

## A Changing Perspective with Weed Management in Semi-arid Cropping Systems

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**Abstract:** No-till cropping systems are improving precipitation-use-efficiency, increasing land productivity, and restoring soil health in semi-arid regions of the world. However, weed resistance, rising costs, and concern about environmental impacts are stimulating questions about the extensive reliance on herbicides with no-till. Scientists and producers are seeking a broader perspective with weed management. One approach is disrupting weed population growth with cultural tactics, thus supplementing herbicides in controlling weeds. This paper describes a successful system based on this approach in the semi-arid steppe of the United States that controls weeds with 50% less inputs, reduces need for herbicides, and increases net returns for producers. Two key components of this approach are rotation design and no-till. Rotations comprised of crops with different life cycles, such as cool-season and warm-season crops, suppress weed population growth. No-till improves crop growth by its favorable impact on water relations and weed management by its detrimental impact on weed seed survival in soil. In addition, cultural tactics improve crop competitiveness to reduce weed seed production. We encourage scientists in semi-arid regions to integrate weed management with design of crop rotations, and also to consider crop diversity in regards to other aspects of crop production.

**Key words:** Crop diversity, no-till, rotation design, weed population management.

Water conservation is essential for successful crop production in semi-arid regions of the world. One practice used worldwide to conserve water is to keep land fallow, where crop and weed growth is eliminated during one cropping season to store precipitation in soil for future crop use. However, fallow degrades soil health by accelerating decomposition of soil organic matter. For example, in the semi-arid steppe of the US, organic matter levels in soils have declined by 60% since the 1930s with winter wheat (*Triticum aestivum* L.)-fallow (Bowman *et al.*, 1990). Wind erosion also is prominent during fallow, especially if fields are frequently tilled (Peterson *et al.*, 1993). Another aspect of fallow is its inefficiency

in storing precipitation in soil; often, less than 25% of the precipitation received during fallow is stored in the soil (Peterson *et al.*, 1996).

No-till practices improve water conservation as well as minimize the negative aspects of fallow by retaining crop residues on the soil surface (Peterson *et al.*, 1993). Furthermore, no-till with crop diversity restores soil health. In the US steppe, organic matter levels increased 20% after eight years with no-till rotations comprised of continuous cropping compared with winter wheat-fallow (Bowman *et al.*, 1999). Soil aggregate stability increased similarly (Wright and Anderson, 2000).

An additional benefit of no-till is that more crops can be grown in semi-arid climates. In the US steppe, maize (*Zea mays* L.), proso millet (*Panicum miliaceum* L.), sorghum (*Sorghum bicolor* (L.) Moench), and sunflower (*Helianthus annuus* L.) are now grown in sequence with winter wheat and fallow (Farahani *et al.*, 1998; Anderson *et al.*, 1999). These new cropping patterns stimulated producers to change their perspective of water management. Instead of focusing on precipitation storage during fallow, producers now consider precipitation-use-efficiency by rotation (Farahani *et al.*, 1998). For example, winter wheat-fallow converts approximately 40% of precipitation received during the crop season and fallow into crop growth; in contrast, winter wheat-maize-proso millet-fallow converts 65% of the precipitation during four years of the rotation into crop growth (Anderson, 2005c).

No-till cropping systems are effective because herbicides replace tillage for weed control. Yet, extensive herbicide use has negative consequences. First, weeds resistant to herbicides are now common (Heap, 2007); consequently, producers are forced to change management tactics, which often increases input costs. Even before weed resistance became prominent, herbicides expenditures comprised 20 to 30% of the input costs for crop production (Derksen *et al.*, 2002). A further concern is impact of herbicides on human health and the environment (Kropff and Walter, 2000).

These concerns highlight a paradox with no-till systems. Herbicides are necessary for weed management, yet their extensive use may curtail future success of no-till. Thus, producers in the US steppe are seeking a

different perspective to weed management. They are asking for alternatives to herbicide-centered management and for cropping systems that are not so dependent on herbicides. One approach is to expand weed management to include strategies that disrupt weed population growth and reduce density of the weed community (Anderson, 2005a). Because of crop diversity and no-till, producers in the US steppe were able to develop a weed population-centered approach to weed management. Cultural tactics decrease number of seeds of different weeds in the soil seedbank, reduce weed seedling establishment, and suppress seed production by weeds that escape control tactics. With this approach, producers effectively control weeds with 50% less inputs compared with the conventional winter wheat-fallow system. Use of herbicides is a choice with this approach, not a requirement for crop success.

Our paper describes this management approach in the US steppe that reduces both weed community density across time and need for herbicides to manage weeds. By explaining the ecological reasons why this approach is successful, we hope to provide scientists in other semi-arid regions of the world with a conceptual framework to guide development of similar management systems. Based on results in the US steppe, we believe that a weed population-centered approach can be a viable alternative to herbicide-centered weed management in semi-arid regions worldwide.

### **A Population-Centered Approach to Weed Management**

A goal of this approach is to increase the number of mortality events with weeds that occur during the growing season. Cultural tactics are chosen for impact on

seedbank dynamics, weed seedling emergence, and weed productivity. Consequently, number of plants that establish and produce seeds for perpetuating the population across time are reduced.

*Favoring weed seed mortality in the soil seedbank*

A diversity of crops with different life cycles enables producers to favor loss of live weed seeds in the soil seedbank. Weed seeds display a typical pattern with survival in soil; number of live seeds declines rapidly across time (Roberts, 1981; Egley and Williams, 1990). For example, downy brome (*Bromus tectorum* L.) and green foxtail (*Setaria viridis* (L.) Beauv.) are two prevalent annual weeds in the US steppe. The number of live seeds of these species remaining one year after seed enters the soil seedbank is approximately 20% (Fig. 1). After two years, less than 5% of the seeds still remain alive.

Density of downy brome, which is especially high in winter wheat-fallow, is being reduced with rotations such as winter wheat-sorghum-fallow or winter wheat-proso millet-fallow (Anderson, 2003). Seed production of downy brome is prevented during the two-year interval of the warm-season crop and fallow before winter wheat is planted again. This two-year interval without seed production lowers downy brome density in the seedbank to less than 4%, a five-fold difference compared to the one-year interval with winter wheat-fallow (Fig. 1). The lower seed density in soil reduces infestations in future crops. A similar benefit of two-year interval of winter wheat and fallow with these rotations is in reducing density of warm-season weeds that infest sorghum or proso millet.

This two-year interval of preventing weed seed production is also effective with rotations that do not include fallow. This trend was

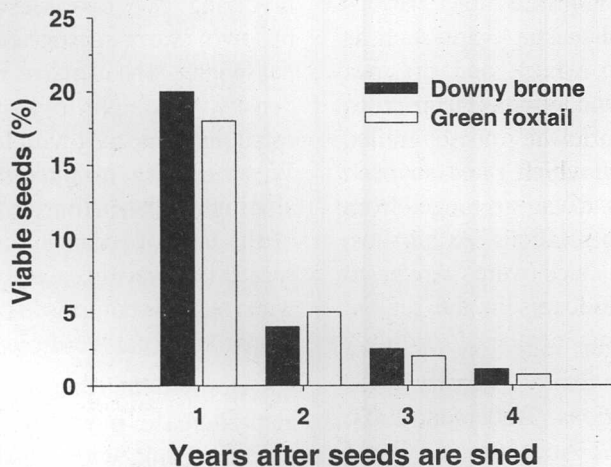


Fig. 1. Persistence of live seeds of downy brome and green foxtail, when seed remains within the top 3 cm of the soil surface. Data collated from several studies conducted in the semi-arid steppe of the US. Source: Anderson, 2003.

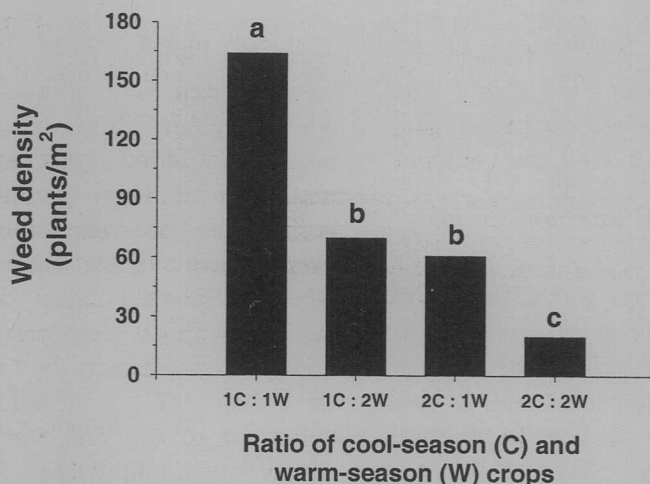


Fig. 2. Weed community density among rotations comprised of various ratios of cool- and warm-season crops. Data averaged across three long-term studies in the US semi-arid steppe. Cool-season crops included winter wheat, spring wheat, and dry pea, and warm-season crops were corn, proso millet, sunflower, chickpea, and soybean. Bars with an identical letter are not significantly different based on Fisher's LSD (0.05). Source: Anderson, 2003; Anderson et al., 2007; Anderson and Beck, 2007.

demonstrated in a series of long-term cropping system studies in the US steppe. Rotations were comprised of various combinations of cool-season crops such as winter wheat, spring wheat, and dry pea (*Pisum sativum* L.) and warm-season crops such as maize, sunflower, proso millet, chickpea (*Cicer arietinum* L.) and soybean (*Glycine max* Merrill). Rotations ranged from two-crop to four-crop rotations. At all sites, weed management tactics were similar to practices used by producers in the region.

Several years after initiation of these studies, weed community density was assessed among rotations (Anderson, 2003; Anderson et al., 2007; Anderson and Beck, 2007). Compared across all sites, weed community density was highest in two-crop rotations, such as winter wheat-proso millet

or winter wheat-chickpea (Fig. 2); in contrast, weed density was always lowest in rotations involving two cool-season crops followed by two warm-season crops, such as dry pea-winter wheat-maize-proso millet. Weed density was eight-fold greater in two-crop rotations compared with four-crop rotations. Weed density in three-crop rotations was also higher than in four-crop rotations because of the lack of balance among crop seasonal types; i.e. warm-season weeds proliferated with rotations comprised of two warm-season crops and one cool-season crop.

Along with rotation design, producers also increase mortality of weed seeds in the seedbank with no-till. Tillage buries weed seeds in soil, thus protecting seeds from environmental extremes and predation; in contrast, leaving weed seed on the soil

surface leads to extensive loss of seed viability (Froud-Williams, 1988). For example, Sagar and Mortimer (1976) compared winter survival of wild oat (*Avena fatua* L.) seeds left on the soil surface to seeds buried 2 to 5 cm in soil. Number of live seeds on the soil surface declined to less than 10% after 5 months; in contrast, over 50% of wild oat seeds buried in soil were still viable.

Seed burial affected survival of green foxtail, similarly in the semi-arid prairies of Canada (Banting *et al.*, 1973). Green foxtail seeds were placed 1 and 10 cm deep in the soil, as well as left on the soil surface. After one year, more than 70% of the seeds buried 10 cm deep were alive, in contrast only 20% seeds survived that remained on the soil surface (Fig. 3). After two years, seed survival was still five-fold higher when seeds were buried 10 cm deep. Even when seeds were buried only 1 cm in soil, survival

was still higher than seeds remaining on the soil surface. Similar results have been found in New Zealand (Popay *et al.*, 1994) and the southeastern US (Egley and Williams, 1990), where weed seeds die more rapidly when left on the soil surface.

With less seeds surviving with no-till, fewer weed seedlings emerge during the cropping season. This trend of fewer seedlings helps producers because herbicides are more effective at lower weed densities (Winkle *et al.*, 1981). Dieleman *et al.* (1999) found that number of broadleaf weeds surviving treatment of foliar-applied herbicides was related to initial density of plants. Hoffman and Lavy (1978) reported a similar trend with weed density and atrazine activity in soil; more plants escaped control at higher densities. Lower densities of weed seedlings lead to fewer plants escaping control tactics, producing seeds, and perpetuating the population.

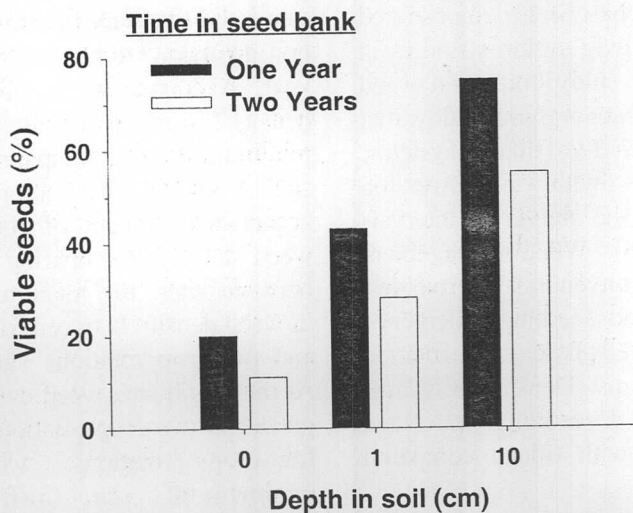


Fig. 3. Impact of seed depth in soil on survival of green foxtail across time. Study conducted in the semi-arid prairies of Canada. Analysis based on 95% confidence intervals indicated that means differed among all treatments within each year. Source: Banting *et al.*, 1973; Thomas *et al.*, 1986.

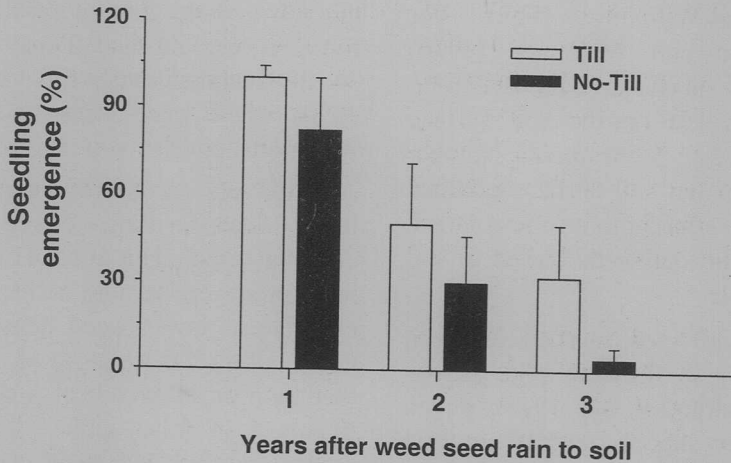


Fig. 4. Effect of tillage on weed seedling emergence across time. Weed seeds were not added to the soil after initiation of study; tillage occurred in the tilled treatment each year. Data expressed as a percentage of the treatment with the highest number of weed seedlings among four studies; standard error bars are based on yearly means among studies. Source: Anderson, 2005a.

The favorable impact of no-till on weed density in rotations has been demonstrated with long-term cropping systems studies in the US steppe. One study compared weed density in winter wheat-sorghum-fallow that was established with two tillage systems, no-till or tillage with non-inversion implements during the non-crop intervals (Wicks *et al.*, 1988). Weed management in crops relied on conventional herbicides. After 18 years, weed seedling emergence was compared across all phases of the rotation in both tillage systems. Density of warm- and cool-season weed seedlings was three to five-fold higher with tillage compared with no-till.

A similar trend was observed in the long-term cropping systems studies involving continuous cropping described above (Anderson *et al.*, 2007; Anderson and Beck, 2007). One site was no-till for duration of

the study whereas a second site was minimum-till, with one tillage operation by non-inversion implements occurring each year. Averaged across all rotations, weed density was five-fold higher at the minimum-till site compared with the no-till site. A second observation was that no-till accentuated impact of rotation design on weed density. Comparing rotation designs between sites, the magnitude of difference in weed density between four-crop rotations and two-crop rotations varied with tillage. At the no-till site, weed density was 13-fold greater in two-crop rotations compared with four-crop rotations, whereas at the minimum-till site, difference between rotation designs was only five-fold (Anderson, 2004b).

This interaction between no-till and rotation design is related to differences in weed seedling emergence across time. A

series of studies compared weed seedling emergence for three years in no-till and tilled treatments (Anderson, 2005a). The sites were naturally infested with weeds, but after initiation of each study, further weed seed rain was prevented. In the first year, weed seedling emergence was similar between tilled and no-till, whereas in the second year, difference between tillage treatments was about two-fold (Fig. 4). In contrast, seedling emergence was eight-fold greater in the third year with the tilled system; the benefit of no-till in reducing seedling emergence increased across time. No-till helps weed management, especially if rotations are arranged in a cycle-of-four, with two-year intervals of cool- and warm-season crops.

#### *Reducing weed seedling emergence*

Producers can reduce weed seedling emergence with crop residues on the soil surface and choice of crop sequences. Crop residues suppress weed germination and emergence by altering environmental conditions affecting germination, physically impeding seedling growth, or inhibiting germination and growth by allelopathy (Crutchfield *et al.*, 1986). Suppression of emergence begins with crop residue levels of 3000 kg ha<sup>-1</sup> and increases approximately 12% for each additional 1000 kg ha<sup>-1</sup> of crop residue (Wicks *et al.*, 1994).

No-till enhances impact of crop residues on weed seedling emergence by retaining crop residues on the soil surface and not burying weed seeds. A study conducted in the US steppe showed that one tillage operation with a sweep plow<sup>1</sup> eliminated suppression of weed emergence by crop

residues, even when residue levels remained high after tillage (Anderson, 1999). The sweep plow, with its shallow mixing of soil, apparently placed weed seeds in more favorable sites for germination and emergence, thereby minimizing impact of crop residues on weed seedling establishment.

Another tactic to reduce weed seedling density in the crop stand is varying planting dates. Producers can delay planting of a crop, which widens the interval to control weed seedlings before planting. But, this tactic is often ineffective (Wicks, 1984) and yields are usually decreased when crops are planted outside their optimum planting date range (Cook and Veseth, 1991).

In contrast, producers can vary planting dates by rotating crops having different optimum planting dates, thus helping weed management without sacrificing crop yield. This benefit was demonstrated with the long-term cropping systems studies in the US steppe noted above (Anderson *et al.*, 2007; Anderson and Beck, 2007). The beneficial impact of rotations comprised of two cool-season crops and two warm-season crops on weed density, shown in Fig. 2, occurs only if crops also differ within a seasonal category, i.e., cool-season crops.

For example, density of downy brome was 40-fold higher with rotations that included two years of winter wheat compared with four-crop rotations, where dry pea replaced winter wheat in one year. Seed decay of downy brome in the seedbank is minimal during the 3-month interval between winter wheat harvest and planting winter wheat again, thus seedling density

<sup>1</sup> A sweep plow is comprised of V-shaped blades 75 cm wide and severs weed roots with minimum soil disturbance, tilling to depth of 5 to 8 cm.

often escalates in the second wheat crop. But, including dry pea in the rotation minimizes population growth because downy brome seedlings can be easily controlled before dry pea is planted in early April. A similar benefit occurs with sequences of warm-season crops that have different planting dates, such as maize-sunflower or maize-proso millet. Sunflower and proso millet are planted three to four weeks later than maize.

### *Reducing weed productivity*

Even with effective weed management, some weeds escape control and produce seeds. Productivity of these weeds can be suppressed by improving crop competitiveness with cultural tactics. Several tactics are available, such as increased seeding rate or fertilizer placement, but a key to effectiveness is combining several tactics together (Anderson, 2005a). For example, wild rye (*Secale* spp.) is a prevalent weed in winter wheat. A single cultural tactic of growing a tall cultivar, increasing seeding rate, or banding fertilizer by the crop seed, suppressed wild rye seed production approximately 5% (Fig. 5). In contrast, integrating all three tactics together into a cultural system reduced seed production by 40%, an eight-fold increase compared to any single cultural practice.

A similar trend occurs with proso millet (Anderson, 2003). A single tactic of banding N by the seed, increasing crop density, or growing a taller cultivar, reduced seed production of redroot pigweed (*Amaranthus retroflexus* L.) approximately 20% (Fig. 5). When these three tactics were combined,

however, seed production was reduced more than 90%.

Crop diversity can further improve crop competitiveness with weeds. With no-till rotations, producers in the US steppe often plant winter wheat after spring wheat, but root diseases are common with this sequence (Cook and Veseth, 1991). Changing the preceding crop, however, suppresses these root diseases and improves winter wheat competitiveness with weeds. For example, wild rye produced 200 seeds/plant in winter wheat with a conventional canopy and following spring wheat (Fig. 6). Improving crop competitiveness with cultural tactics, such as increased seeding rates and N fertilizer placement, reduced wild rye seed production 45%. However, when a forage mixture, oat (*Avena sativa* L.)/dry pea, was grown before winter wheat, the competitive canopy in winter wheat reduced wild rye production to only 49 seeds/plant, a 75% reduction.

### *Ancillary benefit of competitive canopies: Improved tolerance to weed interference*

Competitive canopies also improve crop tolerance to weeds (Anderson, 2003). With proso millet, a cultural system of banding N by the seed, increasing plant density, and growing a taller cultivar reduced yield loss due to weed interference to 2%, contrasting with 29% yield loss due to weeds with the conventional system used by producers. A similar benefit occurred with maize. Yield loss due to grass (*Setaria* spp.) interference was 43% when maize was planted at 37,000 plants ha<sup>-1</sup> in rows 76 cm apart with N fertilizer applied broadcast. In contrast, a cultural system comprised of N banding by the seed row, row spacing of 50 cm, and

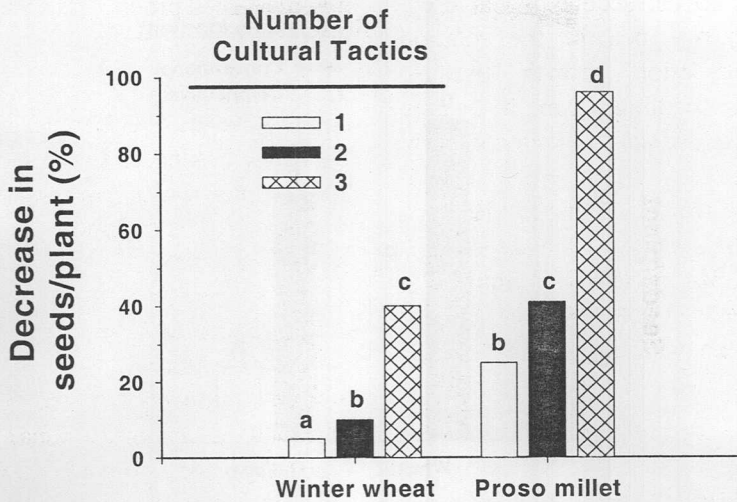


Fig. 5. Impact of cultural tactics on seed productivity of wild rye in winter wheat and redroot pigweed in proso millet. Cultural tactics were designed to improve crop competitiveness with weeds and are described in the text. Study conducted in the US semi-arid steppe. Bars with an identical letter within a crop are not significantly different based on Fisher's LSD (0.05). The letter a above a bar indicates that the cultural treatment did not differ from the conventional system used as a control. Source: Anderson, 2003.

crop density of 47,000 plants  $\text{ha}^{-1}$ , reduced yield loss to only 13%.

Crop tolerance to weeds can also be increased by preceding crops. Maize was more tolerant to *Setaria italica* when dry pea was the preceding crop compared with either soybean or maize. Maize yielded 2950  $\text{kg ha}^{-1}$  following dry pea, but only 200  $\text{kg ha}^{-1}$  when following maize in weed-infested conditions, a 15-fold difference (Fig. 7). Maize also yielded more in weed-free conditions following dry pea than either soybean or maize as preceding crops. Yield of continuous maize is low because maize is allelopathic to itself, especially with no-till (Crookston, 1995). US producers minimize this allelopathy in continuous corn by tilling extensively.

### Producer Experiences with the Population-Centered Approach

The population-centered approach helps weed management in the US steppe because lower weed density reduces need for herbicides. With winter wheat-maize-proso millet-fallow and no-till, producers grow winter wheat and proso millet without in-crop herbicides; weed density is so low that crop yield is not affected by weeds. Need for control tactics during fallow is also reduced with this rotation; producers control weeds during fallow with only two to three herbicide applications, contrasting with producers who till five to seven times with winter wheat-fallow.

This approach also improves economics of crop production. A six-year assessment

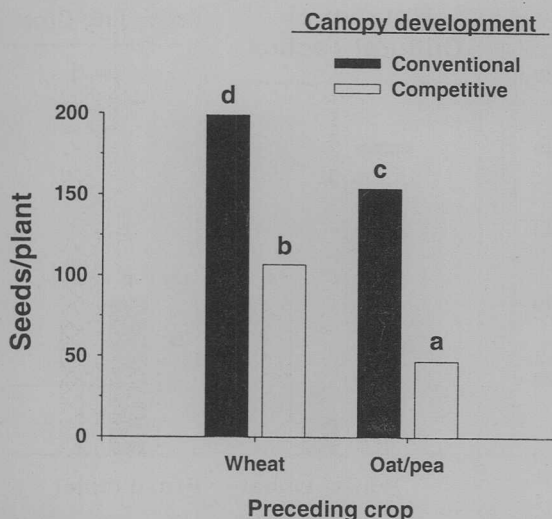


Fig. 6. Seed production of wild rye in winter wheat, as affected by preceding crop and canopy development. The competitive canopy included 50% higher seeding rate and starter fertilizer placed with the seed at planting. Bars with an identical letter are not significantly different based on Fisher's LSD (0.05). Study conducted in the US steppe. Source: R.L. Anderson, research in progress.

showed that weed management for producers using no-till rotations with crop diversity cost \$ 38 ha<sup>-1</sup>; in contrast, producers spent \$ 75 ha<sup>-1</sup> to control weeds in winter wheat-fallow with tillage (AFPC, 2006). Furthermore, net return was four-fold greater for diverse crop rotations compared with winter wheat-fallow. Profit for winter wheat-fallow was \$ 25 ha<sup>-1</sup> whereas no-till rotations with crop diversity yielded a profit of \$ 100 ha<sup>-1</sup>. Improved net returns with diversified rotations reflected both higher land productivity and lower costs with weed management. Reduced cost of weed management comprised one half of the gain in net return with no-till rotations.

A weed population-centered approach is also helping producers in Canada (Derksen *et al.*, 2002) and Australia (Jones and Medd, 1997) manage weeds with less inputs. As found in the US steppe, rotations

comprised of crops with a diversity of life cycles are a key tactic for managing weeds in these countries also.

### Challenges

Crop production has changed dramatically in the US steppe, as no-till rotations with crop diversity increase land productivity two-fold compared with winter wheat-fallow (Anderson, 2005c). Arranging crops in a cycle-of-four, such as winter wheat-maize-proso millet-dry pea or winter wheat-maize-proso millet-fallow, is particularly favorable for both crop production and weed management. A further benefit with no-till rotations, especially continuous cropping, is that producers are restoring the health of their soils.

Several factors contribute to this transformation of semi-arid cropping

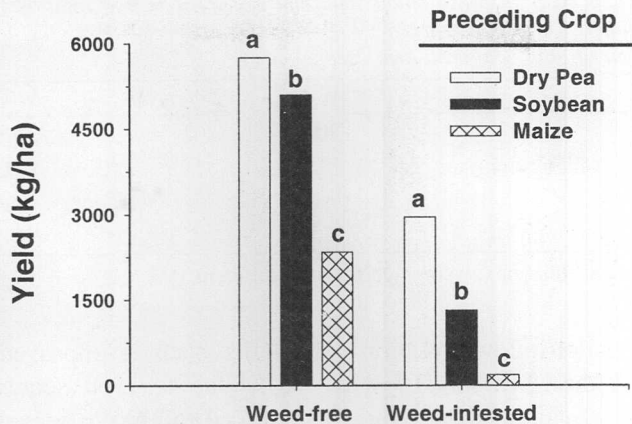


Fig. 7. Impact of preceding crop on yield of maize in weed-free and weed-infested conditions. Bars with an identical letter within a crop are not significantly different based on Fisher's LSD (0.05). Means were analyzed separately for the weed-free and weed-infested treatments. Study conducted in the US steppe. Source: R.L. Anderson, research

systems, but no-till, crop diversity, and design of rotations are especially prominent. A major benefit for producers is that synergistic interactions among these factors improve crop yields and resource-use-efficiency in this semi-arid climate (Anderson, 2005c).

#### Crop diversity

Rotations comprised of crops with different life cycles are essential for weed management to be less dependent on herbicides. When scientists and producers first started exploring alternative rotations, they were concerned that the semi-arid climate would prohibit use of most crops. Crop residue management with no-till alleviated some of this concern, but crop diversity provided a surprising benefit for intensive cropping in semi-arid conditions; some crops improve water-use-efficiency (WUE) of following crops. Both maize and dry pea increased WUE of winter wheat

25 to 35% compared with other crops (Anderson, 2005b). A similar trend occurred with proso millet; proso produced 24% more grain with the same water use when following maize compared with winter wheat (Table 1).

This synergistic interaction among crops lessens impact of drought on cropping success. However, synergism with WUE is specific to a crop sequence; not all sequences improve WUE of following crops (Anderson, 2005b). Also, this synergism among crops was not observed until the rotation had been in no-till for at least five years. Therefore, we encourage scientists involved with long-term rotation studies to measure WUE in conjunction with grain yield. They may identify crop sequences that improve WUE and thus, support more intensive cropping in drier climates.

We also encourage scientists to consider alternate uses of crops. For example, producers in the US steppe using a winter

Table 1. Impact of previous crop on proso millet yield and water use in two rotations, winter wheat-proso (W-M) and winter wheat-maize-proso (W-C-M). Data averaged across 4 years (1996-1999). Study conducted in the US semi-arid steppe

| Agronomic data   | W-M  | W-C-M |
|--|------|-------|
| Grain yield (kg ha <sup>-1</sup> )                           | 2020 | 2320* |
| Available soil water at planting (cm)                        | 14   | 13    |
| Water use (cm)   | 27   | 25    |
| Water-use-efficiency (kg ha <sup>-1</sup> cm <sup>-1</sup> ) | 75   | 93*   |

\* treatment means between rotations were significantly different

Source: Anderson, 2005c.

wheat-maize-proso millet-fallow rotation would like to eliminate the 12-month fallow interval before planting winter wheat. One successful tactic is growing dry pea as a green fallow; crop growth is terminated after six to eight weeks of growth. Even as green fallow, dry pea improves WUE and yield of winter wheat compared with fallow preceding winter wheat (Tanaka *et al.*, 2005).

#### Design of semi-arid cropping systems

Rotation design also is a critical aspect of no-till crop production in the US steppe. Crop diversity and no-till help weed management, but this benefit occurs mainly with rotations where crops are arranged in a cycle-of-four, such as winter wheat-maize-proso millet-dry pea. In contrast, weed management is not improved with short-term rotations; input costs have not been reduced with winter wheat-proso millet or winter wheat-maize-proso millet across time compared with four-crop rotations (Anderson, 2005a).

In addition to weed management, rotations based on the cycle-of-four accrue other benefits. For example, most crops yield the most in the US steppe when grown only once every four years because of reduced root diseases (Anderson *et al.*, 1999). These

benefits, such as improved crop health and WUE due to crop sequences as well as improved soil health because of no-till, have synergistically increased yield potential of crops. Winter wheat rarely yields more than 2650 kg ha<sup>-1</sup> with winter wheat-fallow and tillage; in contrast, wheat yields can exceed 5400 kg ha<sup>-1</sup> during favorable years in a no-till, winter wheat-maize-proso millet-fallow rotation (Anderson, 2004a). Similarly, proso millet yield in some years exceeds 4500 kg ha<sup>-1</sup> in this four-year rotation, whereas with winter wheat-proso-fallow and tillage, proso rarely yields more than 2000 kg ha<sup>-1</sup>. However, this doubling of yield potential of winter wheat and proso millet has not been observed in rotations with only one or two crops.

A similar impact of rotation design was noted in the Netherlands. Seeking farming systems that were sustainable economically and ecologically, scientists developed multifunctional rotations that accrue a multitude of benefits, such as lower pest populations, improved nutrient cycling and soil health, and increased yields due to the rotation effect (Vereijken, 1992). Their research shows that maximum benefits are gained when rotations consist of at least four different crops (Boller *et al.*, 2004).

This increase in crop yield potential with rotation design has also been demonstrated

in India. Lal (2006) reported that a production system based on crop diversity with legumes, soil and water conservation techniques, and integrated nutrient management increased land productivity five-fold compared with traditional monoculture sorghum.

### *Transformation of semi-arid crop production*

No-till and crop rotations have transformed semi-arid crop production in the US steppe; along with this transformation, weed management has also changed. These factors, no-till, crop diversity, and weed management are interrelated. Without diverse crop rotations, weed management requires extensive herbicide inputs, whereas without effective weed control, no-till and intensive cropping are seldom successful. Also, crop diversity provides more opportunities to vary herbicides by mode of action along with reducing herbicide use, thus producers are minimizing selection pressure for weed resistance. Therefore, we encourage producers and scientists to integrate weed management with rotation design and choice of tillage.

We further encourage scientists in drier climates of the world to consider rotations with crop diversity in regards to other aspects of crop production research. Benefits gained with rotation design such as restored soil health, improved pest management, increased resource-use-efficiency, and greater land productivity reflect synergy among factors associated with crop diversity and no-till. However, these benefits are not as prominent in the US steppe with rotations comprised of few crops and tillage (Anderson, 2005c).

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