn–soybean–wheat (*Triticum aestivum* L.) rotation, and (iii) a 4-yr corn–soybean–wheat–red clover (*Trifolium pratense* L.)/orchardgrass (*Dactylis glomerata* L.) hay rotation. Weed seed populations were determined by a greenhouse emergence assay using soil samples taken in the early spring of each year. The seedbanks of smooth pigweed (*Amaranthus hybridus* L.) and common lambsquarters (*Chenopodium album* L.) preceding corn were usually lower following the hay years of the 4-yr rotation or the wheat year of the 3-yr rotation than following the soybean year of the 2-yr rotation. However, annual grass seedbanks preceding corn tended to be higher following the hay years of the 4-yr rotation than following the wheat year of the 3-yr rotation or the soybean year of the 2-yr rotation. Seedbanks in the 3- and 4-yr rotations were similar to those of the 2-yr corn–soybean rotation (higher smooth pigweed and common lambsquarters and lower annual grass) when these longer rotations began with a corn–soybean sequence than with other sequences. Sequences beginning with hay had lower smooth pigweed and common lambsquarters seedbank populations than all other sequences. The seedbank in spring significantly predicted weed abundance at maturity in corn in at least 2 of 4 yr for all species. Results show that longer rotations with more phenologically diverse crops can reduce seedbank populations and abundance of important annual broadleaf weed species in organic production systems.

Crop rotation is considered an essential component of organic farming systems. Section 205.205 of the USDA National Organic Program Standards (www.ams.usda.gov/nop/NOP/standards.html; verified 8 June 2004) requires that "the producer must implement a crop rotation." These regulations further stipulate that the rotation must provide ecosystem services including maintenance or improvement of soil organic matter, control of pests, management of plant nutrients, and control of soil erosion. However, no specific crops, sequences, or number of years are specified to meet this requirement. This lack of specificity is understandable since organic farmers differ considerably in rotational requirements depending on their marketing and production goals and on environmental constraints. Since weed management has been identified as the primary concern of organic farmers (Walz, 1999), it is important to determine optimum rotational strategies for achieving effective weed control on organic farms.

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There is experimental evidence that rotation of two or more crops can reduce weed populations compared with continuous production of one crop. Liebman and Dyck (1993) reviewed 27 comparisons of rotational vs. monoculture crop production and found that weed densities were lower in a test crop following a rotation than following a monoculture in 21 cases, were similar in five cases, and were higher in one case. Giant foxtail (*Setaria faberi* Herrm.) seedbank was higher in continuous corn than in either a corn–soybean or corn–soybean–wheat rotation at three soil depths and in three tillage systems in Indiana (Schreiber, 1992). Total weed seedbank was higher after 3 yr of carrot (*Daucus carota* L.) monoculture than when barley (*Hordeum vulgare* L.) was rotated with carrot (Benoit et al., 2003). Weed seed production was lower in most years in a corn–soybean–wheat–alfalfa (*Medicago sativa* L.) rotation than in continuous corn, particularly with a low-input weed management program (Kegode et al., 1999). Generally, rotations that include crops of different growth habit and/or phenology than the monoculture crop are more disruptive to the life cycles of most weed species by imposing a higher diversity of mortality or stress events across the years of the rotation (Liebman and Dyck, 1993). On the other hand, few differences in weed populations have been observed between monoculture corn and a rotation of corn and soybean, which are phenologically similar crops (Mulugeta and Stoltenberg, 1997; Doucet et al., 1999; Kegode et al., 1999).

Inclusion of a perennial forage or pasture crop in a rotation often can reduce weed populations in low-input or organic systems. The seedbank of annual dicotyledonous weeds declined when fields were in perennial ley crops but increased when in annual crops during conversion to organic farming in Norway (Sjursen, 2001). Weed control and crop yield were better in organic corn and soybean when they were part of a 4 yr corn–soybean–oat (*Avena sativa* L.)–alfalfa rotation than a 2-yr corn–soybean rotation (Porter et al., 2003). Weed seed production in corn was lower when corn was preceded by alfalfa than by soybean or continuous corn in low-input systems (Kegode et al., 1999). There were fewer weed seedlings in corn following alfalfa than in continuous corn in a low-input system without herbicides (Clay and Aguilar, 1998). On the other hand, under weed management systems based on recommended herbicides, weed populations often were less affected by inclusion of hay in the rotation (Clay and Aguilar, 1998;

Kegode et al., 1999; Cardina et al., 2002). In this situation, populations of selected weed species may be higher in a rotation including alfalfa than in rotations including only corn or soybean because these weeds are adapted to the cutting regime of alfalfa and because there are fewer herbicides applied to hay than to corn and soybean (Cardina et al., 2002).

Weed population simulation models have demonstrated that the diversity of crops in rotation can influence the trajectory of weed populations over years (Jordan et al., 1995). Mertens et al. (2002) used a simulation model to show that the sequence of crops as well as the number of different crops can have an important influence on weed populations. They explored all 2- to 6-yr sequences of two crops and demonstrated that the order of crops can have a significant influence on weed population growth rates and the sensitivity of growth rates to parameter changes. These simulations suggest that, in theory, it is not only important to design rotations to increase the diversity of management conditions and environments that weeds must encounter, but also to design the optimum sequence of those environments.

The weed seedbank is an important determinant of future weed populations. Seedling recruitment of many important weed species can be predicted based on seedbank populations, although the degree and precision of these predictive relationships can be variable (Forcella, 1992; Webster et al., 2003). Variation in the initial seedbank can influence the success of weed management, particularly with low-input weed control programs. Zasada et al. (1997) showed that weed density in corn following a low initial weed seedbank was lower than that following a high initial seedbank when no herbicides were used. Buhler (1999) showed that there were smaller differences in weed control and crop yield between mechanical vs. herbicide-based systems in a field with a low initial seedbank than in an adjacent field with a high seedbank. Clearly, this research suggests that maintenance of a low seedbank is critical to the success of weed management programs for organic farming systems.

The USDA Farming Systems Project at Beltsville, MD, is a long-term experiment comparing two conventional systems and three organic cropping systems that differ in length and diversity of crop rotations (www.ba.ars.usda.gov/sasl/research/fsp.html; verified 8 June 2004). Analysis of seedbank data from this project has documented the relationship between weed seed inputs and losses that determine equilibrium population levels across all systems (Teasdale et al., 2003). In this article, we explore the impact of the three Farming System Project organic rotations on weed seedbank dynamics and the abundance of weeds in corn during the first 6 yr of this project.

MATERIALS AND METHODS

The Farming Systems Project was established in 1996 on USDA property at Beltsville, MD. The three organic systems differed in length of rotation. The simplest system consisted of a 2-yr, corn–soybean rotation with a winter annual legume cover crop, hairy vetch (*Vicia villosa* Roth) or crimson clover (*Trifolium incarnatum* L.), grown before corn and a rye (*Secale cereale* L.) cover crop grown before soybean. A second system consisted of a 3-yr, corn–soybean–wheat rotation with similar cover crops before corn and soybean as in the 2-yr rotation. A third system consisted of a 4-yr, corn–soybean–wheat–red clover/orchardgrass hay rotation with a rye cover crop before soybean. Systems were established with entry points for every year of each rotation. Thus, there were two rotational sequences for the 2-yr system, three sequences for the 3-yr system, and four sequences for the 4-yr system (Table 1). However, only three of the four potential 4-yr system sequences are addressed in this paper because of a failure to establish a hay crop in one rotational sequence. These treatments were arranged in a split-plot design with system (2-, 3-, or 4-yr rotations) assigned to whole plots and sequence assigned to subplots. Subplots were 9.1 by 111 m. Systems were randomized within each of four blocks and sequences were randomized within system.

Corn and soybean were planted in 76-cm rows during May with a no-tillage planter. Plots were chisel-plowed and disked before planting from 1996 to 1998. From 1999 to 2001, corn and soybean were planted without tillage and cover crops were flail mowed or rolled with the exception that the hay crop was moldboard-plowed and disked before corn in the 4-yr system. Wheat was drilled in 18-cm rows in October following disking of soybean residue. Hairy vetch or crimson clover cover crops were planted after soybean harvest in October in the 2-yr system, but these cover crops were planted in early September after a disk–fallow period following wheat harvest in the 3-yr system. Rye was planted following corn harvest in October in all systems. The red clover/orchardgrass hay in the 4-yr rotation was planted in late summer after a disk–fallow period following wheat harvest. Nutrients were provided by cover crops and broiler litter. Weeds were controlled in corn and soybean by rotary hoeing and cultivating when planted into a plow/disk-prepared seedbed. When corn and soybean were planted without tillage, weeds were controlled by the cover crop residue and cultivation with equipment designed

Table 1. Rotational sequences of the three organic cropping systems in the long-term Farming Systems Project at Beltsville, MD, during the first 6 yr.

System	Sequence	1996	1997	1998	1999	2000	2001
2-yr	1	corn	soybean	corn	soybean	corn	soybean
	2	soybean	corn	soybean	corn	soybean	corn
3-yr	3	corn	soybean	wheat–fallow	corn	soybean	wheat–fallow
	4	soybean	wheat–fallow	corn	soybean	wheat–fallow	corn
	5	oat†–fallow	corn	soybean	wheat–fallow	corn	soybean
4-yr‡	6	corn	soybean	wheat–hay	hay	corn	soybean
	7	hay	hay	corn	soybean	wheat–hay	hay
	8	–	hay	hay	corn	soybean	wheat–hay

† Spring oat was grown instead of wheat in the first year.
‡ Only three of the four potential rotational sequences were followed during the 4-yr system. The fourth sequence is not included because of failure to establish hay.

for high-residue, minimum-tillage conditions (Teasdale and Rosecrance, 2003).

The weed seed population was sampled during early spring of each year using a greenhouse approach that predicts field emergence more reliably than other techniques (Forcella, 1992). From 1996 to 1998, eight 7.5-cm diameter cores were taken to a 10-cm depth, whereas, from 1999 to 2002, twelve 5-cm diameter cores were taken to a 10-cm depth. Soil cores from the same plot were pooled, passed through a 1.3-cm screen to remove stones and large organic debris, and then spread on top of an equal amount of sterile greenhouse soil in flats. Flats were kept in a greenhouse that permitted day–night fluctuations between 10 and 30°C. Emerged weeds were counted and removed until emergence was nil. Soil was then dried, rewatered, and stirred to initiate further emergence. This cycle was repeated approximately monthly through August. The amount of soil spread on flats from each plot represented an estimated 0.0243 m^2, giving a minimum detection level of 41 seed m^{-2} if seed were uniformly distributed.

The annual broadleaf species, smooth pigweed and common lambsquarters, and several annual grass species were found consistently in most plots in all years. Annual grass species consisted primarily of fall panicum (*Panicum dichotomiflorum* Michx.), giant foxtail (*Setaria faberi* Herrm.), yellow foxtail (*Setaria glauca* (L.) Beauv.), and large crabgrass (*Digitaria sanguinalis* (L.) Scop) but were not enumerated separately. Other species were found intermittently in relatively few plots. Therefore, analysis focused on the dynamics of smooth pigweed, common lambsquarters, and annual grasses in the seedbank of these plots. Analysis of variance was conducted using a mixed model with system, sequence within system, and year considered fixed effects while block and appropriate split-plot error terms were considered random effects. Since all systems shared a common corn crop, analysis of variance also was conducted on seedbank data obtained in the spring preceding and succeeding corn. System and year were considered fixed effects while block and the appropriate split-plot error terms were considered random effects. Data were log-transformed before analysis to equalize variances and back-transformed for presentation. Mean separations were performed with Fisher's protected Least Significant Difference ($P = 0.05$) using appropriate standard errors according to a split-plot design. All analyses were performed using PROC MIXED (SAS Version 8.2, SAS Inst., Cary, NC).

A visual rating of the percentage of soil covered by weeds was conducted at weed maturity in September. Ratings were performed on weeds between the center eight rows for each of the four quadrants of each plot. This was considered a more accurate means of assessing the abundance of weed growth in these large areas than biomass sampling since populations were unevenly distributed. Unpublished data from small sample areas within these plots have shown that there is a linear relation between weed cover and biomass. Analysis of variance was conducted on cover ratings with system and year considered as fixed effects while block, quadrant within block, and appropriate split plot error terms were considered as random effects. Regression analysis was conducted on weed cover as a function of the corresponding spring seedbank for each of the major species.

RESULTS

The initial weed seedbank population in this field was low for all species because of excellent weed control during 3 yr of no-tillage corn preceded by 8 yr of alfalfa hay before the establishment of treatments in 1996. Populations of smooth pigweed, common lambsquarters, and annual grasses averaged 314, 987, and 566 seeds m^{-2}, respectively, in the spring of 1996. Throughout the first 6 yr of these treatments, seedbank populations in most sequences tended to fluctuate within a range that was considerably higher than these initial levels (Fig. 1–3). Analysis of variance showed a significant year × sequence within system interaction for all species. Differences between rotational systems, therefore, were influenced by both the specific crop sequence and the year in that sequence (Fig. 1–3).

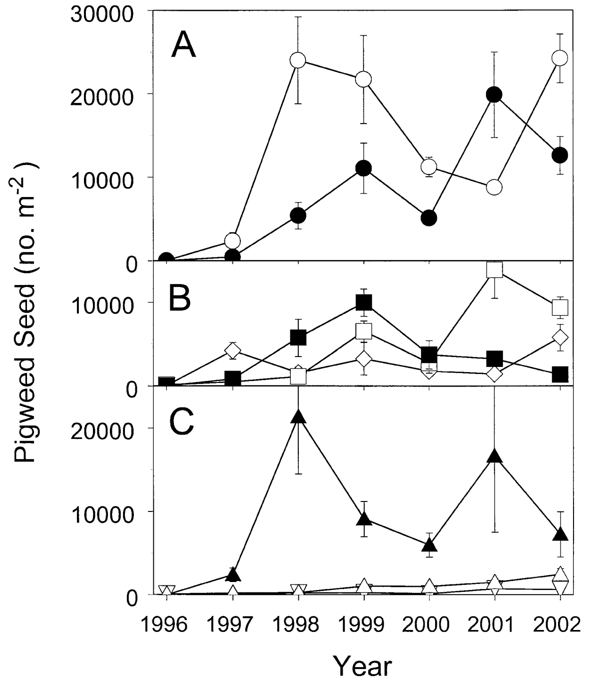

Fig. 1. Smooth pigweed seedbank populations determined in spring for cropping sequences in three organic rotations. Bars represent the standard error of the mean. (A) Two-year rotation included Sequences 1 (closed circle) and 2 (open circle). (B) Three-year rotation included Sequences 3 (closed square), 4 (open diamond), and 5 (open square). (C) Four-year rotation included Sequences 6 (closed triangle), 7 (open triangle), and 8 (inverted triangle). Sequences are described in Table 1.

Smooth pigweed seedbank populations tended to rise through the first 3 yr until the spring of 1999 for all sequences except those beginning with hay (Fig. 1). Populations fell for these sequences during 1999 (i.e., from spring 1999 to spring 2000), probably because of a severe drought that prevented smooth pigweed, as well as crops, from maturing that year. Populations rose during 2000 for those sequences (1, 5, and 6) in all rotational systems that were in corn that year, and also for those sequences (2 and 4) that were in corn during 2001. Populations decreased in all but 1 yr of the wheat–fallow phase of the 3-yr rotational system and maintained relatively low levels. Those sequences that initiated with hay (Sequences 7 and 8) effectively suppressed smooth pigweed populations and kept seedbank levels low. Averaged over all years, smooth pigweed populations in Sequence 2 in the 2-yr rotation and Sequence 6 in the 4-yr rotation tended to be higher than most other se-

Table 2. Mean smooth pigweed, common lambsquarters, and annual grass seedbank for the eight cropping sequences in the Farming System Project during the first 6 yr. Values within columns followed by the same letter are not significantly different ($P = 0.05$).

		Seedbank		
System	Sequence	Smooth pigweed	Common lambsquarters	Annual grass
		1000 seed m^{-2}		
2-yr	1	4.9 bc	8.2 abc	1.5 cde
	2	10.4 a	12.1 a	1.4 de
3-yr	3	3.6 bc	7.8 abc	3.2 bc
	4	2.3 c	3.3 c	1.0 e
	5	2.7 c	4.3 bc	2.4 cd
4-yr	6	8.6 ab	10.7 ab	1.7 cde
	7	0.6 d	1.0 d	5.8 ab
	8	0.2 e	0.9 d	7.5 a

quences whereas Sequences 7 and 8 in the 4-yr rotation were lower than all other sequences (Table 2).

Common lambsquarters seedbank populations behaved similarly to those of smooth pigweed (Fig. 2). Populations in most sequences tended to rise until 1999 followed by a decline during the drought of 1999. Populations fell during the wheat–fallow years of the 3-yr rotation except for Sequence 3 when wet soil conditions during late summer prevented control of weeds by tillage operations during 1998. Both 4-yr rotational sequences that began with hay (Sequences 7 and 8) maintained the common lambsquarters seedbank at low levels. On average, there were high populations in at least one sequence of all systems, but the two sequences beginning with hay were lower than all others (Table 2).

Annual grass populations tended to be lower than smooth pigweed and common lambsquarters populations for most sequences (Fig. 3). Exceptions were high grass populations in Sequence 7 in 1997, 1998, and 2002 because of grass establishment in the hay crops of this sequence. Sequence 8 had a large increase in 2000, presumably because grasses that established in corn in 1999 tolerated the drought sufficiently to produce seed. Wet weather during the summer of 2001 provided ideal conditions for late emergence and seed production by grasses, thus boosting populations in spring of 2002 for most sequences. On average, grass populations tended to be highest in sequences with the lowest smooth pigweed and common lambsquarters populations and low in sequences with high smooth pigweed and common lambsquarters populations (Table 2).

Seedbanks before the corn phase of all systems were analyzed to determine the impact of the crops in the previous years. The crops that preceded corn represented the rotational phase that was unique to each system. There were significant system × year interactions for all species. In the spring before corn, the seedbanks of smooth pigweed and common lambsquarters were lower in the 3-yr rotation following a year of wheat–fallow than in the 2-yr rotation following soybean in 4 of 6 yr (Tables 3 and 4). Seedbanks were lower in the 4-yr rotation following 2 yr of hay than in the 2-yr

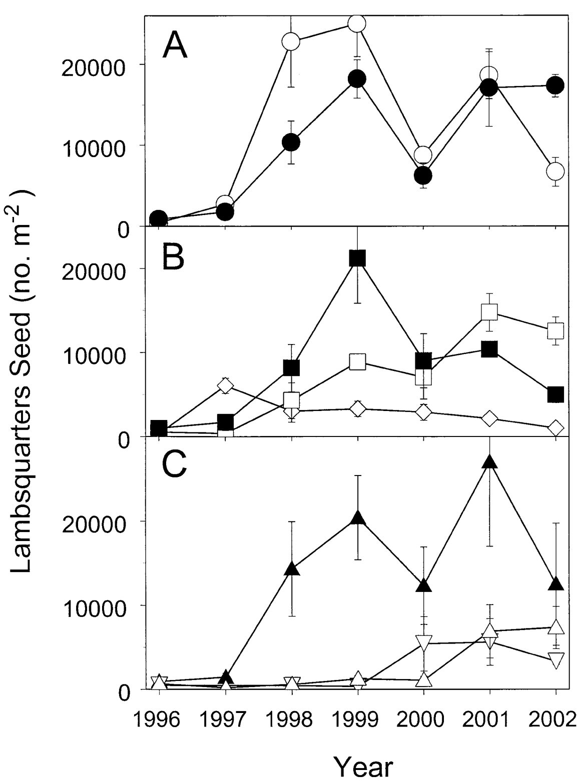

Fig. 2. Common lambsquarters seedbank populations determined in spring for cropping sequences in three organic rotations. Bars represent the standard error of the mean. (A) Two-year rotation included Sequences 1 (closed circle) and 2 (open circle). (B) Three-year rotation included Sequences 3 (closed square), 4 (open diamond), and 5 (open square). (C) Four-year rotation included Sequences 6 (closed triangle), 7 (open triangle), and 8 (inverted triangle). Sequences are described in Table 1.

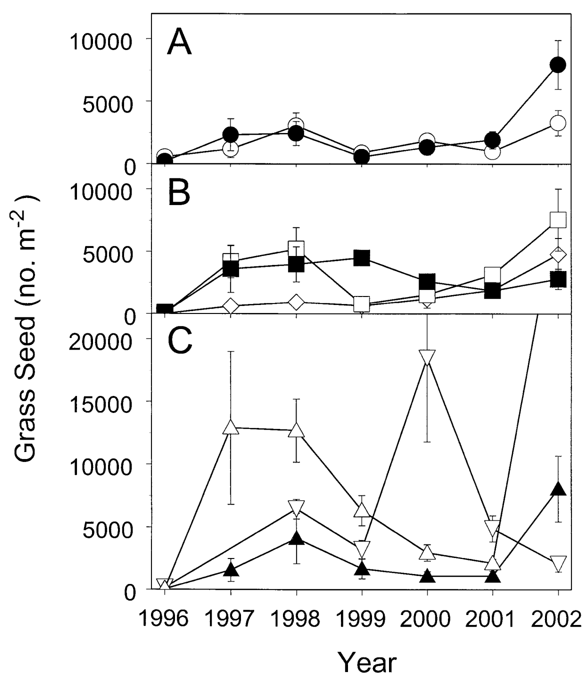

Fig. 3. Annual grass seedbank populations determined in spring for cropping sequences in three organic rotations. Bars represent the standard error of the mean. (A) Two-year rotation included Sequences 1 (closed circle) and 2 (open circle). (B) Three-year rotation included Sequences 3 (closed square), 4 (open diamond), and 5 (open square). (C) Four-year rotation included Sequences 6 (closed triangle), 7 (open triangle), and 8 (inverted triangle). Sequences are described in Table 1.

Table 3. Smooth pigweed soil seedbank and cover rating at maturity during the corn year of three organic crop rotations. Values followed by the same letter within a column and year are not significantly different (P = 0.05).

Year	Rotation	Crop before corn	Seedbank before corn	Cover rating in corn	Seedbank after corn
			1000 seed m^{-2}	%	1000 seed m^{-2}
1997	2-yr	soybean	2.4 a	16 a	24.0 a
	3-yr	wheat–fallow	0.5 b	6 b	1.1 b
1998	2-yr	soybean	5.4 a	26 a	11.1 a
	3-yr	wheat–fallow	1.6 b	8 b	3.3 ab
	4-yr	2-yr hay	0.3 c	7 b	1.0 b
1999	2-yr	soybean	21.7 a	–†	11.3 a
	3-yr	wheat–fallow	10.0 a	–	3.8 a
	4-yr	2-yr hay	0.2 b	–	0.1 b
2000	2-yr	soybean	5.1 a	24 ab	19.9 a
	3-yr	wheat–fallow	2.8 a	21 b	13.9 a
	4-yr	2-yr hay	6.0 a	31 a	16.6 a
2001	2-yr	soybean	8.8 a	59 a	24.3 a
	3-yr	wheat–fallow	1.5 b	12 b	5.8 a
2002	2-yr	soybean	12.6 a	–	–
	3-yr	wheat–fallow	1.4 b	–	–
	4-yr	2-yr hay	2.4 b	–	–

† Corn was not rated in 1999 because crops and weeds were destroyed by a severe drought.

rotation in 3 of 4 yr for smooth pigweed and 2 of 4 yr for common lambsquarters. Seedbanks of annual grass weeds in the spring before corn, on the other hand, were similar in the 2- and 3-yr rotations in 4 of 6 yr and higher in the 4-yr than 2-yr rotations in 3 of 4 yr (Table 5).

The pattern of weed cover ratings in corn followed the same trend as the spring seedbank preceding corn for all weed species (Tables 3–5). Weed cover ratings of smooth pigweed in corn were lower in the 3-yr than in the 2-yr rotation in 3 of 4 yr and were lower in the 4-yr than in the 2-yr rotation in 1 of 2 yr. Common lambsquarters weed cover was lower in the 3-yr than in the 2-yr rotation in 2 of 4 yr and was lower in the 4-yr than in the 2-yr rotation in 1 of 2 yr. Cover ratings of grass weeds tended to be similar or higher in the 3-yr or 4-yr than in the 2-yr rotation. There were similar trends in the seedbank following corn as that preceding corn but values were often increased, presumably because of seed inputs during corn production (Tables 3–5).

The corresponding pattern between the seedbank in spring before corn and the subsequent weed cover ratings in corn suggests that the seedbank can predict the level of weed control achieved in these organic systems. Regression analysis revealed that the spring seedbank predicted weed cover in corn in 2 of 4 yr for smooth pigweed and annual grasses and in 3 of 4 yr for common lambsquarters (Table 6). Years in which predictions were poor corresponded to years in which there was a small range of values for seedbank and/or cover. Seedbanks were relatively small in 1997, accounting for the relatively low R^2 values in that year. Annual variations in emergence and growth of each species in subsequent years undoubtedly depended on specific weather conditions, effectiveness of control methods, and competitive interactions between species. For example, common lambsquarters produced a relatively low level of cover per initial seedbank in the 2-yr rotation in 2001 (1% cover per 18 640 seed m^{-2}) probably because of hot weather in spring that induced secondary dormancy of this species but enhanced emergence and competition by smooth pigweed (which had 59% cover per 8800 seed m^{-2}). Alternately, annual grasses produced a relatively high level of cover in the 3-yr rotation in 2001 (22% cover per 1910 seed m^{-2}) probably because of low seedbanks of potentially competitive broadleaf weeds, and wet midseason weather that allowed late germinating grasses to thrive. The relationship between cover and spring seedbank was usually stronger within a given year than over all years combined (Table 6).

Table 4. Common lambsquarters soil seedbank and cover rating at maturity during the corn year of three organic crop rotations. Values followed by the same letter within a column and year are not significantly different (P = 0.05).

Year	Rotation	Crop before corn	Seedbank before corn	Cover rating in corn	Seedbank after corn
			1000 seed m^{-2}	%	1000 seed m^{-2}
1997	2-yr	soybean	2.7 a	34 a	22.8 a
	3-yr	wheat–fallow	0.4 b	13 b	4.3 b
1998	2-yr	soybean	10.4 a	38 a	18.2 a
	3-yr	wheat–fallow	3.1 b	21 b	3.3 b
	4-yr	2-yr hay	0.6 c	5 c	1.3 b
1999	2-yr	soybean	25.0 a	–†	8.8 a
	3-yr	wheat–fallow	21.2 a	–	9.0 a
	4-yr	2-yr hay	0.4 b	–	5.4 a
2000	2-yr	soybean	6.3 a	39 a	17.1 a
	3-yr	wheat–fallow	7.1 a	29 a	14.8 a
	4-yr	2-yr hay	12.3 a	38 a	27.0 a
2001	2-yr	soybean	18.6 a	1 a	6.7 a
	3-yr	wheat–fallow	2.1 b	0 a	1.0 b
2002	2-yr	soybean	17.4 a	–	–
	3-yr	wheat–fallow	5.0 b	–	–
	4-yr	2-yr hay	7.3 ab	–	–

† Corn was not rated in 1999 because crops and weeds were destroyed by a severe drought.

Table 5. Annual grass soil seedbank and cover rating at maturity during the corn year of three organic crop rotations. Values followed by the same letter within a column and year are not significantly different ($P = 0.05$).

Year	Rotation	Crop before corn	Seedbank before corn	Cover rating in corn	Seedbank after corn
			1000 seed m^{-2}	%	1000 seed m^{-2}
1997	2-yr	soybean	1.2 b	0 a	3.1 a
	3-yr	wheat–fallow	4.2 a	3 a	5.2 a
1998	2-yr	soybean	2.5 b	1 b	0.6 b
	3-yr	wheat–fallow	1.0 b	0 b	0.7 b
	4-yr	2-yr hay	12.7 a	15 a	6.3 a
1999	2-yr	soybean	0.9 b	–†	1.9 b
	3-yr	wheat–fallow	4.5 a	–	2.6 b
	4-yr	2-yr hay	3.2 a	–	18.5 a
2000	2-yr	soybean	1.4 a	2 ab	1.9 ab
	3-yr	wheat–fallow	1.5 a	7 a	3.1 a
	4-yr	2-yr hay	1.1 a	0 b	1.1 b
2001	2-yr	soybean	1.0 a	4 b	3.3 a
	3-yr	wheat–fallow	1.9 a	22 a	4.8 a
2002	2-yr	soybean	7.9 b	–	–
	3-yr	wheat–fallow	2.8 b	–	–
	4-yr	2-yr hay	31.2 a	–	–

† Corn was not rated in 1999 because crops and weeds were destroyed by a severe drought.

DISCUSSION

Seedbanks in these organic systems tended to fluctuate in an irregular manner between values that spanned a 2- to 10-fold range (Fig. 1–3). Regression analysis showed no overall trend toward increasing seedbank of any weed species in any system (Teasdale et al., 2003). Instead, seedbanks tended to rise following years when a high abundance of weeds generated high seed inputs and decline following years when there were minimal seed inputs. A simple multiple regression model of annual seedbank change as a function of seedbank in the spring and weed cover at weed maturity explained more than 60% of the variation for all species (Teasdale et al., 2003). This model showed that despite the potential for high seed inputs and large seedbank increases during years with poor weed control, seedbanks declined rapidly during years of good weed control. This result has promising implications for organic growers since it suggests that 1 or 2 yr with good weed control can rapidly reduce seedbanks following years with imperfect weed control.

Many studies have shown that common lambsquarters becomes an important component of weed populations in organic or mechanical-based cropping systems (Davies et al., 1997; Albrecht and Sommer, 1998; Barberi et al., 1998; Gallandt et al., 1998; Menalled et al., 2001; Sjursen 2001). In our Farming Systems Project, common lambsquarters and smooth pigweed became dominant weeds in the organic systems as well, but were usually lower following the hay years of the 4-yr rotation or the wheat–fallow year of the 3-yr rotation than following the soybean year of the 2-yr rotation (Tables 3 and 4). These summer annual weeds would be adapted to emerge, grow, and produce seed within summer annual crops such as corn and soybean that have a similar phenology. Given the large quantities of seed that common lambsquarters and pigweed species are capable of producing and the difficulty of controlling these weeds in organic row crops, it is understandable that these weed species dominated the seedbank of the 2-yr rotation composed of only summer annual crops. On the other hand, the presence of an established wheat crop in the 3-yr rotation or hay crop in the 4-yr rotation probably suppressed the recruitment of these summer annual weed species in spring. In addition, disking during the fallow period in the 3-yr rotation or cutting of the hay crop in the 4-yr rotation probably destroyed those plants that did become established before they could produce seed in summer.

Table 6. Regression of percentage soil coverage by weeds at maturity in corn as a function of the seedbank in spring.

Year	Smooth pigweed	Common lambsquarters	Annual grasses
		R^2	
1997	0.08	0.39†	0.05
1998	0.57**	0.53**	0.50**
2000	0.04	0.47*	0.00
2001	0.76**	0.01	0.70**
All	0.39**	0.14*	0.15*

* Significant at the 0.05 level.
** Significant at the 0.01 level.
† Significant at the 0.10 level.

Annual grass weeds dominated the 4-yr rotation (Table 2). Annual grass seedbanks preceding corn tended to be higher in the hay years of the 4-yr rotation than in the wheat–fallow year of the 3-yr rotation or in the soybean year of the 2-yr rotation (Table 5). Grass population increases often were associated with gaps in the hay crop that provided a niche for weed establishment. The capacity for prostrate growth and seed production in spite of mowing probably permitted grass populations to increase under these circumstances. Clay and Aguilar (1998) showed that there was greater biomass of grass than broadleaved weeds in alfalfa hay and that more grasses than broadleaved weeds emerged in corn following alfalfa. Cardina et al. (2002) suggested that there was a higher seedbank of large crabgrass and yellow foxtail in a rotation with hay because these species tolerated mowing.

These results suggest that rotations can exert a selection pressure that will favor those weed species that are adapted to the rotational management practices and will reduce populations of unadapted species. Generally, rotations that alternate crops with diverse phenology and diverse weed management practices should be most effective at disrupting population growth of the greatest number of weed species. Our results showed that inclusion of a wheat–fallow and/or a hay crop into organic corn and soybean rotations suppressed troublesome small-seed broadleaved weeds such as common lambsquarters and pigweed species. But use of these alternate crops in organic systems need to be managed so as not to provide a niche for other problem weed species. For example, if a good stand of hay is not maintained, this crop may not provide the level of suppression desired but could favor population increases of species adapted to the cutting regime such as occurred with annual grass species in this experiment.

This research also showed that the effectiveness of rotations at reducing the weed seedbank was dependent on the specific crop that initiated the rotations (Fig. 1–3). Different sequences of the same rotation often had distinctly different effects on seed populations. The seedbank of Sequence 3 of the 3-yr rotation and Sequence 6 of the 4-yr rotation that started with corn followed by soybean was similar to that of both 2-yr corn–soybean sequences that exhibited high smooth pigweed and common lambsquarters populations and low annual grass populations. However, Sequences 7 and 8 of the 4-yr rotation that started with hay crops had an opposite population profile with relatively lower smooth pigweed and common lambsquarters populations and higher annual grass populations. In part, these differences between sequences may result from the fact that there were summer annual crops in four out of the first 6 yr in Sequence 6 but only two out of the first 6 yr in Sequences 7 and 8. But, since these broadleaf weeds have been shown to be a limiting factor to organic production, these results support the importance of initiating rotations with a sequence of crops that increase the probability of suppressing weeds and maintaining low initial seedbank levels.

Maintenance of a lower seedbank often improved weed control in corn in these organic systems (Tables 3–5). Previous research also has demonstrated that the magnitude of the seedbank can influence weed control efficacy and crop yield, particularly in systems not employing herbicides (Zasada et al., 1997; Buhler, 1999). There are many variables that can influence weed seedling recruitment, the effectiveness of control practices, and competitive interactions and that will ultimately determine the vegetative productivity and fecundity of a species in a given year. As a result, the seedbank may not always account for the abundance of weeds. However, in selected years, the seedbank in these systems accounted for up to 76, 53, and 70% of the variation in the vegetative cover of smooth pigweed, common lambsquarters, and annual grasses, respectively (Table 6). These results reinforce the importance for organic farmers to adopt rotations that maximize opportunities for reducing soil weed seed populations and minimize opportunities for rapid buildup of the seedbank.

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