Impact of Sub-Surface Tillage on Weed Dynamics in the Central Great Plains[1]

RANDY L. ANDERSON[2]

Abstract: Maintaining crop residues on the soil surface has changed cropping practices in the Central Great Plains. Where previously winter wheat-fallow was the prevalent rotation, producers now grow warm-season crops in sequence with winter wheat and fallow. Controlling weeds during fallow with herbicides eliminates the need for tillage, thus conserving more crop residues. However, producers are considering sub-surface tillage as an option to manage herbicide-resistant weeds. We reviewed the impact of sub-surface tillage with the sweep plow on weed dynamics and crop growth compared with no-till systems. Cropping systems studies show that rotations can be designed to reduce weed community density several-fold; tillage lessens this rotational effect by burying weed seeds and prolonging their survival in soil. Crop residues on the soil surface reduce weed seedling establishment in no-till systems, but tillage eliminates this effect. Crops also yield less after tillage compared with no-till in this semiarid climate. Tillage may help in managing herbicide resistance, but it also may increase weed density as well as reduce crop yield.

Nomenclature: Winter wheat, *Triticum aestivum* L.
Additional index words: Crop residues, rotation design; seed bank dynamics; sweep plow.

INTRODUCTION

Crop residue management has changed cropping practices in the Central Great Plains. Previously, winter wheat-fallow was the prevalent rotation. Fallow, an interval of time when neither crops nor weeds are allowed to grow so that precipitation can be stored in soil, was developed to help producers stabilize winter wheat yields in this semiarid climate. However, maintaining crop residues on the soil surface improves precipitation storage in soil such that producers can grow more crops in succession before fallow is needed (Peterson et al. 1996). Producers now grow corn (*Zea mays* L.), sunflower (*Helianthus annuus* L.), sorghum [*Sorghum bicolor* (L.) Moench], or proso millet (*Panicum miliaceum* L.) in sequence with winter wheat and fallow.

The benefits of crop residues are closely related to its quantity on the soil surface. Greb (1983) found that precipitation storage during fallow increased 1 cm for every 1,000 kg/ha of winter wheat residues, and Wicks et al. (1994) reported that corn grain yield increased 5 to 8%

---

[1]Received for publication and in revised form .

[2]Research Agronomist, USDA-ARS, 2923 Medary Avenue, Brookings, SD 57006. Author's E-mail: randerson@ngirl.ars.usda.gov.

for each additional 1,000 kg/ha of winter wheat residues. Because crop residues improve crop performance, producers seek to maximize residue quantity on the soil surface.

When winter wheat producers and scientists first recognized the value of residue management in the 1950s, they developed sub-surface tillage implements such as the sweep plow or rod weeder, which led to the stubble mulch system. With stubble mulch, weeds are controlled during fallow with a sweep plow, which 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 because of low soil disturbance, contrasting with tillage by a tandem-disk harrow or moldboard plow that buries 60 to 100% of crop residues (Good and Smika 1978). Crop residue management is further improved with no-till systems, where herbicides replace tillage for weed control during fallow. Several producers in the region now rely completely on no-till systems for crop production.

Producers, however, are concerned about herbicide-resistant weeds in the Central Great Plains. When no-till was first developed, producers relied on atrazine to control weeds during fallow. Now, biotypes of kochia [*Kochia scoparia* (L.) Schrad.], green foxtail [*Setaria viridis* (L.) Beauv.], redroot pigweed (*Amaranthus retroflexus* L.) and barnyardgrass [*Echinochloa crus-galli* (L.) Beauv.] are resistant to atrazine (Heap 2003).

Glyphosate also is used for weed control during fallow because of favorable economics and cropping flexibility. However, species shifts have led to weeds that required higher rates for control. For example, horseweed [*Conyza canadensis* (L.) Cronq.], toothed spurge (*Euphorbia serrata* L.), tumble windmillgrass (*Chloris verticillata* Nutt.), and wild buckwheat (*Polygonum convolvulus* L.) are increasing in producer fields. These species require double the recommended-use rates of glyphosate for their control (Gail Wicks, personal communication).

Because of resistant weeds and species shifts, input costs for weed control during non-crop intervals are escalating, as herbicide alternatives to glyphosate or atrazine are more expensive. For economic reasons and resistance management, no-till producers are considering tillage as an alternative weed control option, and they want to know the impact of occasional subsurface tillage on weed populations. Tillage affects weed dynamics because burial of weed seeds in soil influences seed germination and survival in the seed bank (Froud-Williams et al. 1984; Roberts 1981). For example, one operation with the sweep plow increased seedling emergence of downy brome (*Bromus tectorum* L.) and jointed goatgrass (*Aegilops cylindrica* Host) two-fold compared with a no-till system during the first year after tillage (Anderson 1998). Increased seedling emergence reflects the placement of weed seeds in more favorable sites for germination by the sweep plow.

To help producers assess the value of tillage in managing herbicide resistance, we reviewed recent research in the Central Great Plains that quantified weed dynamics and crop response to systems involving sub-surface tillage compared with no-till. We also discuss possible alternatives to tillage in devising cropping systems that minimize selection pressure for resistant weeds.

SUBSURFACE TILLAGE AND WEED DYNAMICS IN THE CENTRAL GREAT PLAINS

Interaction of Tillage with Rotation Design on Weed Community Density. Winter wheat-fallow has been the prevalent rotation in the Central Great Plains since the 1930s. With this rotation, producers have struggled to control winter annual grasses, especially downy brome (Wicks and Smika 1990). Over a series of decades, Fenster et al. (1969) and Fenster and Wicks (1982) explored various management systems in winter wheat-fallow for downy brome control.

They compared a range of tillage systems, including stubble mulch and no-till, and found that downy brome continued to infest winter wheat regardless of management during fallow. They noted that environmental conditions, such as timing of precipitation after winter wheat planting, influenced downy brome density as much as tillage system.

Moyer et al. (1994), in an extensive review of conservation tillage systems in winter wheat, found similar results in that downy brome was prominent in both conservation and conventional tillage. Conversation tillage was defined on the basis of crop residue quantities on the soil surface, and included both reduced-till and no-till systems. They also reported that other weed species have been shown to increase in both systems, and they suggested that this trend may reflect short-interval rotations comprised of only one or two crops. The authors hypothesized that weed densities may decrease in conservation tillage if rotations were comprised of several crops and sequenced across a longer duration.

The results of Daugovish et al. (1999) in the Central Great Plains support this hypothesis. They examined long-term dynamics of the winter annual grasses, jointed goatgrass and feral rye (*Secale cereale* L.), in winter wheat as affected by tillage and rotation. These species were prominent in winter wheat-fallow with both sweep plow tillage and no-till after 8 yr. If warm-season crops such as sunflower or proso millet were added to the rotation, jointed goatgrass and feral rye were almost eliminated. Their density in rotations that included a warm-season crop was more than 100-fold less than in the winter wheat-fallow rotation. The 2-yr interval between winter wheat crops reduced weed density because of greater loss of viable seeds in soil.

Wicks et al. (1988) further examined the impact of a 2-yr interval on weeds in a winter wheat-sorghum-fallow rotation in western Nebraska, assessing both cool- and warm-season species. This study compared no-till and a tilled system of sweep plow operations as needed for weed control during non-crop intervals; weeds were controlled in crops with herbicides. The weed community consisted of downy brome, barnyardgrass, green foxtail, kochia, redroot pigweed, Russian thistle (*Salsola iberica* Sennen & Pau), stinkgrass [*Eragrostis cilianensis* (All.) E. Mosher], and witchgrass (*Panicum capillare* L.). After 18 yr, the weed community differed between the two tillage systems, with density of all species being less in no-till. For example, downy brome density was five-fold less in no-till compared with the sweep plow system. Similar trends occurred with other species, as density among species was three- to five-fold less in no-till.

With improved moisture conditions in no-till systems (Peterson et al. 1996), producers are seeking to minimize fallow by including more warm-season crops in the rotation. Therefore, in the early 1990s, several cropping systems studies were started in the Central Great Plains to evaluate rotations comprised of winter wheat, various warm-season crops, and fallow. Several years after initiation of the studies, we assessed weed community changes for studies located at Pierre and Wall, South Dakota, and Akron, Colorado (Anderson 2002, 2003). At all sites, crop and weed management tactics were similar to practices used by producers in the region. The weed community at these sites was similar to the rotation study in Nebraska (Wicks et al. 1988), except barnyardgrass was not present.

With all studies, designing rotations based on 2-yr intervals of crops with similar growth periods reduced weed density compared with rotations of shorter duration. For example, at Pierre, various rotations were comprised of cool-season crops such as winter wheat and dry pea (*Pisum sativum* L.), and warm-season crops such as corn, soybean (*Glycine max* Merrill), and chickpea (*Cicer arietinum* L.). Planting of warm-season crops usually occurred in early May, whereas dry pea was planted in late March or early April. Averaged across all phases of the rotation, weed density in winter wheat-fallow (W-F) was 31 plants/m^2, with downy brome being the main weed species (Figure 1). With a winter wheat-chickpea rotation (W-CP), weed community density increased to 60 plants/m^2 and included summer annual weeds such as green foxtail, stinkgrass, witchgrass, and redroot pigweed, as well as downy brome. In winter wheat-corn-chickpea (W-C-CP), downy brome was rarely observed, but density of summer annual weeds was 25 plants/m^2. A 4-yr rotation comprised of two cool-season crops, winter wheat and dry pea, followed by two warm-season crops, corn and soybean (W-C-SB-Pea), reduced weed community density to only 5 plants/m^2. Weed density in the 4-yr rotation was 12-fold less compared with W-CP and five-fold less compared with W-C-CP.

Similar results occurred at the other sites; weed density was lowest in 4-yr rotations comprised of 2-yr intervals of cool- and warm-season crops (fallow, if used, fits in either category). Winter wheat-corn-sunflower-spring wheat at Wall and winter wheat-corn-proso millet-fallow at Akron reduced weed density several-fold compared with rotations such as winter wheat-proso millet or winter wheat-corn-proso millet (Anderson 2003).

Arranging cool- or warm-season crops in 2-yr intervals helps weed management because it favors the natural loss of viable seeds in soil. Survival of weed seeds in soil follows a typical trend, with rapid loss of viable seeds in the first 2 yr after shedding (Egley and Williams 1990; Roberts 1981). With green foxtail and downy brome, less than 10% of seeds are viable after 2 yr in soil (Anderson 2003). In the 4-yr rotation, control strategies in the 2-yr interval of cool-season crops prevents seed production of warm-season weeds, whereas seed production of cool-season weeds is prevented during the 2 yr of warm-season crops. Thus, if weed seeds are not added to the seed bank, the natural loss of viable weed seeds during the 2-yr interval can reduce potential seedling density in future years more than 90%.

However, we were surprised that impact of rotation design on weed density differed among the three sites. Weed density between 4-yr and 2-yr rotations differed only three-fold at Wall and six-fold at Akron, contrasting with the 12-fold difference at Pierre (Table 1). This contrast in weed density does not reflect differences in weed community composition, as the prominent weeds at all sites were downy brome, green foxtail, kochia, redroot pigweed, Russian thistle, stinkgrass, and witchgrass.

A key difference among studies was tillage intensity (Table 1). At Wall, tillage with the sweep plow incorporated herbicides and fertilizer as well as controlled weeds during fallow, with one to three tillage operations occurring each year; at Akron, tillage occurred once during the rotation cycle. The study at Pierre was no-till in all years. Differences among rotations at the three sites suggest that tillage decreases the impact of rotation design on weed dynamics. A second trend with these studies also suggests that tillage favors weeds. Weed community density was assessed in nine rotations at both Wall and Pierre; averaged across all rotations, weed density was six-fold greater at Wall (Anderson 2003).

Tillage usually stimulates a flush of seedlings by placing some weed seeds in more favorable sites in soil for germination, thus reducing weed seed density in the seed bank (Roberts 1981). However, burial of weed seeds in soil by tillage also prolongs their survival over time because soil protects seeds from environmental extremes (Egley 1986; Froud-Williams et al. 1984). For example, green foxtail seed survival after 2 yr was greater than 50% when seeds were buried 10 cm in soil, contrasting with less than 10% of seeds surviving when they remained on the soil surface (Banting et al. 1973; Thomas et al. 1986). Even when green foxtail seeds were buried only 1 or 5 cm in soil, survival was still two-fold greater after 2 yr compared with seeds remaining on the soil surface. This trend also occurs with other species. Sagar and Mortimer

(1976) found that wild oat (*Avena fatua* L.) seed survival over winter was five times greater when seeds were buried 5 cm deep compared with seeds lying on the soil surface. Egley and Williams (1990) found similar results with summer annual weeds.

Initial research on the interaction of weeds and tillage reported that weed densities, especially annual grasses, usually were greater in no-till systems (Froud-Williams et al. 1983; Pollard and Cussans 1981). However, other studies, such as Derksen et al. (1993), found that this trend does not always occur. Moyer et al. (1994) cited numerous examples where a specific weed species responded differently to tillage between studies. To understand the processes whereby tillage influences weed dynamics, Mohler (1993) developed a mathematical model based on published data. His model suggested that weed seedling emergence would be highest in no-till the first yr after seed shed compared to shallow tillage or plowing. In contrast, seedling emergence in no-till would be less during later yr compared to tilled systems because the surface seed pool in no-till is depleted by emergence and mortality. However, this trend occurs only if weed seed entry to the surface seed bank is prevented during this period, otherwise, seedling density remains higher in no-till than tilled systems.

The density trends observed with the rotation studies in the Central Great Plains agree with the model's prediction with no-till. Seed production of cool-season weeds is prevented during the 2-yr interval of warm-season crops, thus eliminating seed entry to the seed bank during those yr. Similarly, seed production of warm-season weeds is avoided during the cool-season crop interval. The 2-yr interval favors the natural decline of weed seed density in the seed bank. However, with the weed community at these sites, tillage with the sweep plow lessened the beneficial effect of the 2-yr interval by prolonging weed survival in the seed bank (Table 1).

Tillage Eliminates Crop Residue Suppression of Weed Establishment. A benefit of crop residues on the soil surface is that weed establishment is reduced (Crutchfield et al. 1986). Compared to a bare soil surface, 1,700 kg/ha of residue reduced weed density 17% whereas 6,800 kg/ha of residue reduced weed density more than 80% (Figure 2). Crop residues suppress weed establishment in a variety of ways, such as altering environmental conditions related to germination, physically impeding seedling growth, or inhibiting germination and growth by allelopathy (Crutchfield et al. 1986; Wicks et al. 1994).

In a study evaluating cultural systems for control of winter annual grasses in winter wheat (Anderson 1997), we noted that quantity of winter wheat residues remaining after harvest varied among cultural systems. Winter wheat grown with conventional practices left approximately 4,000 to 4,500 kg/ha of crop residues on the soil surface after harvest. In contrast, winter wheat produced 6,000 to 6,500 kg/ha of crop residues with a cultural system comprised of higher seeding rate, taller cultivar, and N fertilizer banded with the seed.

Because tillage may stimulate weed emergence (Roberts 1981), we wondered if extra crop residues produced with cultural systems in winter wheat could minimize tillage-induced weed emergence. To test this hypothesis, we compared two production systems in winter wheat, one producing higher residue levels compared with levels achieved with conventional practices, for impact on weed density in corn, sunflower, or proso millet planted the following year (Anderson 1999). We also compared tillage and no-till during the interval after wheat harvest and before planting the warm-season crops in both production systems of winter wheat. Plots were tilled twice with the sweep plow in the fall after winter wheat harvest, followed by one tillage operation in the spring. In no-till, herbicides controlled weeds during the interval between winter wheat harvest and planting. The weed community was comprised primarily of green foxtail, kochia, redroot pigweed, Russian thistle, and witchgrass.

As expected, the high-residue system reduced weed emergence 35 to 50% among the three warm-season crops compared with the normal-residue system in no-till. However, our hypothesis that extra crop residues would mask the effect of tillage on weed emergence was proven false. For example, weed density in corn declined from 108 seedlings/m^2 in the normal residue level with tillage to 76 seedlings/m^2 in no-till (Figure 3). Density declined further to 62 seedlings/m^2 in the high residue treatment with no-till. However, tillage in the high-residue system increased weed density from 62 to 102 seedlings/m^2, thus eliminating the crop residue effect on emergence. Similar results occurred with sunflower and proso millet. Burial of residues and weed seeds by tillage apparently altered the weed seed-soil interaction such that weed emergence was increased regardless of residue quantity on the soil surface.

Because weed seed loss is high when seeds are left on the soil surface over winter (Egley and Williams 1990; Sagar and Mortimer 1976), we hypothesized that delaying the initial tillage with the sweep plow until the next spring may minimize the differences in weed density between tillage systems. Therefore, we compared weed density in proso millet between no-till and sweep plow tillage, with the initial tillage occurring 4 wk before planting proso millet in early June (Anderson 2000). Our goal was to favor the natural loss of weed seeds during winter before tilling. The previous crop was winter wheat grown to produce high quantities of crop residues, and the weed community was primarily redroot pigweed and tumble pigweed (*Amaranthus albus* L.).

Even with delay of tillage until spring, however, pigweed density still was six-fold greater after tillage compared with no-till. The greater loss of weed seeds over winter did not compensate for increased seedling emergence due to tillage. The density of pigweeds in the tilled system reduced proso millet grain yield 17%, but weed interference did not affect grain yield in no-till. A further consequence of tillage was that the pigweed plants infesting proso millet produced 48,300 seeds/m^2, more than nine-fold greater than pigweed seed production in the no-till system.

Crops Yield Less after Tillage. Another consequence of tillage is that crops yield less when tillage with the sweep plow occurs in the non-crop interval before planting. Compared with no-till, yield loss in tilled systems for warm-season crops ranged from 29% for corn to 13% with sunflower (Figure 4). Sorghum and proso millet also yielded less after tillage. With winter wheat, where four to six operations with the sweep plow occurred during the fallow period, yield was reduced more than 30% compared with no-till.

One reason why crops yield less after tillage is less favorable moisture conditions. For example, available soil water at planting time for winter wheat was 7 cm less after stubble mulch fallow compared with a no-till system (Anderson et al. 1999). No-till systems increase soil water because crop residues improve precipitation infiltration as well as reduce water evaporation from the soil surface (Peterson et al. 1996). Tillage, by burying crop residues, reduces efficiency of precipitation storage in this semiarid climate.

Implications for Central Great Plains Weed Management. Producers are adjusting their production systems to address herbicide resistance. Tillage is one option to reduce selection pressure on the weed community. However, tillage with the sweep plow may increase weed density in crops (Table 1; Figure 3) and reduce crop yield (Figure 4). If producers choose to till, it would be least detrimental if tillage preceded winter wheat. Tilling during fallow, 3 to 4 mo before planting winter wheat, does not affect winter wheat yields compared with no-till (Smika 1990), whereas weeds emerging after tillage can easily be controlled with herbicides before planting winter wheat. However, if several tillage operations occur during fallow that precedes winter wheat, yields can be reduced 15 to 35% (Anderson et al. 1999; Smika 1990). Tillage before planting warm-season crops may force producers to increase inputs for weed control in the crop because of higher weed density.

No-till systems provide other options for producers to manage herbicide resistance. The diversity of crops that can be grown because of no-till provides more opportunities for producers to rotate herbicides with different modes of action (Retzinger and Mallory-Smith 1997). In addition, producers following rotations comprised of 2-yr intervals with both cool- and warm-season crops have lowered weed community density such that herbicide inputs can be reduced 50% (Anderson 2003). In 4-yr rotations with no-till, some crops, such as proso millet, do not need herbicides for weed control (Anderson 2000).

Nevertheless, a serious obstacle in no-till systems is weed control during fallow; producers are seeking options to reduce glyphosate or atrazine use during fallow. Herbicides with different modes of action that effectively control weeds during fallow, but costs similar to glyphosate or atrazine would be helpful. Another option is green fallow, where a crop is grown only for vegetative growth before being killed with herbicides. For example, sweetclover (*Melilotus officinalis* Lam.) grown over-winter reduced weed density 75 to 97% during fallow, compared with conventional fallow (Blackshaw et al. 2001). In the Central Great Plains, however, crop growth required for that level of weed suppression reduced winter wheat yield because of excessive water use (Schlegel and Havlin 1997). In contrast, wheat yields were not affected if a green fallow crop such as dry pea was grown in the spring for only 6 wk (Tanaka et al. 1997). If green fallow could suppress weeds for 6 wk, producers may be able to reduce selection pressure by glyphosate on the weed community. The interval of green fallow suppression could be related to periods of peak glyphosate use in previous years.

A further consideration related to tillage is health and productivity of soil. Maintaining crop residues on the soil surface increases soil organic matter as well as minimizes wind erosion (Bowman et al. 1999; Peterson et al. 1993). The winter wheat-fallow system based on tillage reduced soil organic matter levels more than 50% during the last 100 yr; loss of organic matter reflects the low quantity of crop residues returned to soil when growing only one crop every 2 yr. In contrast, no-till systems are improving soil health in this region, as interactions among more favorable water relations, crop residue production, and intensive cropping are continually improving soil organic matter levels and crop performance (Anderson 2003). Tillage disrupts this soil regeneration by its detrimental effect on crop residue conservation and water relations.

LITERATURE CITED

Anderson, R. L. 1990a. No-till proso millet production. Agron. J. 82:577-580.

Anderson, R. L. 1990b. Tolerance of safflower, corn, and proso millet to clomazone. Weed Technol. 4:606-611.

Anderson, R. L. 1997. Cultural systems can reduce reproductive potential of winter annual grasses. Weed Technol. 11:608-613.

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. 2002. Designing rotations to favor natural benefits. *In* Proc., 2002 No-Till on the Plains Conference, Salinas KS. No-Till on the Plains Assoc., P.O. Box 379, Wamego KS. 66547. pp. 7-14.

Anderson, R. L. 2003. An ecological approach to strengthen weed management in the semiarid Great Plains. Advances in Agronomy 80:33-62.

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.

Anderson, R. L., D. J. Lyon, and D. L. Tanaka. 1996. Weed management strategies for conservation-till sunflower. Weed Technol. 10:55-59.

Banting, J. D., E. S. Molberg, and J. P. Gephardt. 1973. Seasonal emergence and persistance of green foxtail. Can. J. Plant Sci. 53:369-376.

Blackshaw, R. E., J. R. Moyer, R. C. Doran, and A. L. Boswell. 2001. Yellow sweetclover, green manure, and its residues effectively suppress weeds during fallow. Weed Sci. 49:406-413.

Bowman, R. A., M. F. Vigil, D. C. Nielsen, and R. L. Anderson. 1999. Soil organic matter changes in intensively cropped dryland systems. Soil Sci. Soc. Am. J. 63:186-191.

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.

Daugovish, O., D. J. Lyon, and D. D. Baltensperger. 1999. Cropping systems to control winter annual grasses in winter wheat (*Triticum aestivum*). Weed Technol. 13:120-126.

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

Egley, G. H. 1986. Stimulation of weed seed germination in soil. Reviews of Weed Science 2:67-89. Lawrence, KS: Weed Science Society of America.

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.

Fenster, C. R., C. E. Domingo, and O. C. Burnside. 1969. Weed control and plant residue maintenance with various tillage treatments in a winter wheat-fallow rotation. Agron. J. 61:256-259.

Fenster, C. R. and G. A. Wicks. 1982. Fallow systems for winter wheat in western Nebraska. Agron. J. 74:9-13.

Froud-Williams, R. J, R. J. Chancellor, and D. H. Drennan. 1984. The effects of seed burial and soil disturbance on emergence and survival of arable weeds in relation to minimal cultivation. J. Appl. Ecol. 21:629-641.

Froud-Williams, R. J., D. H. Drennan, and R. J. Chancellor. 1983. Influence of cultivation regime on weed floras of arable cropping systems. J. Appl. Ecol. 20:187-197.

Good, L. G. and D. E. Smika. 1978. Chemical fallow for soil and water conservation in the Great Plains. J. Soil Water Conserv. 33:89-90.

Greb, B. W. 1983. Water conservation: Central Great Plains. *In* H. E. Dregne and W. O. Willis, eds. Dryland Agriculture. Agronomy 23:57-72. Madison WI: American Society of Agronomy.

Heap, I. 2003. The International Survey of Herbicide Resistant Weeds. [Online] www.weedscience.com [accessed February 3, 2003].

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

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 Protection 13:243-259.

Peterson, G. A., A. J. Schlegel, D. L. Tanaka, and O. R. Jones. 1996. Precipitation use efficiency as affected by cropping and tillage systems. J. Prod. Agric. 9:180-186.

Peterson, G. A., D. G. Westfall, and C. V. Cole. 1993. Agroecosystem approach to soil and crop management research. Soil Sci. Soc. Am. J. 57:1354-1360.

Pollard, F. and G. W. Cussans. 1981. The influence of tillage on the weed flora in a succession of winter cereal crops on a sandy loam soil. Weed Res. 21:185-190.

Retzinger, E. J., Jr. and C. A. Mallory-Smith. 1997. Classification of herbicides by site of action for weed resistance management strategies. Weed Technol. 11:384-393.

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.

Schlegel, A. J. and J. L. Havlin. 1997. Green fallow for the Central Great Plains. Agron. J. 89:762-767.

Smika, D. E. 1990. Fallow management practices for wheat production in the Central Great Plains. Agron. J. 82:319-323.

Tanaka, D. L., A. Bauer, and A. L. Black. 1997. Annual legume cover crops in spring wheat-fallow systems. J. Prod. Agric. 10:251-255.

Thomas, A. G., J. D. Banting, and G. Bowes. 1986. Longevity of green foxtail seeds in a Canadian prairie soil. Can. J. Plant Sci. 66:189-192.

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.

Wicks, G. A. and D. E. Smika. 1990. Central Great Plains. *In* W. W. Donald, ed., Systems of Weed Control in Wheat in North America. Lawrence, KS: Weed Science Society of America. pp. 127-157.

Wicks, G. A., D. E. Smika, and G. W. Hergert. 1988. Long-term effects of no-tillage in a winter wheat (*Triticum aestivum*)-sorghum (*Sorghum bicolor*)-fallow rotation. Weed Sci. 36:384-393.

Table 1. Impact of tillage on differences in weed density when comparing a 4-yr rotation to a 2-yr rotation[a]. The studies at Akron, Colorado and Pierre, South Dakota were started in 1990; the study at Wall, South Dakota was initiated in 1994. Weed community density was assessed in the 8th yr of the study at Akron and Wall, and in the 11th yr of the study at Pierre. (Adapted from Anderson 2002, 2003).

Study site	Frequency of tillage	Magnitude of difference in weed density between 4-yr vs. 2-yr rotations
Wall	One to three times/year	3-fold
Akron	Once/rotation cycle	6-fold
Pierre	No tillage	12-fold

[a]Rotations compared were winter wheat-corn-sunflower-spring wheat vs. winter wheat-proso millet at Wall, winter wheat-corn-proso millet-fallow vs. winter wheat-proso millet at Akron, and winter wheat-corn-soybean-dry pea vs. winter wheat-chickpea at Pierre.

FIGURE CAPTIONS

Figure 1. Weed density in four rotations of a cropping systems study, Pierre, South Dakota. The study was initiated in 1990; weed community was assessed after the final weed management tactic occurred in each crop in 2000 and 2001. Means represent weed density averaged across all crops within each rotation across both years; bars with the same letter are not significantly different based on Fisher's LSD test (0.05). Abbreviations: W, winter wheat; CP, chickpea; C, corn; F, fallow; SB, soybean; and Pea, dry pea. (Adapted from Anderson 2003)

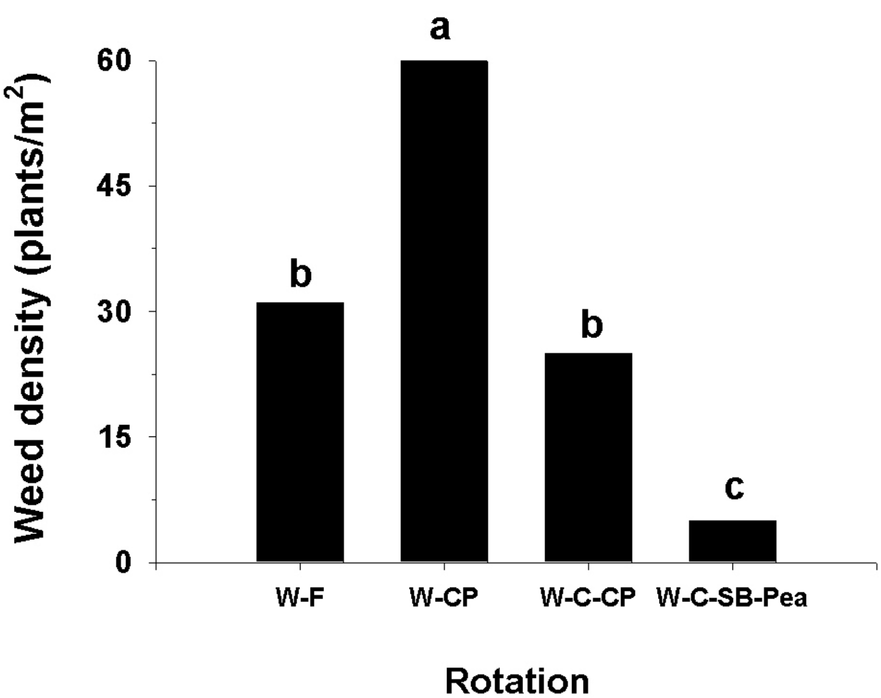

Figure 2. Suppression of weed seedling density as affected by quantity of winter wheat residue on the soil surface. Data represent weed emergence from March through September, and are averaged across two sites and two yr in western Nebraska. Bars with the same letter are not significantly different based on Fisher’s LSD test (0.05). (Adapted from Crutchfield et al. 1986).

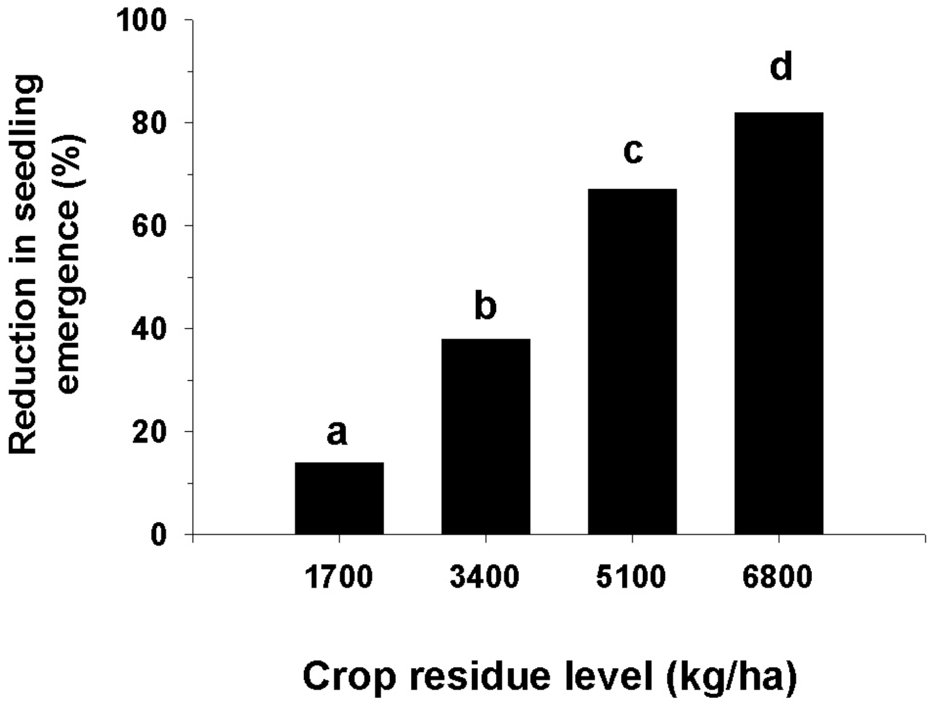

Figure 3. Effect of winter wheat residue and tillage on weed density in corn. Residue level for normal treatment was approximately 4000 kg/ha and 6000 kg/ha for the high treatment. Means were averaged across 3 yr. Bars with the same letter are not significantly different based on Fisher's LSD test (0.05). (Adapted from Anderson 1999).

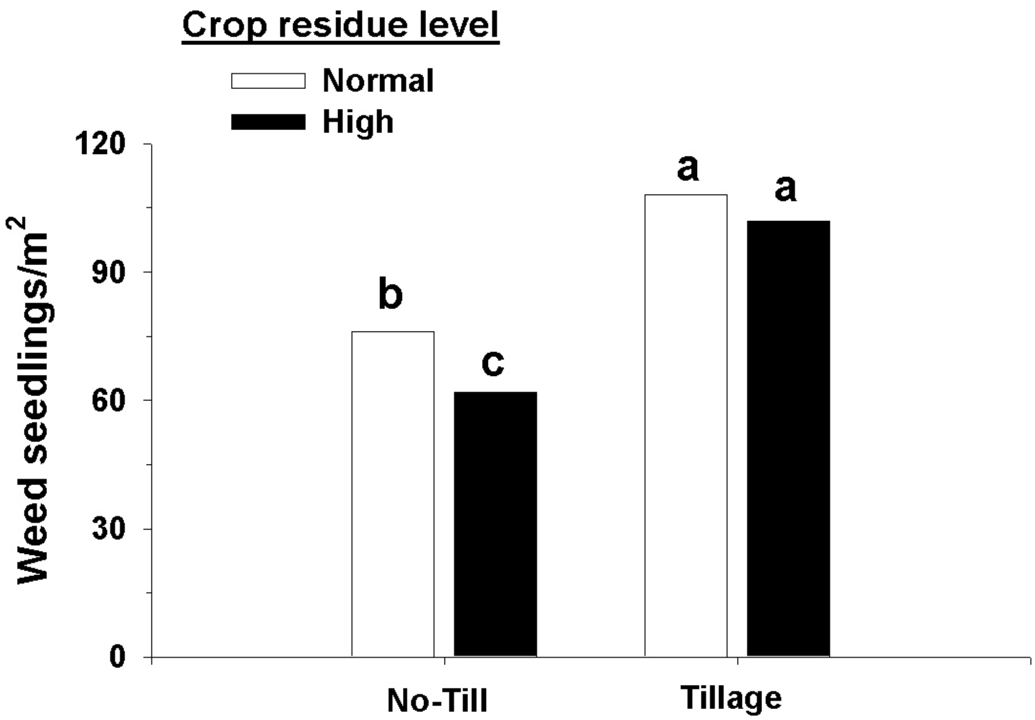

Figure 4. Crop yield reduction in the Central Great Plains in tilled systems compared with no-till systems. All crops were planted after winter wheat with disk-opener planters. With corn, sorghum, proso millet, and sunflower, three operations with the sweep plow controlled weeds during the interval between winter wheat harvest and planting of the summer annual crop. With winter wheat, four to six operations with the sweep plow occurred during the fallow interval before planting winter wheat. Yields were significantly different between no-till and tilled treatments for all crops based on Fisher's LSD test (0.05). (Adapted from Anderson 1990a, 1990b; Anderson et al. 1996, 1999; and Wicks et al. 1988).