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Weed Biology and Competition

A Comparison of Threshold Strategies in Tomatoes and Soybean

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Weed control strategies based on conserving crop yields rather than preventing weed seed production may result in increased weed densities and management costs over the long-term, particularly in less competitive crops such as tomatoes. The effect of crop, tillage, and duration of weed control on weed seed bank size and composition was examined from spring 2001 to spring 2003 near Lafayette, IN. Main plots in 2001 and 2002 contained soybean or tomato planted in rotation (soybean-tomato, tomato-soybean). Subplots were managed with either conventional or no-till practices. Sub-subplots contrasted threshold strategies in which weeds were either controlled for four to six weeks (period threshold, PT) or throughout the growing season (no-seed-threshold, NST). Seed banks were sampled annually in the spring. Emergent weeds were counted at four and twelve weeks after planting (WAP) in 2001 and 2002. Weed seed banks did not significantly change in the NST plots in any year. However, seed bank densities increased substantially following tomatoes in PT plots. In contrast, weed seed bank densities decreased following soybeans in PT plots. The difference in seed banks and emergent weeds between soybean and tomatoes could be attributed primarily to greater suppression of giant foxtail by the soybean canopy. Giant foxtail control was greater in PT soybeans than in PT tomatoes in both years and giant foxtail comprised most of the PT tomato seed bank in 2002 and 2003. Tillage did not affect weed seed banks in any year. This study highlights the need to control later emerging weeds in tomatoes to prevent large increases in the weed seed bank.

Nomenclature: Giant foxtail, *Setaria faberi* Herrm. SETFA; Soybean, *Glycine max* L.; Tomato, *Lycopersicon esculentum* L.
Key words: Competition, crop rotation, integrated weed management, no seed threshold, tillage, weed seed bank.

Weed management in crops has focused primarily on controlling weeds that emerge early in the growth of the crop because later emerging weeds often do not reduce crop yields (Gallandt 2006; Zimdahl 1988). In crops such as soybeans or rice that form a continuous canopy, the timely removal of weeds may provide the crop with a growth advantage that allows it to suppress weeds that emerge after the weed-free period (Chandler et al. 2001; Gibson et al. 2002; Liebman and Gallandt 1997). However, in less competitive crops or in crops that do not form continuous canopies, weeds may continue to emerge throughout the season and contribute substantial quantities of seeds to the soil seed bank. Large inputs to the soil seed bank can result in the need for increased herbicide rates in subsequent years (Taylor and Hartzler 2000). Thus, a weed management strategy that emphasizes crop yields but does not also consider weed seed production can lead to recurring weed problems and prevent growers from minimizing external inputs.

Norris (1999) proposed an approach to address this issue described as a no-seed-threshold (NST). A NST program, in addition to preventing weeds from competing with a crop, does not allow weeds to produce seed. Norris argued that, although weed control in fields under NST would require intense weed control in the initial years, the seed bank would be depleted rather quickly, resulting in reduced weed emergence and thereby lowering weed control inputs in subsequent years. More commonly, growers visually assess weeds and apply herbicides that effectively control weeds long enough to limit the potential for crop yield loss due to weed competition. This is referred to as the period threshold (PT) (Dawson 1986), and varies among crops; e.g., 4 to 6 wk for tomatoes (Bhowmik et al. 1988; Perez et al. 1990) and 6 to 8 wk for soybeans (Cordes et al. 1984; Van Acker et al. 1993). In this approach, timely herbicide applications are made to control weeds during the PT to protect within-season yields; however, weeds that emerge after this period are not controlled and may produce seed (Dawson 1986).

Crops that do not form a continuous canopy may be particularly susceptible to large seed bank increases when a PT strategy is used. Hillger et al. (2006) used detailed questionnaires and multivariate analyses to identify five distinct management systems in Indiana tomato production; three systems produced fresh market tomatoes and two produced tomatoes for processing. In the fresh market systems, weed densities after PT practices were concluded for the season ranged from 23 to 30 plants/m^2 (Hillger et al. 2006). Since weeds are prolific seed producers, it is likely that soil–weed seed banks would be substantially enriched in these systems following tomatoes. If soil weed seed banks increase over time, growers must intensify weed control in subsequent years, or face increased weed problems over time (Gallandt 2006). Some Indiana tomato growers include more competitive crops, such as soybeans, in their rotations to compensate for seed bank increases during the tomato phase of the rotation. However, it is not known if this strategy is sufficient to decrease seed bank densities to pretomato levels.

The objective of this research was to determine the effect of crop sequence, tillage, and duration of weed control on the soil–weed seed bank and on tomato yields.

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Materials and Methods

This study was conducted at the Meigs Horticulture farm, a component of the Throckmorton Purdue Agriculture Center (TPAC), near Lafayette, IN, in a sandy loam soil area in which corn and soybean had been grown in rotation for the previous 3 yr. The entire area was moldboard plowed and disked uniformly in the fall of 2000. A split–split plot experimental design with four blocks was used. Main plots in each year contained soybean or tomato planted in rotation (soybean–tomato, tomato–soybean). Subplots were managed with either conventional or no-till practices. Weeds in the sub-subplots were controlled for 4 to 6 wk (PT) or throughout the growing season (NST).

Roundup-Ready soybeans (Becks 352 RR) were drill-seeded (20-cm row spacing) at a rate of 420,000 seeds/ha on May 25, 2001 and May 28, 2002. Fertilizer was not applied to soybean plots in either year. Fresh market tomato cultivars ('Mountain Spring' in 2001 and 'Primetime' in 2002) were transplanted (1.8-m spacing between rows) on May 21, 2001 and May 24, 2002, staked, and pruned to provide two main stems. Fertilizer, fungicides, and insecticides were applied following recommended practices for fresh market tomatoes (Egel et al. 2006). As soon as plants started to fruit, they were side-dressed with $CaNO_3$ (15 kg/ha) in both years. Drip irrigation was used as necessary to supply water to tomatoes.

The conventional tillage treatment consisted of annual fall and spring tillage (commencing in spring 2001) by a field rotary tiller to a depth of 10 cm. Preplant herbicides (*s*-metolachlor at 1.4 kg ai/ha and metribuzin at 0.4 kg ai/ha) were applied and incorporated to a depth of 2.5 cm to conventionally tilled tomato plots or surface-applied to the no-till tomato plots. For all tillage treatments in both crops, glyphosate (1.1 kg ae/ha) was applied before planting to kill any emerged weeds. No other herbicides were preplant-applied to soybean plots.

Herbicides were applied to all sub-subplots (6 m by 8 m) at 6 WAP in 2001 and, due to a higher weed density pressure, at 4 WAP in 2002 for both crops. The timing for weed control was based on the critical period of weed control for both crops (Bhowmik et al. 1988; Cordes et al. 1984; Perez et al. 1990; Van Acker et al. 1993). Sethoxydim (0.25 kg ai/ha + 1.2 L NIS/ha) and metribuzin (0.4 kg/ha) were applied in tomatoes, and glyphosate (1.1 kg/ha) was applied in soybeans. All herbicides were applied with a pressurized CO_2 backpack sprayer at 200 kPa with an output volume of 190 L/ha with 8002 nozzles.[1] Following the herbicide applications, the NST treatments were hand-weeded every 2 wk to prevent weed seed production.

Soil samples were collected on April 13, 2001, April 15, 2002, and April 6, 2003 to determine the seed bank composition. Since seed distributions in the soil bank are aggregated (Chauvel et al. 1989; Dessaint et al. 1991), an intense sampling regime was used (Ambrosio et al. 1997; Benoit et al. 1989; Kovach et al. 1988). Soil cores were collected at 1-m intervals within each sub-subplot, leaving a 1-m distance from the edge of the sub-subplots, to form a 5 by 7 matrix. In 2001, three soil cores, 10 cm deep by 2 cm in diameter, were taken per vertex. In 2002 and 2003, the soil cores were increased to 5.7 cm in diameter in order to avoid damage to larger-seeded weeds. Soil cores were bulked per sub-subplot and kept in plastic bags inside a cold room at 5 C until all samples were collected.

A seedling emergence technique was used to determine the germinable soil seed bank composition because it is as reliable and quantitative as direct counting (Cardina and Sparrow 1996; Forcella 1992), is easier to perform, and provides a better indication of the soil seed bank in each system (Gross 1990). As soon as all the samples were collected in the field, soil aggregates were broken up by hand and the soil was placed in 645-cm^2 plastic flats. Each flat contained a 0.5-cm-deep layer of vermiculite in the bottom to retain moisture that was separated from the soil by a permeable plastic weed mat. When placed uniformly in the flat, the soil created a 2-cm layer. Flats were then taken to the greenhouse where they were subirrigated by a capillary mat watered by drip irrigation tape with 10-cm emitter spacing. An electronic timer was set to water the plants for 5 min in the early morning and 5 min in the late afternoon. Individuals that emerged were identified by species, counted biweekly, and removed. After 1 mo, the soil from each flat was thoroughly stirred and the germination cycle was repeated. After the second germination cycle, soil flats were placed for 1 mo in a 5 C cooler to overcome the dormancy of remaining seeds. The soil was thoroughly stirred, and flats were placed in the greenhouse for 1 additional month to monitor seedling emergence (Cordes and Bauman 1984). The greenhouse was maintained at a temperature of 22 C under the natural photoperiod.

Emergent weeds in the field were counted and identified by species at 4 (before POST applications) and 12 WAP in each year within seven 0.1-m^2 quadrats in each sub-subplot. Tomatoes were hand-picked from 20 plants per sub-subplot twice a week for 6 wk, starting when tomatoes were at least 5 cm in diameter and when at least 10% maturity was observed (i.e., tomatoes started to turn orange). Soybeans were harvested and weighed by a combine harvester in a 1.5 by 8-m swath within each sub-subplot.

ANOVA (GLM procedure, SAS 1990) was used to evaluate the effect of crop, tillage, and weed control thresholds on emergent and seed bank populations and crop yields. The effect of tillage and weed control thresholds on weed densities depended on whether soybeans or tomatoes were planted. When interaction was detected, tillage and threshold effects were analyzed within each crop. Weed densities were log-transformed prior to statistical analyses to normalize the data. Due to zeros and mean densities less than 1, the logarithmic transformation $[\log((1 + \text{data}) \times 10)]$ (Little et al. 1978) was utilized. Data were back-transformed for presentation.

Results and Discussion

Weed Densities in 2001. Differences in germinable seed bank densities were not detected among treatments at the start of the experiment. The 2001 seed bank contained seven species: common lambsquarters (*Chenopodium album* L. CHEAL), eastern black nightshade (*Solanum ptycanthum* Dunal SOLPT), ivyleaf morningglory (*Ipomoea hederacea* Jacq. IPOHE), giant foxtail, giant ragweed (*Ambrosia trifida* L. AMBTR), prickly sida (*Sida spinosa* L. SIDSP), and redroot pigweed (*Amaranthus retroflexus* L. AMARE). Agricultural seed banks tend to be dominated by a few species (Forcella

Table 1. Seed bank and emergent weed density and frequency in tomato and soybean plots located at Meigs Field near Lafayette, IN.[a,b] Rotations (tomatoes–soybeans or soybeans–tomatoes) were initiated in spring 2001. Weeds were removed biweekly to prevent seed production (no-seed threshold, NSP) or controlled at 4 wk after planting (WAP) and then allowed to emerge (period threshold, PT).[c] Seed banks were sampled on April 13, 2001. Plots were planted on May 21, 2001, and emerged weeds were sampled 4 and 12 WAP.[d]

			4 WAP − NSP/PT mean		12 WAP − PT	
Species	Seeds	Frequency	Plants	Frequency	Plants	Frequency
	No./m^2	%	No./m^2	%	No./m^2	%
Tomato						
SETFA[e]	116 ± 18	100	1.4 ± 0.3	69	2.5 ± 0.82	75
SIDSP	100 ± 27	81	8.7 ± 2.1	88	1.2 ± 0.5	50
AMARE	6 ± 3	19	0.0 ± 0.0	0	0.0 ± 0.0	0
CHEAL	4 ± 3	13	0.0 ± 0.0	0	0.0 ± 0.0	0
SOLPT	2 ± 2	6	0.0 ± 0.0	0	0.0 ± 0.0	0
TAROF	0 ± 0	0	1.2 ± 0.4	50	0.0 ± 0.0	0
IPOHE	13 ± 7	25	1.6 ± 0.4	63	1.9 ± 0.6	63
AMBTR	0 ± 0	0	1.8 ± 0.6	50	0.0 ± 0.0	0
MOLVE	0 ± 0	0	0.0 ± 0.0	0	0.0 ± 0.0	0
PHYSU	0 ± 0	0	0.0 ± 0.0	0	0.0 ± 0.0	0
ABUTH	0 ± 0	0	0.2 ± 0.2	6	0.0 ± 0.0	0
Soybean						
SETFA	93 ± 17	88	21.7 ± 4.5	100	0.0 ± 0.0	0
SIDSP	55 ± 18	63	7.0 ± 1.4	88	5.6 ± 1.8	100
AMARE	6 ± 3	19	0.2 ± 0.1	13	0.0 ± 0.0	0
CHEAL	8 ± 4	19	0.1 ± 0.1	6	0.0 ± 0.0	0
SOLPT	6 ± 4	13	0.3 ± 0.3	6	0.0 ± 0.0	0
TAROF	0 ± 0	0	2.2 ± 0.7	56	0.2 ± 0.2	13
IPOHE	6 ± 4	13	1.2 ± 0.4	50	3. 5± 0.8	88
AMBTR	2 ± 2	6	0.5 ± 0.2	25	1.0 ± 0.4	50
MOLVE	0 ± 0	0	0.3 ± 0.2	19	0.0 ± 0.0	0
PHYSU	0 ± 0	0	0.0 ± 0.0	0	0.0 ± 0.0	0
ABUTH	0 ± 0	0	0.6 ± 0.3	25	0.0 ± 0.0	0

[a] Frequency was calculated as the number of sub-subplots containing the weed species divided by the total number of sub-subplots multiplied by 100.

[b] Values are means ± the standard error of the mean.

[c] No differences were detected between threshold treatments at 4 WAP. Data at 12 WAP are for PT plots only since no weeds were present in NST plots.

[d] Plots were sampled at 4 WAP before postemergence herbicides were applied.

[e] AMARE = redroot pigweed (*Amaranthus retroflexus* L.); AMBTR = giant ragweed (*Ambrosia trifida* L.); ABUTH = velvetleaf (*Abutilon theophrasti* Medik.); CHEAL = common lambsquarters (*Chenopodium album* L.); IPOHE = ivyleaf morningglory [*Ipomoea hederacea* (L.) Jacq]; MOLVE = carpetweed (*Mollugo verticillata* L.); PHYSU = *Physalis longifolia* [(Nutt.) var. *subglabrata* (Mackenzie & Bush) Cronq.]; SETFA = giant foxtail (*Setaria faberi* Herrm.); SOLPT = eastern black nightshade (*Solanum ptycanthum* Dun.); SIDSP = prickly sida (*Sida spinosa* L.); and TAROF = dandelion (*Taraxacum officinale* G.H. Weber ex Wiggers).

1992); giant foxtail and prickly sida accounted for 84 and 90% of the soybean and tomato seed banks, respectively (Table 1). Relatively low initial seed bank densities (Table 1) probably reflect effective weed management in the soybean/corn rotation in preceding years.

At 4 WAP, no difference in emergent weed densities were detected among tillage or threshold treatments. However, giant foxtail densities were much greater in soybean plots than in tomato plots (Table 1). Ten species were present at 4 WAP in the soybean plots, but only six species were present in the tomato plots (Table 1). Carpetweed (*Mollugo verticillata* L. MOLVE) and velvetleaf (*Abutilon theophrasti* Medik ABUTH) were not detected in the 2001 seed bank but were detected at low densities in the 2001 emergent population (Table 1). Preplant herbicides applied in the tomato plots suppressed early season giant foxtail and reduced weed species richness relative to the soybean plots in which no PRE herbicides were used.

Weeds were not present in NST plots at 12 WAP. More weeds were present in the soybean PT plots than in the tomato PT plots (10 plants/m^2 ± 2 SE and 6 plants/m^2 ± 1 SE, respectively) at 12 WAP. Prickly sida and ivyleaf morningglory accounted for 88% of the total weed density in the soybean plots (Table 1). Both weeds were found under the soybean canopy, suggesting that they emerged relatively late in the growing season. Giant foxtail was not found in PT soybean plots but was detected in PT tomato plots (Table 1). Weed densities at 12 WAP were not affected by tillage treatments.

Weed Densities in 2002. Total weed seed bank densities did not differ between threshold treatments in the soybean-tomato rotation in 2002 (Figure 1A). However, in the tomato–soybean rotation, 5,513 seeds/m^2 ± 2,337 SE were detected in PT plots compared to 109 seeds/m^2 ± 32 SE in NST plots (Figure 1B). This was primarily due to the large increase in giant foxtail seed bank densities following 1 yr of PT tomatoes (Table 2). Giant foxtail accounted for 92% of the 2002 PT soybean seed bank but for only 17% of the 2002 PT tomato seed bank (Table 2).

A large giant foxtail seed bank in spring 2002 and the absence of preplant herbicides led to high emergent weed densities in soybeans. Giant foxtail densities 2 wk before transplanting tomatoes were 564 plants/m^2 ± 54 SE in the soybean PT plots and 7 plants/m^2 ± 4 SE in the soybean

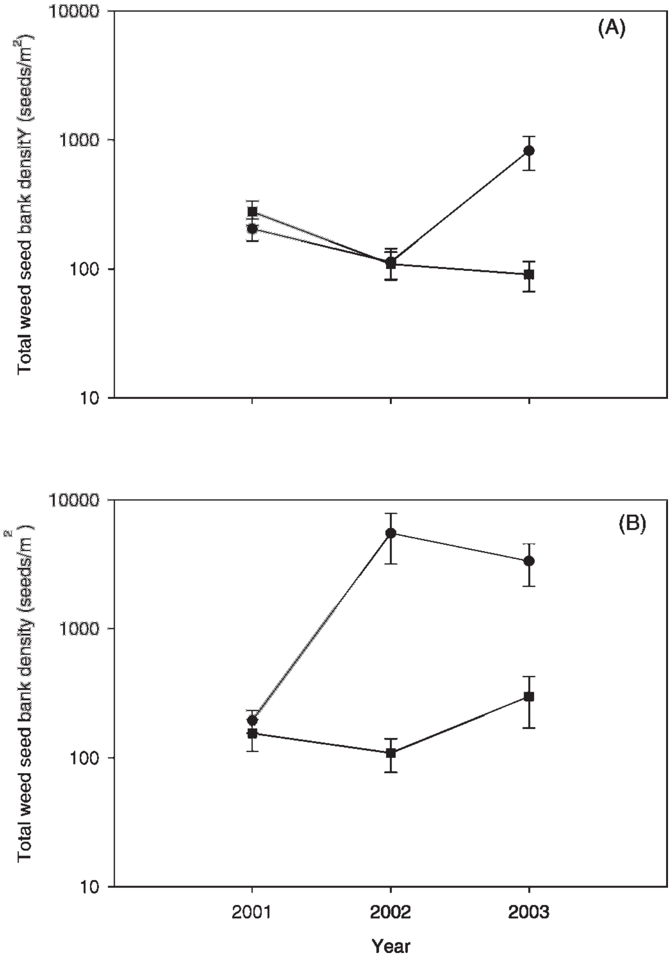

Figure 1. Changes in the soil–weed seed bank in plots located at Meigs Field near Lafayette, IN. The soybean–tomato (A) and tomato–soybean (B) rotations were initiated in spring 2001 and terminated in fall 2002. Weeds were removed biweekly to prevent seed production in the no-seed-threshold (NST) treatment (squares), or controlled at 4 to 6 wk and then allowed to emerge in the period threshold (PT) treatment (circles). Seed banks were sampled on April 13, 2001, April 15, 2002, and April 6, 2003. Values are means ± the standard error of the mean.

NST plots. Glyphosate was applied before transplanting tomatoes; this killed most emergent weeds (C. Mayen, personal observation). However, an additional 184 giant foxtail plants/m^2 had emerged in the PT soybean plots by 4 WAP (Table 2). Interaction was detected among all three main factors at 4 WAP in 2002 for total weed densities. Data were reanalyzed to compare threshold treatments within each tillage treatment. In no-till tomato plots, total weed densities were greater in PT plots (58 plants/m^2 ± 6 SE) than in NST plots (45 plants/m^2 ± 6 SE). No difference was detected between PT plots (26 plants/m^2 ± 7 SE) and NST plots (36 plants/m^2 ± 5 SE) in conventionally tilled tomato plots. In no-till soybean plots, total weed densities were 315 plants/m^2 ± 23 SE and 20 plants/m^2 ± 5 SE for PT and NST plots, respectively. Similarly, in conventionally tilled soybean plots, weed densities were 147 plants/m^2 ± 38 SE and 24 plants/m^2 ± 4 SE for PT and NST plots, respectively.

No weeds were present in the NST plots at 12 WAP in 2002. Weed densities were not affected by tillage in tomato plots; PT plots averaged 21 plants/m^2 ± 8 SE. Ivyleaf morningglory and dandelion (*Taraxacum officinale* G.H. Weber ex Wiggers) accounted for 77% of the total weed density in tomato PT plots (Table 2). Weed densities were affected by soil treatments in the PT soybean plots. Total weed density was 13 plants/m^2 ± 2 SE in the no-till plots but only 3 plants/m^2 ± 1 SE in the conventionally tilled plots. Seven species were found in the no-till plots; giant foxtail and ivyleaf morningglory comprised 24 and 34%, respectively, of the total weed density (data not shown). Only ivyleaf morningglory and giant foxtail were present in the conventionally tilled PT plots; ivyleaf morningglory accounted for 87% of total weed density (data not shown).

Soil Seed Bank in 2003. Giant foxtail accounted for 75% of the total seed bank at the end of the PT soybean–tomato rotation (Table 3). The increase in giant foxtail seed was primarily responsible for the large increase in total seed bank densities from 2002 to 2003 in these plots (Figure 1A). In contrast, the NST seed bank declined slightly from 2002 to 2003 in the tomato–soybean rotation and seed bank frequencies for most weed species were ≤ 25% (Table 3). Eastern black nightshade seed bank densities were high in soybean plots for both threshold treatments (Table 3). In the soybean PT plots, eastern black nightshade was a minor component of the total weed seed bank in 2002 (Table 2) but accounted for 80% of the seed bank in 2003 (Table 3). The large increase in eastern black nightshade limited the decline in total seed bank densities from 2002 to 2003 (Figure 1B), despite a large reduction in giant foxtail seed bank densities (Table 3).

Eastern black nightshade was detected at very low densities in tomato plots and not at all in soybean plots at 12 WAP in 2002 (Table 2). Eastern black nightshade can tolerate the low light environment present under a soybean canopy (Stoller and Myers 1989) and may escape control in soybeans by emerging after glyphosate applications (Hilgenfield et al. 2004). It is possible that the species was present under the soybean canopy or at very low densities in the soybean plots but was not detected during our sampling. Eastern black nightshade produces large quantities of seed and even very low plant densities could greatly enrich the soil seed bank.

Crop Yields. Soybean yields were 2,618 kg/ha ± 38 SE and 2,986 kg/ha ± 179 SE in 2001 and 2002, respectively, and did not differ among tillage or threshold treatments in either year. Similarly, tomato yields were 3.2 kg/plant ± 0.2 SE in 2001 and 2.7 kg/plant ± 0.1 SE in 2002 and did not differ among tillage or between threshold treatments in either year. This suggests that PT management was as effective as NST management in maintaining crop yields and supports the hypothesis that a single well-timed weed control in tomatoes and soybeans can be sufficient to conserve yields within a single season. However, unlike soybeans, PT management in tomatoes was not tested under high weed densities in either year and it is possible that PT management might prove inadequate if the weed seed bank continued to increase.

Giant foxtail, a common and fecund weed in Indiana tomato fields (Conley et al. 2002; Hillger et al. 2006), escaped

Table 2. Seed bank and emergent weed density and frequency in soybean and tomato plots located at Meigs Field near Lafayette, IN, in 2002.[a,b] Rotations (tomatoes–soybeans or soybeans–tomatoes) were initiated in spring 2001. Weeds were removed biweekly to prevent seed production (no-seed threshold, NST) or controlled at 4 wk and then allowed to emerge (period threshold, PT). Seed banks were sampled on April 15, 2002. Plots were planted on May 24, 2002, and emerged weeds were sampled 4 and 12 wk after planting (WAP).[c]

					4 WAP				12 WAP	
	NST		PT		NST		PT		PT	
Species	Seeds	Frequency	Seeds	Frequency	Plants	Frequency	Plants	Frequency	Plants	Frequency
	No./m^2	%	No./m^2	%	No./m^2	%	No./m^2	%	No./m^2	%
Tomato–Soybean										
SETFA[d]	43 ± 10	88	5,092 ± 2,346	100	7.3 ± 1.1	100	184.1 ± 36.8	100	1.9 ± 0.2	38
SIDSP	13 ± 8	38	320 ± 94	100	7.1 ± 3.1	100	32.5 ± 11.5	100	0.4 ± 0.3	25
AMARE	0 ± 0	0	33 ± 26	38	0.2 ± 0.2	13	1.9 ± 1.9	13	0.0 ± 0.0	0
CHEAL	6 ± 4	25	10 ± 3	63	0.0 ± 0.0	0	0.0 ± 0.0	0	0.2 ± 0.2	13
SOLPT	0 ± 0	0	7 ± 7	13	0.0 ± 0.0	0	0.6 ± 06	13	0.0 ± 0.0	0
TAROF	1 ± 1	13	0 ± 0	0	4.0 ± 2.5	13	3.3 ± 3.3	13	1.2 ± 1.2	13
IPOHE	4 ± 4	13	17 ± 5	88	3.1 ± 0.8	88	5.0 ± 1.4	88	2.7 ± 0.6	88
AMBTR	0 ± 0	0	1 ± 1	13	0.0 ± 0.0	0	2.9 ± 2.0	25	1.2 ± 0.8	25
MOLVE	42 ± 36	50	33 ± 19	50	0.0 ± 0.0	0	0.0 ± 0.0	0	0.0 ± 0.0	0
POROL	0 ± 0	0	0 ± 0	0	0.0 ± 0.0	0	0.0 ± 0.0	0	0.4 ± 0.4	13
ABUTH	0 ± 0	0	0 ± 0	0	0.4 ± 0.3	13	1.2 ± 0.6	50	0.0 ± 0.0	0
Soybean–Tomato										
SETFA	16 ± 8	38	18 ± 9	50	0.8 ± 0.8	13	0.6 ± 0.3	38	0.8 ± 0.4	38
SIDSP	3 ± 2	25	16 ± 5	63	4.4 ± 1.2	88	6.1 ± 1.8	88	1.5 ± 0.6	63
AMARE	4 ± 4	13	7 ± 5	25	0.2 ± 0.2	13	0.2 ± 0.2	13	0.0 ± 0.0	0
CHEAL	30 ± 13	63	23 ± 10	63	0.4 ± 0.3	25	2.9 ± 2.9	13	0.2 ± 0.2	13
SOLPT	36 ± 29	50	10 ± 9	25	1.2 ± 0.6	50	0.2 ± 0.2	13	0.4 ± 0.3	25
TAROF	4 ± 4	13	4 ± 4	13	30.1 ± 4.1	100	28.2 ± 7.5	100	6.7 ± 3.9	38
IPOHE	8 ± 5	25	12 ± 6	38	1.9 ± 1.3	50	1.9 ± 1.0	50	9.6 ± 1.6	100
AMBTR	9 ± 9	13	9 ± 5	38	0.6 ± 0.4	25	1.2 ± 0.6	50	0.4 ± 0.3	25
MOLVE	4 ± 4	13	9 ± 8	25	0.6 ± 0.4	25	0.2 ± 0.2	13	1.7 ± 1.2	25
POROL	0 ± 0	0	0 ± 0	0	0.0 ± 0.0	0	0.0 ± 0.0	0	0.0 ± 0.0	0
ABUTH	0 ± 0	0	0 ± 0	0	0.2 ± 0.2	13	0.4 ± 0.3	25	0.0 ± 0.0	0

[a] Frequency was calculated as the number of sub-subplots containing the weed species divided by the total number of sub-subplots multiplied by 100.

[b] Values are means ± the standard error of the mean.

[c] Plots were sampled at 4 WAP before postemergence herbicides were applied.

[d] AMARE = redroot pigweed (*Amaranthus retroflexus* L.); AMBTR = giant ragweed (*Ambrosia trifida* L.); ABUTH = velvetleaf (*Abutilon theophrasti* Medik.); CHEAL = common lambsquarters (*Chenopodium album* L.); IPOHE = ivyleaf morningglory [*Ipomoea hederacea* (L.) Jacq]; MOLVE = carpetweed (*Mollugo verticillata* L.); POROL = common purslane (*Portulaca oleracea* L.); SETFA = giant foxtail (*Setaria faberi* Herrm.); SOLPT = eastern black nightshade (*Solanum ptycanthum* Dun.); SIDSP = prickly sida (*Sida spinosa* L.); and TAROF = dandelion (*Taraxacum officinale* G.H. Weber ex Wiggers).

control in PT tomato plots in both years. Giant foxtail densities increased substantially following tomatoes in our study but decreased following soybeans. Grasses appear to be less problematic than broadleaf weeds in glyphosate-resistant soybeans; giant foxtail was not ranked among the top five weeds by Indiana corn and soybean growers in 2004 (Gibson et al. 2005). Although giant foxtail emergence tends to peak relatively early in the growing season, it can emerge into midsummer (Buhler et al. 1997). The absence of a closed canopy between rows in tomatoes may extend the period of giant foxtail emergence relative to soybeans and contribute to the buildup of this weed during the tomato phase of the rotation.

Giant foxtail and prickly sida were detected in 60% or more of the soil of sub-subplots in spring 2001 (Table 1). Seed bank frequencies for both species were still > 60% in 2003 (Table 3); however, unlike giant foxtail, prickly sida seed bank densities were not substantially affected by crop rotation. The low initial seed bank frequencies of the remaining weed species limit our ability to assess their response to treatments. However, five and six species had seed bank frequencies > 60% in the soybean–tomato and tomato–soybean PT rotations in 2003, respectively (Table 3). In the NST plots, frequencies were ≤ 38% for nine of eleven species in both rotations (Table 3). Thus, PT management favors not only large increases in the populations of certain weed species, such as giant foxtail, but also increased the proportion of a field infested with multiple weed species. Greater seed bank densities and frequencies in 2003 PT plots also suggests that still larger population increases might have occurred in subsequent years if the experiment had been continued.

Liebman and Gallandt (1997) suggested that the delay of weed emergence relative to the crop should be a basic principle guiding the development of weed management strategies. In this approach, weeds that emerge early in the season are controlled through chemical or cultural practices while weeds that emerge after such control practices are suppressed by the crop, primarily through shading. However, in crops with closed canopies, weeds that emerge after control practices are concluded may face little interference. In this scenario, less suppressive phases of a crop rotation system may allow weed populations to increase and create a dynamic in

Table 3. Seed bank density and frequency in plots located at Meigs Field near Lafayette, IN, in 2003.[a,b] Rotations (tomatoes–soybeans or soybeans–tomatoes) were initiated in spring 2001. Weeds were removed weekly to prevent seed production (no-seed threshold, NST) or controlled at 4 wk and then allowed to emerge (period threshold, PT). Seed banks were sampled on April 6, 2003.

	NST		PT	
Species	Seeds	Frequency	Seeds	Frequency
	No./m^2	%	No./m^2%	
Tomato–Soybean				
SETFA[c]	15 ± 10	38	79 ± 43	88
SIDSP	1 ± 1	13	67 ± 13	100
AMARE	7 ± 5	25	39 ± 32	25
CHEAL	46 ± 12	10	176 ± 58	100
SOLPT	188 ± 128	75	2,675 ± 1,254	88
TAROF	0 ± 0	0	0 ± 0	0
IPOHE	4 ± 4	13	32 ± 14	63
AMBTR	0 ± 0	0	18 ± 14	50
MOLVE	32 ± 10	75	55 ± 17	88
POROL	1 ± 1	13	196 ± 196	13
ABUTH	4 ± 4	13	10 ± 6	23
Soybean–Tomato				
SETFA	28 ± 10	75	613 ± 250	100
SIDSP	17 ± 13	25	78 ± 23	75
AMARE	16 ± 16	13	21 ± 12	38
CHEAL	0 ± 0	0	7 ± 2	63
SOLPT	4 ± 4	13	39 ± 21	75
TAROF	0 ± 0	0	0 ± 0	0
IPOHE	4 ± 4	13	25 ± 6	75
AMBTR	0 ± 0	0	14 ± 9	38
MOLVE	14 ± 6	63	19 ± 12	38
POROL	0 ± 0	0	7 ± 6	25
ABUTH	8 ± 8	13	0 ± 0	

[a] Frequency (%) was calculated as the number of replicates within a treatment containing the weed species divided by the total number of replicates multiplied by 100.

[b] Values are means ± the standard error of the mean.

[c] AMARE = redroot pigweed (*Amaranthus retroflexus* L.); AMBTR = giant ragweed (*Ambrosia trifida* L.); ABUTH = velvetleaf (*Abutilon theophrasti* Medik.); CHEAL = common lambsquarters (*Chenopodium album* L.); IPOHE = ivyleaf morningglory [*Ipomoea hederacea* (L.) Jacq]; MOLVE = carpetweed (*Mollugo verticillata* L.); POROL = common purlsane (*Portulaca oleracea* L.); SETFA = giant foxtail (*Setaria faberi* Herrm.); SOLPT = eastern black nightshade (*Solanum ptycanthum* Dun.); SIDSP = prickly sida (*Sida spinosa* L.); and TAROF = dandelion (*Taraxacum officinale* G. H. Weber ex Wiggers).

which weed seeds produced during one phase result in large emergent populations that require more suppressive crops in subsequent phases. In this study, the giant foxtail seed bank increased substantially following tomatoes in PT plots, resulting in high emergence densities in soybeans the next year. Although giant foxtail was controlled in soybeans, it seems likely that control in less competitive crops would have been problematic. Vegetable growers in the Midwest often rotate primarily among vegetable crops (Hillger et al. 2006; Rzewnicki 2000). Consequently, vegetable production systems in the Midwest may contain no phases in which the crop strongly interferes with weed growth.

Although tillage can affect weed seed bank size and species composition (Kegode et al. 1999; Murphy et al. 2006; Buhler 1995), differences in weed seed bank densities were not detected between no-till and conventional tillage treatments. Cardina et al. (2002) examined the effects of 35 yr of continuous crop rotation and tillage system treatment on weed seed banks at two sites in Ohio. Crop rotation had a greater influence on weed seed banks than tillage system, but seed densities were generally greater in no-till than in more intensive tillage systems. In our study, the crop had a strong effect on weed seed banks but tillage did not. Similarly, emergent weed densities were not affected by tillage in 2001 or in the tomato–soybean plots in 2002. However, in 2002, conventional tillage in the soybean–tomato rotation limited weed emergence in PT plots to the same level as in NST plots, presumably by burying seed. Conventional tillage combined with the suppressive effect of soybeans was as effective at reducing weed seed banks and weed emergence in the second year of the rotation as manual weeding to completely prevent weed seed production. Thus, the benefits of a NST approach may be possible in competitive crops without mandating a substantial investment in late-season management.

The design of optimal integrated weed management (IWM) systems requires knowledge of how different phases in a rotation affect weed populations and communities. Such knowledge can assist growers in identifying and addressing potential weaknesses in their system. Period threshold, which is widely practiced by growers, might be appropriate in a competitive crop such as soybeans. However, in fresh market tomatoes, the period threshold approach resulted in a large increase in the soil seed bank, which led to greater emergent weed densities in soybeans during the following year. The inclusion of a suppressive crop such as soybean in rotation with vegetables may limit large population increases in the soil seed bank. However, it should be noted that total weed seed bank densities were greater in 2003 than in 2001 for both the tomato–soybean and soybean–tomato rotations in PT plots (Figure 1A and 1B). Thus, rotating PT soybeans with PT tomatoes may not provide sufficient weed suppression to maintain or decrease weed seed banks. The NST treatment was very effective at reducing seed banks in this study; however, this required substantial manual weeding. High cost and scarcity of labor make it unlikely than manual weeding to prevent weed seed production would be adopted on a large scale in the Midwest. Alternative strategies that increase the competitive ability of crops through planting and density, increase the shading of weed seedlings through intercropping (Baumann et al. 2002), or rely on mechanical or chemical cultivation to directly prevent seed production have the potential to reduce seed production in tomatoes and other crops. Additional research designed specifically to test the effectiveness of late-season control practices in reducing soil seed banks is needed.

Sources of Materials

[1] TeeJet Extended Range spray tips, Spraying Systems Co., North Avenue and Shmale Road, Wheaton, IL 60189.

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