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A Multi-Tactic Approach to Manage Weed Population Dynamics in Crop Rotations

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ABSTRACT

No-till systems have enabled producers to change crop rotations in the semiarid Central Great Plains. Previously, winter wheat (*Triticum aestivum* L.)–fallow was the prevalent rotation; now producers grow warm-season crops along with winter wheat and fallow. Initially, weed management was difficult in no-till rotations. However, an ecological approach to weed management, which integrates knowledge of weed population dynamics with cultural tactics and long-term planning, has enabled producers to control weeds with 50% less herbicides. This article explains the cultural tactics and ecological reasoning that led to this successful approach; our goal is to provide insight and ideas for other scientists and producers to plan multi-tactic weed management. The ecological approach emphasizes three goals related to weed population dynamics: enhancing natural loss of weed seeds in soil, reducing weed seedling establishment, and minimizing seed production by established plants. Cultural tactics used in this approach can be grouped into five categories: rotation design, crop sequencing, no-till, crop residue management, and competitive crop canopies. Success of the approach requires cultural tactics in each category.

Producers in the semiarid Great Plains are searching for a broader approach to weed management than relying primarily on herbicides. Several factors are stimulating this change in perspective. Herbicide-resistant weeds are now common (Lyon et al., 1996; Heap, 2005), forcing producers to use more expensive management tactics. A second factor is that some crops grown in the Great Plains, such as proso millet (*Panicum miliaceum* L.) or forages, have few herbicides available for weed control. Thus, producers are seeking alternative tactics to supplement herbicides for weed management.

Pedigo (1995), reviewing the progress of integrated pest management (IPM), found that IPM still emphasizes single-tactic, pesticide-based programs. To encourage a broader approach to IPM, he suggested that scientists and producers consider a dualistic approach of prevention and control, with an emphasis on multi-tactic management. Prevention seeks to reduce overall density of pests and improve tolerance of crops to pest injury with cultural tactics. Mortensen et al. (2000), agreeing with Pedigo's suggestion for multi-tactic management, further encouraged scientists to integrate weed management with cropping system design.

Crop rotations are changing in the Central Great Plains because of crop residue management and improved water relations (Farahani et al., 1998). Warm-season crops such as corn (*Zea mays* L.), proso millet, sorghum [*Sorghum bicolor* (L.) Moench], and sunflower (*Helianthus annuus* L.) are now grown with winter wheat and fallow. Integrating crop diversity with other cultural tactics enabled producers to effectively control weeds with 50% less herbicide inputs compared with their initial experiences with no-till rotations (Anderson, 2003). The cultural approach reduced weed community density in their fields, thus minimizing the need for herbicides to control weeds.

Pedigo (1995) suggested that scientists develop conceptual models to guide development of multi-tactic programs. In this article, we explain the cultural tactics and ecological reasoning that led to this approach with weed management in the Central Great Plains; this example may provide insight and ideas for producers and scientists elsewhere to develop similar programs. Even though crop choices and cultural tactics may vary in other regions, a systematic approach to integrating tactics that disrupt weed population growth may lead to successful weed management that is less dependent on herbicides.

DESIGN OF ECOLOGICALLY BASED WEED MANAGEMENT

In the Central Great Plains, annual weeds are the prevalent species infesting grain crops. Prominent weeds include downy brome (*Bromus tectorum* L.), jointed goatgrass (*Aegilops cylindrica* Host), kochia [*Kochia scoparia* (L.) Schrad.], Russian thistle (*Salsola iberica* Sennen & Pau), green foxtail [*Setaria viridis* (L.) Beauv.], field sandbur [*Cenchrus longispinus* (Hack.) Fern.], and redroot pigweed (*Amaranthus retroflexus* L.). With annual weeds, the seed is the key component of population dynamics. The ecologically based approach emphasizes cultural tactics that enhance natural loss of weed seeds in soil, reduce weed seedling establishment, and minimize seed production by individual plants. Cultural tactics can be grouped into five categories: rotation design, crop sequencing, no-till, crop residue management, and competitive crop canopies (Fig. 1). In the following text, we describe tactics used for each category and explain the ecological basis for their impact on weed dynamics.

Rotation Design: Sequencing of Cool-Season and Warm-Season Crops

Rotating cool- and warm-season crops can reduce weed community density (Streibig, 1979; Thomas and Frick, 1993). Different planting and harvest dates among these crops provide opportunities for producers to prevent either plant establishment or seed production by weeds. For example, green foxtail emerges between mid-May and early July, then begins flowering in early August. Winter wheat is harvested in early July; thus, producers can easily control green foxtail before it flowers and

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Abbreviations: IPM, integrated pest management.

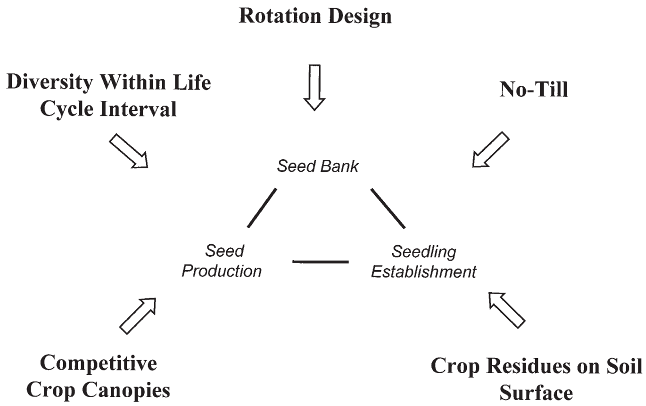

Fig. 1. Five components of an ecologically based weed management system for cropping systems in the Central Great Plains. Cultural tactics in each component disrupt weed population dynamics by minimizing weed seed survival in soil (seed bank), seedling establishment, or seed production.

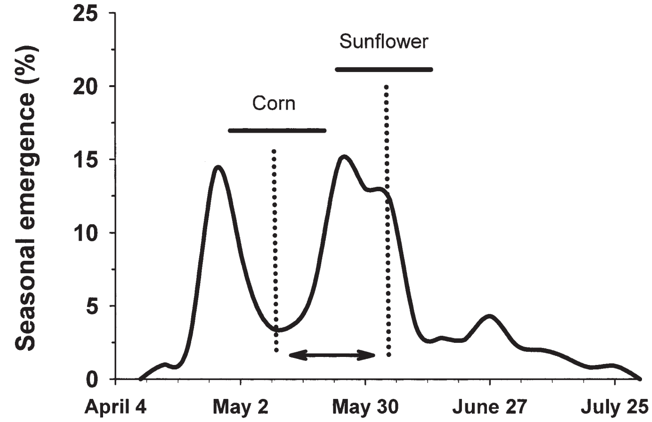

Fig. 2. Seedling emergence pattern of a weed community at Akron, CO. Data averaged across 7 yr. Horizontal lines underneath corn and sunflower represent normal planting dates for these crops. The double-ended arrow highlights the potential difference in seedling emergence between average planting dates of these crops (adapted from Anderson, 1994).

produces seeds. A similar opportunity occurs with cool-season weeds; they are easily controlled before planting warm-season crops such as corn or sunflower. This rotational strategy is particularly valuable in the Central Great Plains, as both cool- and warm-season crops are economically viable.

The benefit of this strategy is related to weed seed survival in soil, as seeds in soil are the main source of weed infestations in future crops (Roberts, 1981). Seeds in soil can germinate, die of natural causes, or be consumed by fauna or microorganisms; consequently, the number of live seeds in soil declines with time. With downy brome and green foxtail, approximately 20% of seeds are alive 1 yr after seed shed, whereas <5% of their seeds are alive after 2 yr (Anderson, 2003). This rapid decline of live seeds in soil is typical of most annual weed species (Roberts, 1981; Egley and Williams, 1990).

Rotating crops with different life cycles enables producers to favor the natural loss of weed seeds across time by preventing new seeds from being added to the soil. But long-term rotation studies in the Central Great Plains show a surprising trend; weed density increases if rotations consist of one cool-season crop followed by one warm-season crop, such as winter wheat–proso millet (Anderson, 2003). In contrast, if rotations are arranged in a cycle of four, with two cool-season crops followed by two warm-season crops, weed density declines with time. Comparing trends across three rotation studies, weed seedling emergence was eightfold greater in two-crop rotations compared with rotations comprised of two cool-season crops followed by two warm-season crops. Fallow, if used, serves in either life-cycle category.

Impact of Crop Diversity within a Life-Cycle Interval

Long-term rotations studies in the Central Great Plains have shown that weed density increases if a crop is grown 2 yr in a row, such as corn followed by corn compared with corn followed by sunflower. The trend is related to the region's weed community pattern of seedling emergence (Fig. 2). Cool-season weeds represent the first peak, whereas warm-season species dominate the second peak (Anderson, 1994). Corn is normally planted in early May whereas sunflower is planted 3 to 4 wk later; this delay with planting provides producers with an additional opportunity to control 35 to 50% of potential weed seedlings before planting sunflower; these seedlings emerge in corn and require post-planting control.

A similar trend occurs with winter wheat; density of cool-season weeds rapidly escalates when winter wheat is grown 2 yr in a row in a cycle-of-four rotation (Anderson, 2003). Thus, diversifying crops with different planting dates within a life-cycle category (warm-season crops) accentuates the benefit gained with rotations comprised of 2-yr intervals of cool- and warm-season crops. Two rotations commonly used now in the region are winter wheat–corn–proso millet–fallow and winter wheat–corn–sunflower–fallow; like sunflower, proso millet is planted 3 to 4 wk later than corn.

Tillage Lessens the Impact of Rotation Design on Weed Population Dynamics

Producers occasionally till to apply anhydrous ammonia fertilizer; however, weed density often is higher in the subsequent crops. This trend occurs because tillage buries weed seeds in soil, which increases long-term survival of seeds. Weed seeds die rapidly if left on the soil surface and exposed to environmental extremes and predation (Sagar and Mortimer, 1976; Roberts, 1981). No-till systems enhance this natural loss of weed seeds by maintaining seeds on the soil surface.

Longer survival of weed seeds in soil should lead to more weed seedlings in future crops; however, research has shown conflicting trends with tillage and weed densities. For example, in an extensive review of weeds in wheat, Moyer et al. (1994) cited numerous examples of weed species that were favored by both no-till and tilled systems. Seeking to understand the interaction between tillage and weed seedling emergence, Mohler (1993) devel-

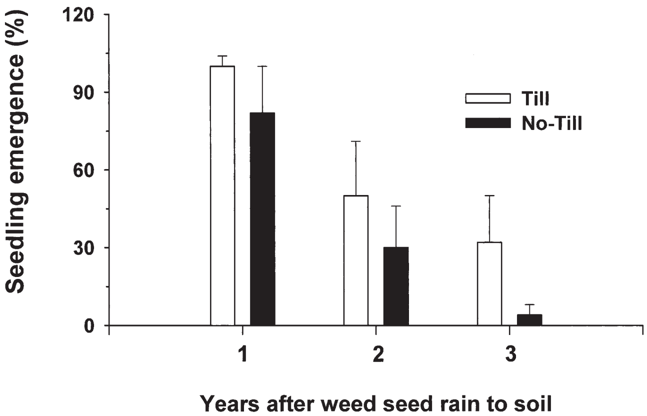

Fig. 3. Effect of tillage on weed seedling emergence across time. Weed seeds were not added to the soil after initiation of studies; tillage occurred in the tilled treatment each year. Data expressed as a percentage of the treatment with highest number of weed seedlings in each study. Standard error bars were derived from yearly means among studies (adapted from Egley and Williams, 1990; Popay et al., 1994; Anderson, 1998).

oped a mathematical model for seedling emergence based on published literature. The model predicts that weed seedling emergence will be greater with no-till compared with tilled systems in the first year after seed rain. However, if weed seed is not added to the soil, seedling emergence in no-till will decline more rapidly with time than in tilled treatments. This prediction reflects rapid loss of seed viability on the soil surface compared with seeds buried in soil.

This hypothesis is supported by field studies comparing weed emergence between no-till and tilled systems. In these studies, seedling emergence was counted for 3 yr after weed seeds were added to the soil; weed seed production was prevented for the duration of each study. In the first year, seedling emergence was similar between tilled and no-till, whereas in the second year, the difference between tillage treatments was about twofold (Fig. 3). In contrast, seedling emergence was eightfold greater in the third year with the tilled system; the difference between tillage systems increased with time.

This interaction among seedling emergence, tillage, and time is one factor why no-till rotations with 2-yr intervals of cool- and warm-season crops are effective in reducing weed density. By preventing weed seed production across 2 yr, such as eliminating seed production of cool-season weeds during the warm-season crop interval, weed seedling density is drastically reduced when a cool-season crop is grown in the third year.

The interaction of tillage, seedling emergence, and rotation design was further demonstrated with two rotation studies in the Great Plains (Anderson, 2004). One study was no-till whereas the second study included one tillage operation with a sweep plow[1] each year. Weed management in both studies was based on practices used by producers. In 2001, after two complete cycles of the longest rotation, we counted weed seedlings emerging during the growing season in quadrats where no herbicides had been applied. The weed community was similar at both sites, with downy brome, kochia, redroot pigweed, green foxtail, and stinkgrass [*Eragrotis cilianensis* (All.) E. Mosher] comprising >85% of the seedlings recorded.

[1] A sweep plow consists of V-shaped blades that sever plant roots at a tillage depth of 5 to 8 cm. Each operation buries only 10% of crop residues on the soil surface because of low soil disturbance.

Table 1. Effect of rotation design and tillage on weed seedling emergence at two long-term rotation studies in the Central Great Plains. Data collected in the ninth year of each study. Different letters after means within a study indicate that rotation means differed based on Fisher's Protected LSD (0.05) (adapted from Anderson, 2004).

Study	Rotation design† 1:1	2:2	Difference between rotations within a tillage system
	—— seedlings ——		
Tilled‡	225a	44b	5-fold
No-till	94f	7g	13-fold

† Rotations represent ratios of cool- and warm-season crops. With the tilled study, rotations compared were winter wheat–proso millet (1:1) and spring wheat–winter wheat–corn–sunflower (2:2); rotations with the no-till study were winter wheat–chickpea (*Cicer arietinum* L.) (1:1) and field pea–winter wheat–corn–soybean (2:2). Planting time for winter wheat was late September, late March for field pea and spring wheat, early May for corn and chickpea, late May for soybean, and early June for sunflower and proso millet.

‡ Tilled system involved at least one operation with the sweep plow each year.

Two rotation designs were compared, a rotation of one cool-season crop followed by one warm-season crop (shown as 1:1 in Table 1) with a rotation comprised of two cool-season crops followed by two warm-season crops (shown as 2:2). As mentioned earlier, more weeds were found in the two-crop (1:1) rotations than with the cycle-of-four rotations at both sites. However, more weeds were recorded in both rotations at the tilled site compared with the no-till study. Also, tillage affected the difference in seedling density between rotations in each study. With tillage, weed density was fivefold greater in the 1:1 rotation compared with the 4-yr rotation; in contrast, a 13-fold difference occurred between rotation designs with no-till. Because weed seeds survive longer after burial in soil, tillage lessens the impact of rotation design on weed community density.

Even when using herbicides, more weeds are present in rotations with tillage. Because tillage weakens weed management, no-till producers now use liquid fertilizers in place of anhydrous ammonia to eliminate the need for tillage with fertilizer management.

Crop Residues Reduce Weed Seedling Establishment

When no-till systems were first established in the Central Great Plains, it was noted that weed seedlings were less common in areas where high quantities of winter wheat residues remained after harvest. This trend occurs because crop residues alter environmental conditions related to weed seed germination, physically impede seedling growth, or inhibit germination and growth by allelopathy (Crutchfield et al., 1986). Wicks et al. (1994) found that each 1000 kg/ha of winter wheat residues on the soil surface reduced weed seedling establishment 14%.

However, tilling for weed control minimizes this benefit with crop residues. In a study designed to enhance crop residue suppression of weeds, tilling with the sweep plow increased weed density 35 to 50% in the next crop compared with a no-till system, even though high quantities of crop residue still remained on the soil surface and the field had been in no-till for several years (Anderson, 1999). Burial of weed seeds in soil by the sweep plow apparently alters the seed–soil interactions such that weeds emergence increases regardless of residue quantity on the soil surface.

To enhance crop residue suppression of weed emergence, producers can plant winter wheat at higher seeding rates, band low rates of N and P with the seed at planting, and grow taller cultivars. These practices increase residue production 2000 to 2500 kg/ha (Anderson, 2003). Similar suppression of weed emergence occurs with proso millet residues.

Competitive Crop Canopies Reduce Weed Growth and Seed Production

Even with excellent weed control, some plants escape control and produce seeds. To minimize this seed contribution to the soil, crop competitiveness with weeds can be improved with cultural practices. One approach is to grow crops in narrower rows, which minimizes the quantity of solar radiation reaching weeds within the crop canopy. A key to success, however, is that several tactics need to be combined together (Anderson, 2003). With sunflower, a single cultural tactic, such as narrower row spacing, higher plant population, or delayed planting, reduced weed biomass 5 to 10% compared with conventional practices used by producers (Fig. 4). When two practices were combined, biomass suppression approached 20 to 25%. However, weed biomass was reduced almost 90% when three tactics were integrated together. Combining tactics together synergistically enhanced sunflower suppression of weed growth. A similar trend occurred in corn with narrow row spacing, higher plant population, and fertilizer placement; again, a system of three cultural practices greatly reduced weed growth (Fig. 4).

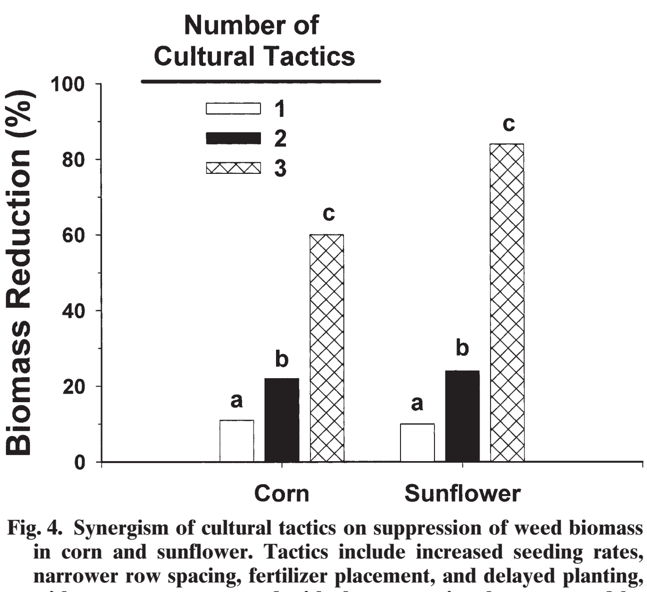

Fig. 4. Synergism of cultural tactics on suppression of weed biomass in corn and sunflower. Tactics include increased seeding rates, narrower row spacing, fertilizer placement, and delayed planting, with treatments compared with the conventional system used by producers. Bars with an identical letter within a crop are not significantly different based on Fisher's Protected LSD (0.05). Means for single tactic treatments did not differ from the conventional system (adapted from Anderson, 2003).

This synergistic trend with cultural tactics in suppressing weed growth also occurs with proso millet and winter wheat (Anderson, 2003). With proso millet, a cultural system of three tactics—N banding by the seed, higher plant population, and delayed planting—reduced both biomass and seed production of redroot pigweed 90% (Anderson, 2000).

Producers enhance benefits gained with tactics in other categories of their management system by minimizing seed productivity of weed escapes with competitive canopies. As mentioned earlier, some producers started using liquid fertilizers to reduce the need for tillage; this formulation also allows producers to place fertilizers near the seed row without tillage.

BENEFITS OF ECOLOGICALLY BASED WEED MANAGEMENT

Diverse crop rotations with no-till in the Central Great Plains have increased net economic returns fourfold compared with the winter wheat–fallow rotation (Agricultural and Food Policy Center, 2005). Improved economics with diversified rotations reflect both higher land productivity (Anderson et al., 1999) as well as lower input costs.

Cost of weed management with the multi-tactic approach (Fig. 1) is 50% less because lower weed community density reduces the need for herbicides. With winter wheat–corn–proso millet–fallow, winter wheat and proso millet can be grown without in-crop herbicides; weed density is so low that crop yield is not affected by weeds (Anderson, 2003). Furthermore, lower weed community density improves herbicide performance; both soil- and foliar-applied herbicides are more effective at lower weed density (Winkle et al., 1981; Dieleman et al., 1999). The need for weed control tactics during fallow is also reduced. Producers can control weeds in no-till fallow with only two to three herbicide applications, contrasting with producers who till five to seven times with conventional winter wheat–fallow.

This approach, however, requires integration of tactics from all components. For example, warm-season weeds proliferate in a winter wheat–corn–proso millet rotation, comprised of two warm-season crops and one cool-season crop, even though weed management includes crop diversity, no-till, crop residue conservation, and competitive canopies (Anderson, 2003). A similar trend occurs with a 5-yr rotation of winter wheat–corn–proso millet–corn–fallow; density of warm-season weeds increases across time. As mentioned earlier, tillage minimizes the benefits of this cultural approach by prolonging seed survival in soil and increasing weed seedling emergence.

This conceptual framework (Fig. 1) also helps with future planning. Producers are concerned about N fertilizer costs and long fallow intervals (12–14 mo) as well as excessive glyphosate [*N*-(phosphonomethyl)glycine] use. To address these concerns, producers are testing legumes for green fallow (growing crops for 6 to 8 wk before termination) in a winter wheat–corn–proso millet–green fallow rotation. Their goal is to supply biological N, eliminate one glyphosate application by suppressing weeds, and reduce length of the noncrop interval before winter wheat (Anderson, 2005). Producers initially considered soybean [*Glycine max* (L.) Merr.], a warm-season legume. However, noting the benefits gained for weed management with rotation design and life cycle intervals, producers shifted their emphasis to field pea (*Pisum sativum* L.) and lentil (*Lens culinaris* L.), cool-season legumes. They recognize that including soybean in winter wheat–corn–proso millet–green fallow would favor warm-season weeds.

REFERENCES

Agricultural and Food Policy Center. 2005. Representative farms economic outlook for the January FAPRI/AFPC baseline. Available at www.afpc.tamu.edu (accessed 14 Apr. 2005; verified 17 Aug. 2005). Agric. and Food Policy Center, College Station, TX.

Anderson, R.L. 1994. Characterizing weed community seedling emergence for a semiarid site in Colorado. Weed Technol. 8:245–249.

Anderson, R.L. 1998. Seedling emergence of winter annual grasses as affected by limited tillage and crop canopy. Weed Technol. 12: 262–267.

Anderson, R.L. 1999. Cultural strategies reduce weed densities in summer annual crops. Weed Technol. 13:314–319.

Anderson, R.L. 2000. A cultural systems approach eliminates the need for herbicides in semiarid proso millet. Weed Technol. 14:602–607.

Anderson, R.L. 2003. An ecological approach to strengthen weed management in the semiarid Great Plains. Adv. Agron. 80:33–62.

Anderson, R.L. 2004. Impact of sub-surface tillage on weed dynamics in the Central Great Plains. Weed Technol. 18:186–192.

Anderson, R.L. 2005. Improving sustainability of cropping systems in the Central Great Plains. J. Sustain. Agric. 26:97–114.

Anderson, R.L., R.A. Bowman, D.C. Nielsen, M.F. Vigil, R.M. Aiken, and J.G. Benjamin. 1999. Alternative crop rotations for the central Great Plains. J. Prod. Agric. 12:95–99.

Crutchfield, D.A., G.A. Wicks, and O.C. Burnside. 1986. Effect of winter wheat (*Triticum aestivum*) straw mulch level on weed control. Weed Sci. 34:110–114.

Dieleman, J.A., D.A. Mortensen, and A.R. Martin. 1999. Influence of velvetleaf (*Abutilon theophrasti*) and common sunflower (*Helianthus annuus*) density variation on weed management outcomes. Weed Sci. 47:81–87.

Egley, G.H., and R.D. Williams. 1990. Decline of weed seeds and seedling emergence over five years as affected by soil disturbance. Weed Sci. 38:504–510.

Farahani, H.J., G.A. Peterson, and D.G. Westfall. 1998. Dryland cropping intensification: A fundamental solution to efficient use of precipitation. Adv. Agron. 64:197–223.

Heap, I. 2005. The international survey of herbicide resistant weeds. Available at www.weedscience.com (accessed 21 June 2005; verified 17 Aug. 2005).

Lyon, D.J., S.D. Miller, and G.A. Wicks. 1996. The future of herbicides in weed control systems of the Great Plains. J. Prod. Agric. 9:209–215.

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

Mortensen, D.A., L. Bastiaans, and M. Sattin. 2000. The role of ecology in the development of weed management systems: An outlook. Weed Res. 40:49–62.

Moyer, J.R., E.S. Roman, C.W. Lindwall, and R.E. Blackshaw. 1994. Weed management in conservation tillage systems for wheat production in North and South America. Crop Prot. 13:243–259.

Pedigo, L.P. 1995. Closing the gap between IPM theory and practice. J. Agric. Entomol. 12:171–181.

Popay, A.I., T.I. Cox, A. Ingle, and R. Kerr. 1994. Effects of soil disturbance on weed seedling emergence and its long-term decline. Weed Res. 34:403–412.

Roberts, H.A. 1981. Seed banks in soils. Adv. Appl. Biol. 6:1–55.

Sagar, G.R., and A.M. Mortimer. 1976. An approach to the study of the population dynamics of plants with special reference to weeds. Adv. Appl. Biol. 1:1–47.

Streibig, J.C. 1979. Numerical methods illustrating the phytosociology of crops in relation to weed flora. J. Appl. Ecol. 16:577–587.

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

Wicks, G.A., D.A. Crutchfield, and O.C. Burnside. 1994. Influence of wheat (*Triticum aestivum*) straw mulch and metolachlor on corn (*Zea mays*) growth and yield. Weed Sci. 42:141–147.

Winkle, M.E., J.R.C. Leavitt, and O.C. Burnside. 1981. Effects of weed density on herbicide absorption and bioactivity. Weed Sci. 29:405–409.