Agronomy (Trends in Agril. Sci.) 1994,2: 49 - 61

Innovative crop residue management systems for the U.S. Southern Great Plains

Paul W. Unger, Ordie R. Jones and Harry H. Schomberg
United States Department of Agriculture, Agricultural Research Service, Conservation and Production Research Laboratory, Bushland, Texas 79012, U.S.A

ABSTRACT

Crop residue management has received much attention in the semiarid southern U.S. Great Plains since severe wind erosion damaged millions of hectares of land in the region during the severe drought of the 1930s. Research at several Great Plains locations during the 1940s and 1950s resulted in development of stubble mulch tillage (SMT), which is widely used throughout the Great Plains. Besides aiding wind erosion control, SMT also aids water erosion control and water conservation. However, even greater soil and water conservation benefits occur when conservation tillage (CST) practices are used that retain most crop residues on the surface, as with no-tillage. Such systems have been investigated for most crops of the region under dryland (non-irrigated), limited irrigation, and full irrigation conditions, and favorable results usually were obtained when adequate residues were available. With limited residue production, as in some cases of dryland cropping, the potential for soil and water conservation is reduced, but effective systems are available. Current residue management research in the region is aimed at understanding the processes controlling residue decomposition and in developing improved CST practices for presently-used and potential alternative crops and cropping systems.

INTRODUCTION

The U.S. southern Great Plains (SGP) lie between about 97 and 105°W. Long. and 32 and 37°N. Lat. in New Mexico, Oklahoma, and Texas. This region has limited precipitation, high potential evapotranspiration, limited water supplies for irrigation, and high potential for erosion, especially by wind. Hence, major goals for the SGP are erosion control and water conservation. The soils range from clays to deep sands and generally are fertile.

Land in the SGP was developed, mainly for grain crop production, in the late 1800s and early 1900s by plowing under the native short grasses. Subsequent crop production involved clean tillage with moldboard plows or disk implements (harrows or plows) that incorporated most crop residues with soil. Crop yields were mostly satisfactory during the early years because precipitation generally was favorable. However, a major drought in the 1930s, along with poor plant growth and the lack of surface residues, resulted in severe wind erosion, widespread land damage, and major economic losses. Major environmental pollution occurred in portions of the U.S. and Canada due to wind-borne dust. People in the SGP suffered severe hardships during the drought and many left the region because many considered the land as no longer suitable for agriculture. Although damage was widespread, agriculture survived and successful crop production systems were developed. A major contributing factor was the development of crop production practices that retain crop residues on or near the soil surface to help control erosion. Such residues also provide water conservation benefits that improve crop yields, which often results in more residues being available for further enhancing erosion control and water conservation. Thus, surface residue management is important for sustaining land productivity and protecting the environment.

This report reviews the development and current status of crop residue management practices adaptable to the region. Sources of information include published reports and summaries of research in progress.

HISTORICAL ASPECTS OF RESIDUE MANAGEMENT IN THE SGP

The role of crop residues on the surface in controlling soil erosion, improving water infiltration, and reducing soil water evaporation was recognized by the 1930s (Bennett, 1939; Duley and Kelly, 1939; Hallsted and Mathews, 1936; Russel, 1939). The effects of management practices on soil water storage, runoff, and evaporation for one of the early studies are presented in Table 1. Greatest water conservation was achieved when surface residue amounts were greatest, but technologies for controlling weeds, preparing seedbeds, and planting were not available at that time to produce crops under high-residue conditions. However, those early studies led to development of stubble mulch tillage (SMT) and other forms of conservation tillage. Conservation tillage, according to the CTIC (1993) definition, is any tillage or planting system the results in a minimum of 30% surface cover after planting of the next crop for water erosion control and an amount equivalent to 1.1 Mg/ha of small grain residue for wind erosion control. However, greater or lesser amounts of residue cover may be required on some soils to effectively control erosion (Kemper and Schertz, 1992).

Development of SMT began in 1938 at Lincoln, Nebraska, in the central U.S. Great Plains (Allen and Fenster, 1986). With SMT, the soil surface is undercut usually with a sweep or blade implement at a depth of about 7 to 10 cm to control weeds and prepare a seedbed. Such tillage retains most crop residues on the surface, which helps control erosion. It is generally well-adapted to the drier western parts of the Great Plains where SMT results in effective weed control. Under more humid conditions, weed control often is difficult with SMT and, as a result, crop yields often are reduced (McCalla and Army, 1961).

In the U.S. SGP, SMT research began at the USDA-ARS Conservation and Production Research Laboratory (present name), Bushland, Texas, in 1941. In that study on Pullman clay loam (Torrertic Paleustoll), SMT was compared with moldboard plowing and one-way-disk tillage for winter wheat production in continuous winter wheat (*Triticum aestivum* L.) and winter wheat-fallow cropping systems. Results after 7 years indicated that average grain yields on continuous wheat plots with SMT were 21% greater than with moldboard plowing and 14% greater than with one-way-disk tillage (Whitfield et al., 1949). On wheat-fallow plots, yields were 15% greater with SMT than with one-way-disk tillage. The yield increases, at least in part, were attributed to an accumulative improvement in soil physical conditions and a better soil water-plant nutrient balance than with other tillage methods. In addition, the study indicated that SMT was effective for water conservation and erosion control without financial sacrifice by the producer.

Because of the favorable results from the above study and other similar studies, SMT subsequently became the primary practice to help control erosion throughout the U.S. Great Plains. It is still the major tillage system for grain production on dryland in the U.S. Great Plains, and is often used under similar conditions in other parts of the world. Although developed primarily to control wind erosion, SMT also controlled water erosion and increased water conservation (McCalla and Army, 1961). As a result, many studies involving SMT have been conducted to improve water conservation and erosion control, not only in the U.S. Great Plains, but also in many other regions where dryland crops are

Table 1. Water storage, runoff, and evaporation from field plots at Lincoln, Nebraska, April to September 1939.[a]

Treatment	Storage (mm)	Runoff (mm)	Evap. (mm)	Evap. loss (%)[b]
Straw, 2.2 Mg/ha, normal subtillage	30	26	265	83
Straw, 4.5 Mg/ha, normal subtillage	29	10	282	88
Straw, 4.5 Mg/ha, extra loose subtillage	54	5	262	82
Straw, 9.0 Mg/ha, normal subtillage	87	Trace	234	73
Straw, 18.0 Mg/ha, no tillage	139	0	182	57
Straw, 4.5 Mg/ha, disked in	27	28	266	83
No straw, disked	7	60	254	79
Contour basin listing	34	0	287	89

[a] Adapted from Russel (1939).
[b] Based on total precipitation, which was 321 mm for the period.

produced.

A study that included SMT was conducted on Pullman clay loam at Bushland from 1941 to 1969. For that dryland study, plant available soil water content at planting averaged 91 mm with one-way-disk tillage and 103 mm with SMT where winter wheat was grown annually. Grain yields averaged 590 and 690 kg/ha for the respective treatments. With wheat-fallow (one crop in 2 years), respective water contents at planting were 128 and 154 mm and respective yields were 930 and 1060 kg/ha (Johnson and Davis, 1972). Besides resulting in greater water storage and grain yields, SMT resulted in retention of sufficient residues on the soil surface to help control wind erosion, except during a major drought in the 1950s when crops failed with all treatments. Grain yields averaged 58% greater for one-way-disk tillage and 54% greater for SMT with wheat-fallow than with continuous wheat for the area harvested. However, because grain yields were not doubled by use of fallow, total grain production was greater with continuous wheat.

One disadvantage of using tillage implements to control weeds is the reduction in the amount of crop residues remaining on the soil surface. Approximate amounts of residues remaining after each operation with some common tillage implements are shown in Table 2. Each SMT operation reduces surface residues about 10%, which results in substantial reductions after the three or four operations required during the interval between crops of continuous wheat and up to seven operations between crops in a wheat-fallow system (one crop in 2 years). Hence, when chemicals (herbicides) for weed control became available in the late 1940s and early 1950s, interest soon developed in using herbicides rather than tillage to control weeds because of the potential for retaining more residues on the surface to improve soil and water conservation. Most residues are retained on the surface for a much longer time with weeds controlled by herbicides (no-tillage, NT) than where tillage is used for weed control and seedbed preparation.

Research involving NT crops on dryland was started at Bushland on Pullman soil in the early 1950s. With NT, weeds are controlled with herbicides and there is no soil disturbance other than that needed to open narrow slits or holes for placing seed in soil. Use of NT in early studies at Bushland resulted in more residues being maintained on the soil surface, which improved erosion control. However, crop yields often were lower with NT in the early studies on dryland in the SGP due to low soil water storage coupled with rather poor weed and volunteer crop plant control (Army et al., 1961; Wiese and Army, 1958, 1960; Wiese et al., 1960, 1967). Apparently, the NT dryland crops did not produce enough residues to increase infiltration, reduce evaporation, and, hence, increase soil water storage as compared to that obtained by using SMT.

Table 2. Machine effect on approximate amount of surface residues remaining after each operation.[a]

Tillage machine	Percent
Subsurface cultivators -- Wide-blade sweep cultivator and rodweeder	90
Mixing-type cultivators -- Heavy-duty cultivator, chisel plow, and other-type machines	75
Mixing and inverting disk machines -- One-way flexible disk, one-way disk, tandem disk, offset disk harrow	50
Inverting machines -- Moldboard and inclined disk plow	10

[a] Adapted from Anderson (1968).

Unger (1978) placed wheat residues on the surface of Pullman clay loam at Bushland at the time of wheat harvest (start of fallow). Compared with the no-residue treatment, the 8.0- and 12.0-Mg/ha residue treatments about doubled soil water storage by the time that grain sorghum was planted 10 to 11 months later (end of fallow) and sorghum yields (Table 3). This study clearly showed that surface residues are effective for increasing soil water storage and dryland crop yields in the SGP.

DEVELOPMENTS AND CURRENT STATUS OF RESIDUE MANAGEMENT ON DRYLAND

Winter wheat and grain sorghum are well-adapted grain crops for the semiarid SGP. They often are grown in rotation on dryland to reduce the risk of failure associated with annual cropping and to overcome the low precipitation-use efficiencies associated with crop-fallow systems. As pointed out above, however, dryland crops may not produce adequate residues to greatly improve water conservation or for tillage systems to qualify as conservation tillage, based on the surface residue requirements. But this has not thwarted efforts to develop improved soil and water conservation practices by managing the

Table 3. Straw mulch effects on soil water storage during fallow,[a] water storage efficiency, and dryland grain sorghum yield at Bushland, Texas, 1973-1976.[b]

Mulch rate (Mg/ha)	Water storage[c] (mm)	Storage efficiency[c] (%)	Grain yield (kg/ha)	Total water use (mm)	WUE[d] (kg/m^3)
0	72 c[e]	22.6 c	1780 c	320	0.56
1.0	99 b	31.1 b	2410 b	330	0.73
2.0	100 b	31.4 b	2600 b	353	0.74
4.0	116 b	36.5 b	2980 b	357	0.84
8.0	139 a	43.7 a	3680 a	365	1.01
12.0	147 a	46.2 a	3990 a	347	1.15

[a] Fallow duration of 10 to 11 months.
[b] From Unger (1978).
[c] Water storage determined to 1.8-m depth. Precipitation averaged 318 mm.
[d] Water use efficiency based on grain produced, growing season precipitation, and soil water changes.
[e] Values within a column followed by the same letter are not significantly different at the 5% level (Duncan's multiple range test).

available residues in SMT or NT cropping systems.

Jones (1975) evaluated yields and water use efficiencies for dryland winter wheat and grain sorghum produced on Pullman soil at Bushland on sloping land (< 1%), graded terraces, conservation bench terraces (lower one-third of interval between terraces leveled), and bench terraces (entire area between terraces leveled). The SMT system was used under all conditions. The cropping systems were wheat-grain sorghum-fallow and continuous grain sorghum (the crops were not evaluated under all land management conditions). Results were compared to those of Unger (1972) for continuous wheat and to those of Johnson and Davis (1972) for wheat-fallow. On a system basis, grain yields were greatest (1780 kg/ha) for continuous grain sorghum on a bench terrace and least (550 kg/ha) for wheat-fallow on sloping land (Table 4). Other cropping system-land management combinations gave intermediate results. Although residue management was identical in all cases (SMT), this study showed that management practices other than tillage method greatly influence dryland grain production in the SGP.

For wheat and grain sorghum grown in rotation on dryland, low residue production along with soil crusting due to intense rainfall may reduce the water conservation benefits often ascribed to NT. Jones et al. (1994) compared NT and SMT management of residues from a wheat-sorghum-fallow rotation on water runoff, infiltration, and storage in field-sized (2 to 4 ha) watersheds on Pullman soil at Bushland from 1981 to 1992. Infiltration was determined with a rainfall simulator, runoff was determined with H-flumes, and soil water contents were determined gravimetrically. Final infiltration rates were similar for both systems, but rates declined more rapidly on NT than on freshly-tilled SMT fields, primarily because of surface sealing with NT, even though surface cover was greater than 50%. Cumulative infiltration after 2 hours was 90% greater with SMT than with NT during fallow after sorghum and 25% greater during fallow after wheat. These differences for the first simulated rain were attributed to soil loosening by SMT, which disturbed the consolidated crust, decreased bulk density, and increased surface roughness and depression storage capacity. The first simulated rain, however, consolidated and smoothed the surface of SMT fields, and infiltration results from subsequent tests were similar for both systems. Storm runoff averaged 40.1 mm/year with NT and 25.5 mm/year with SMT, with most occurring during fallow after sorghum. Despite increased runoff, soil water storage (Fig. 1) was greater with NT because of reduced evaporation. Each SMT operation brought moist soil to the surface, which often became air-dry before precipitation rewetted the soil. Plant available water storage with NT was 18% greater than with SMT during fallow after sorghum and 10% greater during fallow after wheat. Wheat grain yields averaged 1310 kg/ha with SMT and 1260 kg/ha with NT; sorghum yields averaged 3070 with SMT and 3420 kg/ha with NT (Jones, 1992).

Table 4. Mean annual grain yields of dryland grain production systems, Bushland, Texas, 1959-1972.[a]

Grain production system	Cropping system	Mean annual yield grain sorghum		Mean annual yield, wheat	
		Kg per cropped ha	Kg per system ha	Kg per cropped ha	Kg per system ha
Conservation bench terrace					
Level bench	Cont. grain sorghum[b]	2230 a[c]	740	--	--
Watershed	Wheat-sorghum-fallow	2010 ab	450	920 bc	200
Graded terrace	Wheat-sorghum-fallow	1890 ab	610	970 ab	320
Bench terrace	Cont. grain sorghum	1780 b	1780	--	--
< 1% sloping plots	Cont. grain sorghum[d]	1240 c	1240	--	--
	Cont. wheat[e]	--	--	750 c	750
	Wheat-fallow[e]	--	--	1100 a	550

[a] From Jones, 1975.
[b] Continuous grain sorghum.
[c] Values within a column followed by the same letter or letters are not significantly different at the 5% level (Duncan's multiple range test).
[d] From Unger (1972).
[e] From Johnson and Davis (1972).

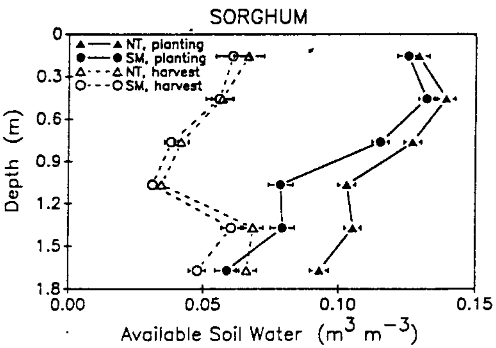

Figure 1. Tillage effects on plant available soil water content at planting and harvest of grain sorghum grown in a wheat-sorghum-fallow sequence, 1986 to 1992, Bushland, Texas (from Jones et al., 1994).

A major reason for the water storage advantage with NT as found by Jones (1992) apparently was reduced evaporation. For example, Steiner (1989) showed that soil water evaporation for several experiments decreased as tillage intensity decreased and surface residue amounts increased. Crop-specific relationships were obtained when residues were expressed on a mass/unit area basis. However, a single equation described the relationship between evaporation and residues of different crops when the residues were expressed on a thickness or volume per unit area basis.

Unger (1994a) studied the effects of 12 tillage systems ranging from NT (herbicides only) to SMT (no herbicides) on water storage and use, crop growth, yields, and yield components for dryland wheat and sorghum grown in rotation on Pullman soil at Bushland from 1984 to 1991. Included were some tillage-herbicide combination treatments for which herbicides replaced some of the tillage operations. Tillage systems did not affect mean water storage during fallow nor mean water use by either crop. All yield, growth, and yield component factors differed among growing seasons. Wheat grain and straw yields were not affected by tillage. Mean wheat grain yield was 2920 kg/ha. Mean sorghum grain yield was greatest (3910 kg/ha) for the system of reduced tillage after sorghum and NT after wheat, and least (3480 kg/ha) for the system of reduced tillage after each crop. Sorghum stover yields were not affected by tillage. This study showed that a wide range of tillage systems is adaptable for a dryland wheat-grain sorghum cropping system for the semiarid SGP.

Although feed grain crops are widely grown to support the beef cattle feeding industry in the SGP, grain yields of crops such as grain sorghum can be sharply reduced by plant water stress at critical growth stages. In contrast, forage crops, for example, forage sorghums (*Sorghum bicolor sudanense* or *S. saccharatum*), are not sensitive to critical stage effects on dry matter production and, hence, do not require such timely rainfall to produce good yields. As a result, total nutrient production by forage sorghums may be equal to that produced by grain sorghum. Unger (1988) compared the growth, yields, water use, and water-use efficiency of one grain and five forage sorghum cultivars under NT conditions at Bushland from 1984 to 1986. Only NT was used because other studies had shown that this method is effective for dryland sorghum production in the SGP. Total dry matter (TDM) yields by grain and forage sorghums (8140 vs. 8610 kg/ha) did not differ significantly. Total crude protein (grain plus stover) was greater for the grain than for all but one of the forage sorghums. Grain sorghum stover, however, has low nutrient value and usually is not harvested. Thus, when considering only the grain of grain sorghum, nutrient production by grain sorghum was lower than for forage sorghum. Water-use efficiencies for TDM and nutrient production were greater for forage sorghums than for grain sorghum. Grain sorghum had a longer growing season that resulted in greater total water use than that used by the forage sorghums. The study showed that forage sorghums, which can be utilized by grazing or as silage or hay, are viable alternative crops to grain sorghum under NT dryland conditions in the SGP. A major disadvantage regarding forage crops would be removal of most aboveground plant materials when they are harvested. This could limit soil and water conservation efforts due to the lack of adequate surface residues.

Winter wheat is widely used for grazing by livestock in the SGP. It usually is planted in late summer or early fall, then grazed from late fall until late winter or early spring if it is to be harvested for grain. Grazing is continued when the crop is used only for forage production. In either case, timely establishment is important for optimum production. However, precipitation variability at planting time sometimes prevents timely crop establishment, which then limits growth, and, hence, production. In tests at El Reno, Oklahoma, on Bethany (Pachic Paleustoll) and Renfrow (Udertic Paleustoll) silt loams, Dao (1993) showed that NT resulted in consistently greater soil water contents to the 1.2-m depth than moldboard plowing and SMT and that it reduced seasonal variability in water infiltration compared with plowing. The use of NT not only increased soil water storage, but also minimized the detrimental effects of climate variability on annual winter wheat production.

In another study on Bethany and Renfrow soils at El Reno from 1983 to 1987 involving wheat cultivars, Dao and Nguyen (1989) showed that mean grain yields with NT usually were similar to those with plowing. Yields were slightly better with NT in years with cold autumns that had erosive rains or in years with dry springs. However, there was a cultivar response. Early-maturity cultivars consistently had stable yields with good resilience against climatic variations, but late-maturity ones may not be suitable for grain production with NT. With NT, the vegetative phase was prolonged, which indicated a potential benefit for a wheat production system that included a grazing component. A potential disadvantage of early-maturity cultivars, at least in parts of the SGP, is increased risk of early-spring freeze damage (personal communication, J.T. Musick, Bushland, Texas 1994).

Gerard (1987) evaluated the effects of applying surface residues on rainfall runoff from a sandy loam near Chillicothe, Texas. Runoff from bare soil was 37% compared with an average of 3% with conservation tillage, which left half of the applied residues (7.5 or 15.0 Mg/ha) on the soil surface. Runoff averaged 12% when all residues were incorporated into the soil. Runoff from grass plots during the first year of growth was similar to that from residue-incorporated plots.

Cotton (*Gossypium hirsutum* L.) is an important crop in portions of the SGP that have adequate heat units during the growing season. Much of the cotton is grown on sandy soils, which are highly susceptible to erosion by wind. Cotton stalks remaining after harvest are of limited value for controlling wind erosion. However, trash (cotton burs, leaves, etc.) removed from lint during the ginning process often is used as a mulch to help control erosion on sandy soils. On a sandy clay loam at Big Spring, Texas, gain in soil water storage was nearly 30% as surface cover by mulch was increased from 0 to 100% (Fryrear and Koshi, 1971). About 11.0 Mg/ha of mulch completely covered the surface. For 1968 and 1969, precipitation stored as soil water averaged 41, 58, and 73% with 0, 11.0, and 22.0 Mg/ha of gin trash on the surface. Soil water contents were increased to a 3-m depth, and cotton lint yields averaged 200, 260, and 280 kg/ha with the respective treatments. Koshi and Fryrear (1971) reported similar results.

Cotton gin trash effectively controls wind erosion when an adequate amount is applied. Fryrear and Koshi (1974) obtained wind erosion control with annual applications of 11.0 Mg/ha of gin trash on the surface, but not with 5.5 Mg/ha. In that study, annual applications at 11.0 Mg/ha as compared with bare soil increased water storage to a 3-m depth, soil organic matter to a 0.3-m depth, and cotton lint yields by 16 to 36%.

Because of limited amounts available, gin trash usually is applied only to highly erosive sites within a field. Consequently, other means are needed to control wind erosion where cotton is grown. Bilbro and Fryrear (1991) used gin trash and pearl millet (*Pennisetum glaucum*) residues as mulch treatments in the blank rows of a two-planted-row, two-blank-row (1-m spacing) skip-row planting pattern for rainfed cotton over 4 years. Mulches were applied only in 1982. Gin trash mulch rates were 7.0, 23.0, and 40.0 Mg/ha, and millet mulch rates were 10.0, 20.0, and 30.0 Mg/ha. Check plots were not mulched. In 1982, average lint yield for mulched plots was 53% greater than on check plots (607 vs. 396 kg/ha). Cotton was not established in 1983 and 1984 because of inadequate soil water at planting time. Lint yields were 13% greater on mulched than on check plots in 1985. Soil water contents throughout the 4-year study were consistently greater on plots that received the most mulch, and millet-mulched plots consistently had more stored water than their gin trash counterparts. The study indicated that producers should be able to reduce soil erosion losses by consistent use of mulches of cotton gin trash, millet residues, or other comparable organic materials, either grown in place or applied. In addition, mulches improve soil water conservation and, hence, cotton lint yields, which should improve profitability for the producer.

Several conservation tillage studies have been conducted in the SGP in recent years that involved cotton grown after a cover crop or a grain crop. Keeling et al. (1989) evaluated conservation tillage with a wheat cover crop (W-CST), conservation tillage without a cover crop (CST), and conventional (clean) tillage (CVT) for continuous cotton production on Acuff loam (Aridic Paleustoll) at Lubbock, Texas, and on Pullman clay loam at Halfway, Texas, in 1986 and 1987. For the W-CST treatment, wheat was killed in April when it was 15 cm tall. Dryland cotton lint yield was significantly greater with W-CST (1700 kg/ha) than with CVT (1450 kg/ha) at Halfway and was numerically greater with W-CST (1490 vs. 1390 kg/ha) at Lubbock. Net returns were $42/ha (US$, 1986 and 1987 prices) greater at Lubbock and $135/ha greater at Halfway with W-CST than with CVT. Increases in net returns with CST over CVT were $83/ha at Lubbock and $134/ha at Halfway. The authors indicated that conservation tillage is a viable alternative to clean tillage for cotton production where the wind erosion potential is high. Besides being effective for helping control erosion, conservation tillage increased net revenue.

Segarra et al. (1991) evaluated continuous cotton on dryland under CVT, reduced tillage (RT), NT, and wheat cover crop (WCC) conditions, and cotton in rotation with wheat (W-C) or sorghum (S-C) on Acuff soil at Lubbock. As compared with CVT, lint yield increases ranged from 129 kg/ha with the WCC treatment to 535 kg/ha with the W-C treatment. These same treatments resulted in net revenue increases of $44/ha and $304/ha, respectively (US$, 1989 prices). As for the study by Keeling et al. (1989), these studies indicate use of conservation tillage practices alone or in rotation with crops that produce appreciable amounts of residue is an effective means of helping erosion control without sacrificing net revenue returns.

Because of the importance of surface residues for soil and water conservation, it is highly desirable to manage crop residues in a manner that will provide the greatest benefits, and this often involves retaining the largest amount on the surface. This is especially true when residue production is low, as is frequently the case for dryland crops. When developing strategies to effectively use residues for soil and water conservation, prediction of changes in residue orientation (standing vs. flat), redistribution, and decomposition is important. Changes in standing stem population and residue biomass over time are areas of critical interest for predicting crop residue effects on soil erosion. Steiner et al. (1994) showed that prediction of changes in orientation from standing to flat could be made by using an equation similar to those used for residue decomposition. The equation was modified to include a thresholding variable to account for the period between harvest and initiation of stem fall. Daily temperature and moisture coefficients were used to scale the field environment to standard conditions (decomposition days), which improved the prediction over diverse climates. The number of decomposition days required before the stems began to fall was about 15 for barley (*Hordeum vulgare* L.), oats (*Avena sativa* L.), and wheat. Residue stem fall rates were similar for barley, spring wheat, and winter wheat, but were slightly faster for oats. The results have been incorporated into a model for predicting changes in residue cover and decomposition (Schomberg et al., in press).

Crop residues can influence N availability to crops because of their low N content, which can result in periods of N immobilization. Allowing crop residues to remain on the soil surface may have a greater impact on nutrient management than when residues are incorporated. Schomberg et al. (1994) found that N remained immobilized in sorghum residues on the surface an average of 472 days and in wheat an average of 391 days. For incorporated residues, average times were 125 and 100 days, respectively. An advantage of the longer immobilization period with surface residues could be improved N availability to crops grown under a crop-fallow sequence. The amount of soil N immobilized was 13.7 g/kg with wheat residue on the surface compared with 12.2 g/kg when buried. The trend was opposite for sorghum residues (9.9 g/kg surface vs. 11.1 g/kg buried). These results indicate the need to include residue management effects on nutrient availability when developing N management programs.

Soil and water conservation, crop yield improvement, and crop production sustainability are primary goals of crop residue management. In recent years, however, crop residue management has received considerable attention relative to organic carbon (OC) sequestration in soils and, hence, its effect on atmospheric CO_2 increases and potential climate change (Varvel, 1994). As in studies at many other locations, soil organic matter (SOM), of which OC is a major component, decreased with time in the long-term continuous wheat and wheat-fallow study at Bushland (Johnson and Davis, 1972). The greatest decrease occurred for the most intensive tillage treatment, namely, one-way-disk tillage. For all treatments, decreases were most rapid during the early years of the study and they became progressively slower in subsequent years.

In a wheat-sorghum-fallow study at Bushland, SOM content was greater at the 0- to 1-cm depth where NT rather than SMT was used, but mean contents to a 20-cm depth were similar (Unger, 1991). The NT treatment was in place for 9 years. In contrast, mean OC (averaged over 5 years and 37 sampling dates) to a 15-cm soil depth was 617 mg/kg greater with NT than with SMT at Clovis, New Mexico (Christensen et al., 1994). Although SOM or OC contents in these relatively short-duration studies were similar or not greatly improved by use of NT as compared with SMT, both tillage methods retain more SOM than clean (residue incorporating) tillage. In addition, these tillage methods, especially NT, retain undecomposed residues at the surface, thus resulting in overall greater OC sequestration than clean tillage, which incorporates the residues with soil.

RESIDUE MANAGEMENT SYSTEMS INVOLVING IRRIGATED CROPS

Limited Irrigation

A limited-irrigation approach to crop production can involve either not irrigating all crops in rotations involving two or more crops, or not fully irrigating drought-tolerant crops that respond favorably to well-timed irrigations. One system that has given highly favorable results is an irrigated winter wheat-dryland grain sorghum-fallow rotation, which results in two crops in 3 years. A fallow period of 10 to 11 months occurs between harvest of either crop and planting of the next crop. Irrigating the wheat increases residue production to levels above those normally produced by dryland crops, and to a level adequate for subsequently enhancing water infiltration and suppressing soil water evaporation during fallow. This was demonstrated by Unger et al. (1971) when irrigated wheat residues were managed by combinations of disk, sweep, and herbicide treatments for weed and volunteer wheat control during fallow from wheat harvest in July until sorghum planting time the following June. The herbicides were atrazine [6-chloro-*N*-ethyl-*N'*(1-methylethyl)-1,3,5-triazine-2,4-diamine][1] and 2,4-D [(2,4-dichlorophenoxy)acetic acid]. Soil water storage with treatments involving herbicides was about double the average obtained for the tillage-only treatments. Although sorghum yields were not determined in that study, dryland sorghum in subsequent studies has responded favorably to the additional water stored during the fallow period, as indicated in the following examples.

In 1970, winter wheat was planted after harvest of irrigated corn (*Zea mays* L.) without tillage or after rotary tillage and on an adjacent fallowed area to obtain high, medium, and low initial surface residue levels, respectively. Within these treatments, the wheat was irrigated one to five times to obtain different levels of wheat residue production. Low-residue treatment plots were disked once after wheat harvest to incorporate some residues with soil. Atrazine and 2,4-D were applied to all plots after wheat harvest to control weeds and volunteer wheat. Surface residue amounts, soil water storage during fallow, and sorghum grain yields differed significantly due to treatments. Water storage ranged from 11 to 45% of fallow-period precipitation, and generally increased with increasing amounts of surface residues. The greatest residue level, however, did not result in greatest water storage, possibly because the initial soil water content was greater or because residues

---

[1] Mention of a trade name or product does not constitute a recommendation, endorsement, or exclusion for use by the U.S. Department of Agriculture, nor does it imply registration under FIFRA as amended.

intercepted more of the precipitation. Grain yields ranged from 2970 to 6010 kg/ha for the dryland sorghum that was planted without tillage (NT). The highest yield, resulting from corn residue incorporation by rotary tillage and five irrigations for wheat, was 2240 kg/ha greater than that of sorghum on an adjacent fallowed area where clean tillage (residues incorporation) was used (Unger and Parker, 1975).

Disk tillage, sweep tillage, and NT were used to control weeds and manage wheat residues during fallow in an irrigated wheat-dryland grain sorghum-fallow rotation on Pullman soil at Bushland. Soil water storage averaged 15, 23, and 35% of the precipitation during fallow; plant available soil water to a 1.8-m depth at sorghum planting averaged 152, 170, and 217 mm; sorghum grain yields averaged 1930, 2500, and 3140 kg/ha; and water-use efficiencies for grain production averaged 6.63, 7.73, and 8.86 kg/ha-mm for the respective treatments (Unger and Wiese, 1979).

Unger (1984) evaluated the effects of moldboard-, disk-, rotary-, sweep-, and no-tillage treatments during fallow after wheat in an irrigated wheat-dryland grain sorghum-dryland sunflower (*Helianthus annuus* L.) rotation (three crops in 3 years) at Bushland on Pullman soil. Soil water contents to the 1.8-m depth at sorghum planting averaged 149, 158, 143, 179, and 207 mm, and sorghum grain yields averaged 2560, 2370, 2190, 2770, and 3340 kg/ha with the respective treatments. Sunflower seed yields obtained after sorghum in the rotation were not affected by tillage treatments imposed before sorghum. Also, tillage before sorghum did not affect yield of the next wheat crop that was planted soon after sunflower harvest (no fallow).

Baumhardt et al. (1985) evaluated the irrigated wheat-dryland grain sorghum-fallow rotation on Pullman soil at Bushland and Lubbock, and obtained results similar to those reported by Unger and Wiese (1979) and Unger (1984). When irrigated wheat was followed by dryland sunflower or irrigated corn, water storage trends after wheat were similar to those above, but yield responses were less than for grain sorghum (Unger, 1981, 1986).

Harman et al. (1989) obtained greater cotton lint yields and net returns with NT than with CVT for cotton grown in rotation with barley. The study was conducted on Sherm clay loam (Torrertic Paleustoll) at Etter, Texas, from 1983 to 1985. The barley was irrigated and followed by a 48-week fallow period after harvest until cotton planting the next year. After cotton harvest, stalks were shredded, all plots were disked, beds were rebuilt, and barley was planted and furrow irrigated for emergence. After barley harvest, standing stubble was retained on the surface of NT plots by controlling weeds with herbicides until cotton planting. Disking and field cultivation were used for weed control on CVT plots. Average water storage during fallow was 45 mm greater with NT than with CVT, which resulted in a 110-kg/ha lint yield increase with NT. Although average herbicide costs were $155/ha greater with NT, long-term annual profits were $82/ha (US$, 1987 prices) greater with NT than with CVT because of the increased yield and lower machinery depreciation costs. These results indicate that growing an irrigated crop in rotation with a dryland crop with conservation tillage is a viable alternative for improving water conservation from precipitation and reducing the dependency on limited water supplies available for irrigation in the SGP.

To decrease crop dependence on irrigation water and to improve dryland crop production, Unger (1977) grew winter wheat on the same plots with and without irrigation in alternative years and compared this with irrigated wheat grown continuously with disk tillage (DT) and non-irrigated wheat grown continuously with sweep tillage (ST). Where crops were alternated, treatments were NT, SW, and DT. Without irrigation, average grain yield was greater for the alternative system (2250 kg/ha) than for the continuous system (2080 kg/ha). With irrigation, the yield difference was not significant (4390 kg/ha with the alternative and 4250 kg/ha for the continuous system). Considering the combined system and tillage effects, using ST before irrigated wheat and DT before dryland wheat where crops were alternated increased average grain yields by 10% over those for the continuous irrigated and continuous dryland treatments. The alternative system also improved water-use efficiency, which suggested that such system has potential for conserving water and increasing grain yields relative to those obtained with continuous irrigated and dryland wheat production.

Unger (1994b) studied the effects of treatments that involved retaining all residues on the surface (NT + Res), removing some residues at harvest (NT-ResH) or at planting (NT-ResP), and CVT on soil water storage and use, and yields of continuous winter wheat produced with limited irrigation. Water storage between crops was greater with NT + Res (95 mm) and NT-ResH (100 mm) than with CVT (79 mm), but amount of soil water depletion was not affected by treatments, apparently because of irrigation. Average grain yield was greater with NT + Res (4560 kg/ha) than with CVT (4260 kg/ha) and NT-ResH (4180 kg/ha). Residue production was about 9000 kg/ha, and much of this remained on the surface at planting of the next crop with the NT + Res treatment. An estimated 2200 kg/ha of residues were on the surface at planting with the NT-ResH and NT-ResP treatments. The residues provided considerably more (a minimum of about 70%) than the 30% surface cover usually required to control erosion on highly erodible land. With the CVT treatment, few residues remained on the surface at planting. This study indicated that use of limited irrigation and no-tillage can result in adequate surface residues to control erosion in the SGP.

Because both winter wheat and grain sorghum respond well to timely irrigation, they sometimes are grown with limited irrigation. Unger (1994c) determined effects of residue management on soil water storage and use, yields, and yield components for wheat and sorghum grown in rotation with limited irrigation on Pullman soil at Bushland. Treatments were 1) no-tillage with standing (NT-st) residues, 2) no-tillage with shredded (NT-sh) residues, and 3) no-tillage after wheat and tillage after sorghum (NT-T). Tillage did not affect soil water storage after wheat, but storage ranged from 68 mm with NT-T to 101 mm with NT-st after sorghum. Soil water use by wheat ranged from 93 mm with NT-T to 131 mm with NT-st, but tillage did not affect soil water use by sorghum. Tillage did not affect wheat yields because differences in soil water storage and use were small and irrigations minimized the water content differences. Tillage did not affect sorghum yields because using no-tillage during fallow after wheat resulted in similar water storage in all cases. This study showed that practices that retain surface residues are effective for producing wheat and grain sorghum in rotation under limited-irrigation conditions in the SGP.

Full Irrigation

Although water for irrigation is limited in the SGP, irrigation remains important for crop production in parts of the region. An early study showed that crops could be successfully planted when large amounts of residues were present, as from a previous irrigated crop, by using the NT method (Musick et al., 1972). This study on Pullman soil at Bushland involved planting winter wheat or barley into stubble of an irrigated grain sorghum crop. Planting methods were NT into standing residues, NT into shredded residues, and CVT with a single-disk-opener drill (0.25-m opener spacing) after tilling the plots with a rototiller having an attached bed-furrow shaper. Shredding stubble before NT planting gave no advantage, and may be disadvantageous in seasons when snow could be trapped by the standing stubble. The NT planting increased early spring growth in a season when soil water was limited, standing stubble trapped a significant amount of snow, and soil temperatures were higher than normal. Growth during late fall until early spring was decreased by NT in a season when irrigation was frequent for stimulating plant growth for grazing and temperatures were below normal. Differences in early growth, however, did not significantly influence wheat yields, which averaged 3670 kg/ha with CVT and 3750 kg/ha with NT.

Allen et al. (1975a) evaluated double cropping of irrigated grain sorghum after irrigated wheat harvest on Pullman soil at Bushland using NT and DT methods. Sorghum with NT emerged sooner, grew taller, and matured up to 5 days earlier than with DT. Grain yields for the 5-year study averaged 5690 kg/ha with NT and 5070 kg/ha with DT, a 12% increase with NT. Because of the greater yields and no differences in total water use, water use efficiency was greater with NT. In addition, NT required only one-fifth as much time between crops to prepare the seedbed and plant sorghum, and reduced fuel requirements by 55%, including that used for harvest.

Under graded-furrow conditions on Pullman soil at Bushland, Allen et al. (1975b) evaluated rainfall and irrigation-water runoff from DT and NT areas cropped continuously to grain sorghum. Residues from a previous sorghum crop were present when the study was initiated. A contact herbicide applied before seeding controlled small volunteer sorghum plants, but failed to control large plants. The NT seeding was satisfactory, either with unit planters or a grain drill. For four irrigations in 1971 totaling 364 mm, runoff totaled 97 mm with DT and 41 mm with NT. When 63 mm of rain fell immediately after applying 82 mm of water for the fifth irrigation, runoff totaled 58 mm with DT and 46 mm with NT. Less runoff with NT than with DT was attributed to residues in furrows that slowed water advance, caused deeper water penetration, and increased water storage. The additional water increased plant growth, but grain yields were not increased because uncontrolled volunteer sorghum plants resulted in plant populations above the optimum for grain production.

Allen et al. (1980) evaluated tillage methods ranging from clean tillage (disk-chisel) to limited tillage (mulch-till) for continuous grain sorghum production with adequate or limited irrigation. Clean tillage involved disking (disk harrow) and subsoiling 20 cm deep in the fall, and disking, chiseling to apply anhydrous ammonia (NH_3) 15 cm deep, bedding, and sweep-rod weeding in the spring. Limited tillage involved NH_3 application in the furrow by subsoiling 0.20 m deep in the fall and sweep-rod weeding in the spring. With limited and clean tillage, grain yields (6860 vs. 6350 kg/ha) and irrigation water infiltration (483 vs. 437 mm) differences were not statistically significant with adequate irrigation. In the same study with limited irrigation, limited tillage resulted in significantly greater yields (5920 vs. 5160 kg/ha) and infiltration (386 vs 347 mm) than clean tillage. Time and fuel energy requirements for limited tillage were about half those for clean tillage. Greater yield and lower production cost with mulch tillage resulted in $40/ha (US$) greater net income than clean tillage.

Allen et al. (1976) successfully managed continuous winter wheat by using limited tillage and chemical weed-volunteer crop plant control under irrigated conditions on Pullman soil at Bushland. The treatments compared were 1) NT -- 2,4-D and a contact herbicide for weed control, and NH_3 chiseled into the furrows; 2) limited tillage -- 2,4-D application, disk bed, NH_3 chiseled into furrows, and sweep-rod weeding before planting; and 3) clean tillage -- tandem disk, chisel 20 cm deep, disk, disk bed, NH_3 chiseled into furrows, and sweep-rod weeding before planting. Grain yields and water-use efficiency with adequate irrigation were slightly greater with NT than with clean tillage, but the yield increase was offset by the additional cost of herbicides with NT. Limited tillage seemed more practical and dependable as an alternative to clean tillage. Limited tillage and NT reduced time and fuel requirements by 40 and 50%, respectively.

Musick et al. (1977) evaluated NT and DT effects on irrigated wheat and irrigated grain sorghum grown in rotation on level bordered and graded-furrow plots on Pullman soil at Bushland. During the 11-month fallow after wheat, precipitation storage efficiencies were 35% with NT and 21% with DT on level bordered plots; they were 47% with NT and 28% with DT on graded-furrow plots. Because of greater water storage, sorghum yielded 5100 kg/ha with NT compared with 4080 kg/ha with DT on leveled plots with 150 mm of irrigation. With 300 mm irrigation, yields were 6460 kg/ha with NT and 5970 kg/ha with DT. On graded furrows, NT retained 169 mm of irrigation water and sorghum yielded 5420 kg/ha; with DT, 93 mm of water was retained and yields were 4260 kg/ha. These results indicated that NT can be used after irrigated wheat to increase soil water storage and successfully establish the next crop without applying a preplant or an emergence irrigation. This is a promising technique for reducing irrigation water needs and increasing water-use efficiency in the SGP where water for irrigation is limited.

Keeling et al. (1989) evaluated lint yields and net returns for irrigated cotton produced on Acuff loam at Lubbock, Texas, and on Pullman clay loam at Halfway, Texas. Treatments were conservation tillage with a wheat cover crop (W-CST), conservation tillage without a cover crop (CST), and CVT. For the W-CST treatment, wheat was killed in April when it was 15 cm tall. Lint yields averaged 1960 kg/ha with CVT, 2040 with CST, and 2160 with W-CST at Lubbock. As compared with CVT, net returns were $77/ha greater with CST and $108/ha greater with W-CST. At Halfway, yields were not significantly different due to treatments, but were numerically greater with CST (2380 kg/ha) and W-CST (2360 kg/ha) than with CVT (2250 kg/ha). As a result, net returns were increased by $125/ha with CST and $92/ha with W-CST as compared with CVT.

Segarra et al. (1991) grew irrigated cotton on Acuff soil at Lubbock under CVT, reduced tillage (RT), NT, and wheat cover crop (WCC) conditions and in rotation with wheat (W-C) and sorghum (S-C). Compared with CVT, average lint yields ranged from a decrease of 86 kg/ha with S-C to an increase of 82 kg/ha with WC, resulting in a net return decrease of $37/ha with S-C and an increase of $50/ha with W-C.

SUMMARY

Residue management has been an integral part of crop production research in the SGP since the 1930s' drought, but the research emphasis has changed through the years to meet changing priorities. The early research, concerned with development of practices to control mainly wind erosion, led to development of SMT. Research soon showed that use of SMT, which retained more crop residues on the soil surface than clean tillage, also increased soil water conservation. Protection against erosion and amount of water conserved increased with increases in amounts of surface residues. As a result, subsequent research focused on development of practices that permitted effective and economical crop production under conditions that retained more surface residues. A major boost was the introduction of herbicides to control weeds. As a result, some or all tillage for weed control could be eliminated, which allowed more residues to be retained on the soil for soil and water conservation purposes. Presently, the emphasis is on obtaining a better understanding of processes controlling residue decomposition and on developing improved practices for presently-used and potential alternative crops.

REFERENCES

Allen, R.R. & Fenster, C. R. 1986. *J. Soil Water Conserv. 41*:11-16.

Allen, R.R., Musick, J.T. & Dusek, D.A. 1980. *Trans. Am. Soc. Agric. Eng. 23*:346-350.

Allen, R.R., Musick, J.T. & Wiese, A.F. 1975a. *Trans. Am. Soc. Agric. Eng. 18*:1109-1113.

Allen, R.R., Musick, J.T. & Wiese, A.F. 1975b. *Texas Agric. Exp. Stn. Prog. Rpt. 3332C*, College Station. pp. 66-78.

Allen, R.R., Musick, J.T. & Wiese, A.F. 1976. *Trans. Am. Soc. Agric. Eng. 19*:234-236, 241.

Anderson, D.T. 1968. In: Conservation Tillage in the Great Plains, Proc. of a Workshop, February 1988, Lincoln, NE. Great Plains Agric. Council Publ. 32, Univ. of Nebraska, Lincoln. pp. 83-91.

Army, T.J., Wiese, A.F. & Hanks, R.J. 1961. *Soil Sci. Soc. Am. Proc. 25*:410-413.

Baumhardt, R.L., Zartman, R.E. & Unger, P.W. 1985. *Agron. J. 77*:645-646.

Bennett, H.H. 1939. Soil Conservation, McGraw-Hill, New York & London.

Bilbro, J.D. & Fryrear, D. W. 1991. *J. Soil Water Conserv. 46*:66-69.

Christensen, N.B., Lindemann, W.C., Salazar-Sosa, E. & Gill, L.R. 1994. *Agron. J. 86*:298-303.

CTIC (Conservation Technology Information Center). 1993. *Conserv. Impact 11(5)*:6.

Dao, T.H. 1993. *Soil Sci. Soc. Am. J. 57*:1586-1595.

Dao, T.H. & Nguyen, H.T. 1989. *Agron. J. 81*:923-929.

Duley, F.L. & Kelly, L.L. 1939. *Nebraska Agric. Exp. Stn. Res. Bull. 112*, Lincoln.

Fryrear, D.W. & Koshi, P.T. 1971. *Trans. Am. Soc. Agric. Eng. 14*:492-499.

Fryrear, D.W. & Koshi, P.T. 1974. Surface mulching with cotton gin trash improves sandy soils, U.S. Dept. Agric.-Agric. Res. Serv. Conserv. Res. Rpt. 18, U.S. Gov. Print. Off., Washington, DC. 10 pp.

Gerard, C.J. 1987. In: Gerik, T.J. & Harris, B.L. (Eds.) Conservation Tillage: Today and Tomorrow, Proc. Southern Region No-Tillage Conf., July 1987, College Station, TX. *Texas Agric. Exp. Stn. Misc. Publ. MP-1636*, College Station. pp. 72-75.

Hallsted, A.L. & Mathews, O.R. 1936. *Kansas Agric. Exp. Stn. Bull. 273*, Manhattan.

Harman, W.L., Michels, G.J. & Wiese, A.F. 1989. *Agron. J. 81*:615-618.

Johnson, W.C. & Davis, R.G. 1972. Research on stubble-mulch farming of winter wheat. U.S. Dept. Agric.-Agric. Res. Serv. Conserv. Res. Rpt. 16. U.S. Gov. Print. Off., Washington, DC. 32 pp.

Jones, O.R. 1975. *Soil Sci. Soc. Proc. 39*:98-103.

Jones, O.R. 1992. In: Proc. Fourth Annual Conf. Colorado Conserv. Tillage Assn., February 1992, Sterling, CO. pp. 21-25.

Jones, O.R., Hauser, V.L. & Popham, T.W. 1994. *Trans. Am. Soc. Agric. Eng. 37*:473-479.

Keeling, W., Segarro, E. & Abernathy, J.R. 1989. *J. Prod. Agric. 2*:269-273.

Kemper, W.D. & Schertz, D. 1992. Paper presented at Residue Management Workshop, March 31-April 2, 1992, Kansas City, MO.

Koshi, P.T. & Fryrear, D.W. 1971. *Agron. J. 63*:817-822.

McCalla, T.M. & Army, T.J. 1961. *Adv. Agron. 13*:125-196.

Musick, J.T., Allen, R.R., Dusek, D.A. & Wood, F.O. 1972. *Texas Agric. Exp. Stn. Prog. Rpt. PR-3043*, College Station. 7 pp.

Musick, J.T., Wiese, A.F. & Allen, R.R. 1977. *Trans. Am. Soc. Agric. Eng. 20*:666-672.

Russel, J.C. 1939. *Soil Sci. Soc. Am. Proc. 4*:65-70.

Schomberg, H.H., Steiner, J.L., Evett, S.R. & Moulin, A. *Theoret. and Appl. Climatol.* (in press).

Schomberg, H.H., Steiner, J.L. & Unger, P.W. 1994. *Soil Sci. Soc. Am. J. 58*:372-381.

Segarra, E., Keeling, J.W. & Abernathy, J.R. 1991. *J. Prod. Agric. 4*:566-571.

Steiner, J.L. 1989. *Soil Sci. Soc. Am. J. 53*:911-916.

Steiner, J.L., Schomberg, H.H., Douglas, Jr., C.L. & Black, A.L. 1994. *Agron. J. 86*:76-81.

Unger, P.W. 1972. *Texas Agric. Exp. Stn. Bull. 1126*, College Station. 20 pp.

Unger, P.W. 1977. *Agron. J. 69*:944-950.

Unger, P.W. 1978. *Soil Sci. Soc. Am. J. 42*:486-491.

Unger, P.W. 1981. *Soil Sci. Soc. Am. J. 45*:941-945.

Unger, P.W. 1984. *Soil Sci. Soc. Am. J. 48*:885-891.

Unger, P.W. 1986. *Soil Sci. Soc. Am. J. 50*:764-770.

Unger, P.W. 1988. *Agron. J. 80*:193-197.

Unger, P.W. 1991. *Agron. J. 83*:186-189.

Unger, P.W. 1994a. *Agron. J. 86*:310-314.

Unger, P.W. 1994b. *J. Soil Water Conserv. 49*:(in press).

Unger, P.W. 1994c. *Soil Sci. Soc. Am. J. 58*: (in press).

Unger, P.W., Allen, R.R. & Wiese, A.F. 1971. *J. Soil Water Conserv. 26*:147-150.

Unger, P.W. & Parker, J.J. 1975. *Texas Agric. Exp. Stn. Prog. Rpt. PR-3330C*, College Station. pp. 43-54.

Unger, P.W. & Wiese, A.F. 1979. *Soil Sci. Soc. Am. J. 43*:582-588.

Varvel, G.E. 1994. *Agron. J. 86*:319-325.

Whitfield, C.J., Van Doren, C.E. & Johnson, W. 1949. *Texas Agric. Exp. Stn. Bull. 711*, College Station. 15 pp.

Wiese, A.F. & Army, T.J. 1958. *Agron. J.*

50:465-468.
Wiese, A.F. & Army, T.J. 1960. *Agron. J.* *52*:612-613.
Wiese, A.F., Bond, J.J. & Army, T.J. 1960. *Weeds* *8*:284-290.
Wiese, A.F., Burnett, E. & Box, Jr., J.E. 1967. *Agron. J.* *59*:175-177.