Effect of Surface Residues on Soil Water Storage[1]

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I. Introduction

The amount and availability of soil water are major factors influencing crop production. These factors influence crop and variety selection, planting time and method, fertilization, and weed control practices. Some soils may contain too much water and require drainage before crops can be successfully grown. For other soils, plant-available soil water may be limited and irrigation or water conservation practices may be needed for successful crop production. Management of crop residues to maintain them on the soil surface has generally increased water conservation. Three general factors affecting water conservation with surface residues are: (1) protecting the soil surface against raindrop impact energy to

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maintain surface soil structure, thereby increasing infiltration and reducing runoff; (2) reducing evaporation; and (3) trapping and holding snow. The use of crop residues for water conservation has received more research attention in the arid and semiarid regions of the United States than in humid and subhumid regions. The arid and semiarid regions generally lie west of the 100th meridian, where annual precipitation is usually less than 500 mm, except for a narrow region of high rainfall immediately parallel to the west coast and in some intermountain valleys.

The value of stored soil water for crop production in arid and semiarid regions has long been recognized. Consequently, extensive research has been conducted since the early 1900s at numerous locations in arid and semiarid regions of the United States to develop practices for increasing the amount of water stored in soil from precipitation for subsequent use by crops. Most of the early research involved tillage methods, row spacings, fallowing, crop rotations, etc., and responses of various crops to these practices. The value of surface residues for conserving water was generally not considered until the late 1930s. Hallsted and Mathews (1936) stated that "trash and crop residues on the surface check runoff and allow more of the water to be absorbed by the soil," and some of the first studies involving residues were those by Duley and Kelly (1939), Duley and Russel (1939), and Russel (1939).

For this report, we review the early studies with surface residues. We then review the effects of surface residues on soil water storage as use of such residues has become practical in cropping systems, beginning with stubble mulch tillage in the 1940s, then progressing to the recent conservation tillage methods in which little or no tillage is performed. We also review the effects of surface residues on soil water evaporation and on trapping and holding snow.

II. Early Studies with Surface Residues

Duley and Kelly (1939) measured infiltration of simulated rainfall into soils ranging in surface texture from sandy loam to clay loam. The subsoils had textures ranging from sand to clay. The soils had either a bare cultivated surface or were covered with 5.6 metric tons per hectare of wheat straw (*Triticum aestivum* L.). For the six soils, total water infiltration averaged about five times greater, and final infiltration rate averaged about three times greater with the straw cover than with the bare surface. The differences in infiltration were attributed to the development of a very thin, dense surface layer on the bare soil. The straw prevented the formation of such a layer on the protected soil. They concluded that surface conditions had a greater effect on infiltration than soil type, slope, previous water content, and rainfall intensity. Although water contents were not reported, results of the study also suggested that more rainwater would be stored for subsequent use by plants in the straw-covered soil than in the bare soil.

The study by Duley and Russel (1939) involved straw (4.5 t ha^{-1}) on the soil surface, straw at the same rate disked or plowed into the soil, and several tillage treatments without straw. Effects of the treatments on soil water storage for the period from 23 April to 8 September 1938, are given in Table 1. Total rainfall for the period was 455 mm. The amount of water stored with the surface straw treatment was more than 2.5 times greater than that for the plowed treatment (no straw) and about two times greater than for the basin listing treatment. The latter treatment prevented runoff, yet less water was stored than with the straw treatment. This indicated that preventing runoff was not the total solution to conserving water in the U.S. Great Plains and that evaporation control afforded by surface residues was a major factor in soil water conservation. In several other experiments conducted by Duley and Russel (1939), soil water storage with straw on the surface was about 50 to 80 mm greater than that for a plowed treatment with straw.

Further evidence that reducing evaporation from the soil surface was a major factor in soil water conservation was provided by Russel (1939), who conducted field and soil column studies to determine the effect of surface residues on evaporation. Results of a field study are presented in Table 2. Water storage was greatest and evaporation was least where 17.9 t ha^{-1} of straw was on the surface. Evaporation loss was greatest with contour basin listing. These results indicated that reduced evaporation and favorable infiltration were important factors in improving soil water conservation.

Although the foregoing studies demonstrated the beneficial effects of

Table 1. Effect of straw and tillage treatments on soil water storage, 23 April to 9 September 1938, at Lincoln, Nebraska (adapted from Duley and Russel, 1939)

Treatment	*Precipitation[a] stored*		*Depth of water penetration (m)*
	mm	*%*	
Straw, 4.5 t ha^{-1}, on surface	247	54.3	1.8
Straw, 4.5 t ha^{-1}, disked in	176	38.7	1.5
Straw, 4.5 t ha^{-1}, plowed in	155	34.1	1.5
No straw, disked	89	19.6	1.2
No straw, plowed	94	20.7	1.2
Decayed straw, 2 t ha^{-1}, plowed in	79	17.4	1.2
Basin listed	126	27.7	1.5

[a] Precipitation totaled 455 mm.

Table 2. Water storage, runoff, and evaporation from field plots at Lincoln, Nebraska, 10 April to 27 September 1939

Treatment	*Storage (mm)*	*Runoff (mm)*	*Evaporation (mm)*	*Evaporative loss (%)*[a]
Straw, 2.2 t ha^{-1}, normal subtillage	30	26	265	83
Straw, 4.5 t ha^{-1}, normal subtillage	29	10	282	88
Straw, 4.5 t ha^{-1}, extra loose subtillage	54	5	262	82
Straw, 9.0 t ha^{-1}, normal subtillage	87	Trace	234	73
Straw, 17.9 t ha^{-1}, no tillage	139	0	182	57
Straw, 4.5 t ha^{-1}, disked in	27	28	266	83
No straw, disked	7	60	254	79
Contour basin listing	34	0	287	89

[a] Based on total precipitation, which was 321 mm for the period.

Adapted from Russel, 1939.

surface residues for conserving water, large-scale field operations with large amounts of crop residue on the surface were not practical at that time because suitable equipment for controlling weeds, maintaining crop residue on the soil surface, and planting crops under high-residue conditions had not yet been developed. However, those were the initial studies with stubble mulch tillage (subtillage), which subsequently was widely researched, especially in the U.S. Great Plains.

III. Stubble Mulch Tillage

Stubble mulch tillage was developed primarily for controlling wind erosion, but its value for reducing runoff and controlling water erosion was also soon apparent. The early research on stubble mulch farming summarized by McCalla and Army (1961), who concluded that stubble mulch farming was the most practical way to control wind erosion and that it reduced water erosion when adequate amounts of residue were present. However, additional soil conservation measures were needed to control water erosion effectively.

One factor contributing to the failure of stubble mulch tillage to control soil erosion by water is the relatively low amount of residue produced by rain-fed (dryland) crops in the Great Plains. Low residue production also contributed to the generally small increases in soil water storage with stubble mulch tillage as compared to clean tillage. Average soil water contents to a 1.5-m depth differed only 0.7% among stubble mulch, plow, and one-way disk treatments from 1941 to 1947 in Montana. The difference to a 1.8-m depth among similar treatments in Idaho was about 0.3%. In Kansas, available water contents to a 1.8-m depth were 135, 152, and 180 mm with one-way disk, plow, and stubble mulch tillage treatments, respectively. Subsequent wheat grain yields were 610, 450, and 930 kg ha^{-1}, respectively (McCalla and Army, 1961). At Bushland, Texas, soil water contents to a 1.8-m depth at wheat planting time were 12 and 27 mm greater with stubble mulch than with one-way disk tillage for continuous wheat and wheat–fallow systems, respectively (Figure 1). Respective grain yield increases with stubble mulch tillage were 110 and 130 kg ha^{-1} for the two systems (Johnson and Davis, 1972, Johnson *et al.*, 1974). For seven locations in the Central Great Plains, the average increase in soil water content with stubble mulch over clean tillage was about 25 mm (Smika, 1976a). Besides low residue production, other factors contributing to the low increases in water storage with stubble mulch tillage were the frequent tillage for timely weed control, which repeatedly exposed moist soil to the atmosphere and increased water loss to evaporation, and the failure of stubble mulch tillage to control all weeds effectively, which resulted in loss of some water via transpiration by weeds.

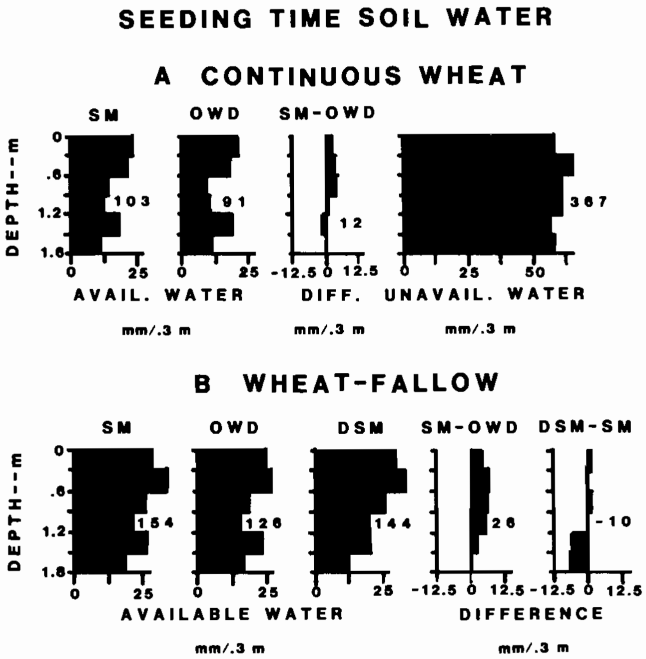

Figure 1. Average seeding-time soil water contents in continuous wheat (1942–1969) and wheat-fallow (1943–1969) plots at the USDA Conservation and Production Research Laboratory, Bushland, Texas. SM = stubble mulch, OWD = one-way disk, and DSM = delayed stubble mulch tillage (Johnson and Davis, 1972).

IV. Early Chemical Fallow (No Tillage)

When suitable chemicals (herbicides) became available, interest developed in substituting herbicides for tillage to control weeds (chemical fallow) and, thereby, to maintain more crop residues for a longer period of time on the soil surface to improve erosion control and water conservation. Although herbicides had previously been used on pastureland and in orchards (Wiese and Staniforth, 1973), the first experiments involving chemical fallow on cropland were initiated in Montana in 1948 (Baker *et al.*, 1956). Their study showed that where herbicides controlled the weeds, grain yields were comparable to those where conventional tillage was used for weed control. During the next 10 years, chemical fallow studies were initiated at several locations in the Great Plains. However, little progress was made with chemical fallow because the available herbicides did not kill all weeds during the fallow period (Wiese and Staniforth, 1973).

Another factor contributing to the lack of progress with chemical

Table 3. Straw mulch effects on soil water storage efficiency at Sidney, Montana; Akron, Colorado; and North Platte, Nebraska, from 1962 to 1965 (Greb *et al.*, 1967)

Mulch rate (t ha^{-1})	*Fallow period precipitation (mm)*	*Water storage efficiency (%)*
0	355	16
1.7	355–549	19–26
3.4	355–648	22–30
6.7	355–648	28–33
10.1	648	34

fallow was the fact that many of the studies involved dryland crops that produced relatively low amounts of residue. Although chemical fallow provided good protection against wind erosion, the limited amounts of residue were inadequate to improve water infiltration or suppress soil water evaporation. The limitation due to low amounts of residue was not recognized during the early studies but became apparent from studies by Greb *el al.* (1967) and Unger (1978), which showed that soil water storage during fallow progressively increased with increasing amounts of crop residues on the soil surface. Results of these studies are presented in Tables 3 and 4.

V. Chemical Fallow with Improved Herbicides

Although the early chemical fallow studies resulted in little progress, some progress occurred when atrazine [2-chloro-4-(ethylamino)-6-(iso-

Table 4. Straw mulch effects on soil water storage during fallow[a], water storage efficiency, and grain sorghum yield at Bushland, Texas, 1973–1976 (Unger, 1978)

Mulch rate (t ha^{-1})	*Water storage[b] (mm)*	*Storage efficiency[b] (%)*	*Grain yield (kg ha^{-1})*
1	72 c[c]	22.6 c[c]	1780 c[c]
1	99 b	31.1 b	2410 b
2	100 b	31.4 b	2600 b
4	116 b	36.5 b	2980 b
8	139 a	43.7 a	3680 a
12	147 a	46.2 a	3990 a

[a] Fallow duration of 10 to 11 months.

[b] Water storage determined to a 1.8-m depth. Precipitation averaged 318 mm.

[c] Column values followed by the same letter are not significantly different at the 5% level (Duncan's Multiple Range Test).

Table 5. Effect of fall weed-control treatments in new wheat stubble on soil water storage and grain yields in dryland rotations (Data from Greb, 1974, 1978)

		Soil water storage at		
Rotation and Fall weed control treatments	*Fall weed growth (kg ha^{-1})*	*Fall dormancy[a] (mm)*	*Wheat or millet planting[b] (mm)*	*Grain yield (kg ha^{-1})*
Wheat-fallow				
Akron, Colo. 1969–1972 (Greb, 1974)			Winter wheat	
Check, spring disk	1140	28	89	2420
Fall sweep, single	650	53	112	2690
Fall sweep, double	370	64	127	2940
Contact herbicide + atrazine + fall sweep	325	64	127	2940
Fallow-wheat-millet				
Akron, Colo. 1973–1977 (Greb, 1978)			Millet	
Check, spring disk	1175	1	114	1990
Fall sweep, double	505	19	133	2260
Contact herbicides + fall sweep	560	13	127	2210
Fall sweep + atrazine	390	17	135	2410

[a] From 25 October to 10 November.

[b] From 1 to 10 September for wheat and 1 to 10 June for millet.

propylamino)-*s*-triazine] and propazine [2-chloro-4,6-bis(isopropylamino)-*s*-triazine] herbicides became available for controlling weeds in cropping systems involving grain sorghum [*Sorghum bicolor* (L.) Moench]. A common cropping sequence in the Great Plains is winter wheat (10 months)-fallow (11 months)-sorghum (4 months)-fallow (11 months), whereby two crops are produced in 3 years.

Using the cropping sequence mentioned above, W.M. Phillips (1964) applied atrazine or propazine at 3.4 kg ha^{-1} to separate plots after wheat harvest, for weed control during the fallow period until grain sorghum was planted the next year. In some cases, 2,4-dichlorophenoxy acetic acid (2,4-D) at 1.1 kg ha^{-1} was also applied to control some existing weeds. The atrazine treatment gave excellent weed control. Propazine also gave good control, except for some grassy weeds that had emerged at the time of herbicide application. The cultivated plots required several tillage operations for weed control. The treatments did not differentially affect soil water storage, but sorghum on herbicide-treated plots yielded 4730 kg of grain per hectare and only 3040 kg ha^{-1} on cultivated plots.

After a few years, the weed population shifted from mainly broadleaf weeds that were susceptible to atrazine to grassy weeds [field sandbur, *Canchrus longispinus* (Hackel) Fern.] that were resistant, but grain sorghum yields were not significantly different from those with conventional tillage. When the atrazine-treated plots were tilled once at the time of atrazine application and again before planting or after sorghum emergence, no additional weed control measures were needed and the sorghum yielded 3720 kg of grain per hectare compared with 2290 kg ha^{-1} with conventional tillage (Phillips, 1969).

Although soil water contents were not reported for the above study, the higher grain sorghum yields with the atrazine–tillage (limited tillage) treatment were possibly attributed to higher soil water contents at planting and more efficient use of growing-season rainfall. Improved soil water storage and subsequently higher winter wheat and millet grain yields did result from various limited tillage treatments as illustrated by data (Table 5) from two studies in Colorado (Greb, 1974, 1978). The limited tillage treatments reduced weed growth, increased soil water storage, and increased grain yields compared with those of the check (spring disk) treatment. However, differences among the limited tillage treatments were generally small in most cases, indicating the importance of early (fall) weed control for conserving water and increasing crop yields.

Results from several other studies in the central Great Plains are presented in Tables 6, 7, and 8 (Smika and Wicks, 1968; Wicks and Smika, 1973). The results indicate that the gain in soil water was less for treatments involving plowing or disking, which incorporated surface residues, than for treatments involving stubble mulch or limited tillage or use of herbicides only. The greatest gain resulted from the herbicide

Table 6. Effect of tillage and herbicide treatments on soil water contents at the end of the fallow period[a] and on wheat and sorghum yields in a 3-year wheat-fallow-sorghum-fallow rotation (Smika and Wicks, 1968)

Treatment from wheat harvest to sorghum planting		*Treatment from sorghum harvest to wheat planting*[b]	*Soil water gain*[c,d] *(mm)*	*Grain yields*[d]	
Fall	*Spring*			*Wheat (kg ha^{-1})*	*Sorghum (kg ha^{-1})*
Subtillage	Disk	Subtillage (5)	186 b	3490 a	4080 b
Subtillage	Atrazine	Subtillage (4)	213 ab	3760 a	4200 b
Atrazine	Atrazine	Subtillage (4)	211 ab	3630 a	4580 ab
Atrazine	Atrazine	Contact herbicide (4–6)	223 a	3490 a	4890 a
Subtillage	Atrazine	Contact herbicide (4–6)	216 ab	3630 a	5020 a

[a] Fallow duration of about 11 months.

[b] Values in parentheses denote number of operations.

[c] Determined to a 3-m depth.

[d] Average values in a column followed by the same letter or letters are not significantly different at the 5% level (Duncan's Multiple Range Test).

Table 7. Effect of tillage and herbicide treatments on soil water contents at the end of the fallow period and on wheat yields in a 2-year (wheat–fallow) rotation (Smika and Wicks, 1968)

Operations during fallow[a]			
Initial operation following wheat harvest	*Subsequent operations*[b]	*Soil water gain*[c,d] *(mm)*	*Grain yield*[d] *(kg ha^{-1})*
Plow	Subtillage (5)[c]	186 c[d]	3090 b
Subtillage	Subtillage (5)	238 b	3360 ab
Atrazine followed by subtillage	Subtillage (5)	272 b	3290 ab
Atrazine	Subtillage (4)	275 b	3360 ab
Atrazine	Contact herbicides (4–6)	325 a	3560 a

[a] Fallow duration of about 14 months.

[b] Values in parentheses denote number of operations.

[c] Determined to a 3-m depth.

[d] Average values in a column followed by the same letter or letters are not significantly different at the 5% level (Duncan's Multiple Range Test).

Table 8. Effect of tillage and herbicide treatments on number of operations needed for weed control, residues maintained on the surface, soil water storage during fallow, and wheat yields in a 2-year (wheat-fallow) rotation

	Operations during fallow[a]				
Treatment	*Tillage*[b]	*Herbicide application*	*Residues maintained*[c] *(%)*	*Soil water gain*[d] *(mm)*	*Grain yield (kg* ha^{-1}*)*
Plow	8.5	0.0	0	146	2690
Stubble mulch	8.7	0.0	21	203	2880
Atrazine + stubble mulch	7.6	1.4	21	215	2910
Atrazine + contact herbicide + stubble mulch	5.1	2.8	25	237	3040
Atrazine + contact herbicide	0.0	6.0	46	274	3170

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[a] Fallow duration of about 14 months.

[b] The plow treatment included one moldboard plowing in the spring. Other tillage was with sweep implement.

[c] Average amount of residues at start of fallow was 6600 kg ha^{-1}.

[d] Determined to a 3-m depth.

treatments, which permitted a high percentage of residues to be maintained on the soil surface and no tillage to degrade surface soil structure to reduce water infiltration (Table 8). In general, grain yields increased with increases in stored soil water.

The foregoing examples have shown some major increases in water conservation and crop yields as a result of using various residue management practices compared with those obtained with clean tillage. The progressive improvement in water conservation and crop yields at Akron, Colorado, as influenced by changing management practices is illustrated in Table 9 (Greb, 1979). The approximate doubling of precipitation storage (soil water gain) and of grain yields is attributed to better weed control and to maintenance of residues on the surface, which enhances water infiltration and suppresses evaporation. However, the yield increases per unit increase in soil water content at planting are greater than those reported by Johnson (1964), which suggests that improved varieties, fertility, and weed control, as well as improved use of

Table 9. Progress in fallow systems with respect to water storage and wheat yields, Akron, Colorado (adapted from Greb, 1979)

		Fallow water storage		
Years	*Tillage during fallow*[a]	*mm*	*% of precip.*	*Wheat yield (kg ha^{-1})*
1916–1930	Maximum tillage; plow, harrow (dust mulch)	102	19	1070
1931–1945	Conventional tillage; shallow disk, rod weeder	118	24	1160
1946–1960	Improved conventional tillage; begin stubble mulch in 1957	137	27	1730
1961–1975	Stubble mulch; begin minimum tillage with herbicides in 1969	157	33	2160
1976–1990	Projected estimate; minimum tillage; began no tillage in 1983	183	40	2690

[a] Based on 14-month's fallow, from mid-July to second mid-September.

growing season precipitation, probably contributed to the yield increases.

VI. Managing Irrigated Crop Residues

As previously stated, residue production by dryland crops may be too low in many cases to influence soil water storage markedly, even when most of the residues are maintained on the soil surface. This situation often occurs in the southern Great Plains. However, irrigated crops, such as winter wheat, produce relatively large amounts of residue. Consequently, limited- and no-tillage studies involving residues from irrigated winter wheat were initiated at Bushland, Texas in the late 1960s (Unger *et al.*, 1971). For the fallow period from wheat harvest in July 1968 until sorghum planting in May 1969, combinations of disk, sweep, and herbicide treatments were used to control weeds and volunteer wheat. The irrigated wheat produced 11 tons of residue per hectare. Water storage with treatments involving herbicides (atrazine and 2,4-D alone or after one sweep tillage) was about double the average water storage for all tillage-only treatments (disk, sweep, or disk plus sweep).

In 1970, winter wheat was planted after irrigated corn (*Zea mays* L.) without tillage or after rotovator tillage and on a conventionally tilled fallowed area, which resulted in areas of high, medium, and low residue levels, respectively (Unger and Parker, 1975). Within these treatments, one to five irrigations of the wheat resulted in different residue production levels. After wheat harvest, low-residue treatment plots were disked once to incorporate some residues with soil. All plots were treated with atrazine and 2,4-D to control weeds and volunteer wheat. Due to treatments imposed, surface residues at sorghum planting time (11 months after wheat harvest) ranged from about 0.2 to 6.7 t ha^{-1} and stored from 11 to 45% of the fallow period precipitation (467 mm) as soil water. The highest water storage, however, was not associated with the highest residue level, possibly because of either a higher initial soil water content or precipitation interception and absorption by residues. The dryland sorghum, planted without tillage, yielded from 2970 to 6010 kg of grain per hectare. The high yield was 2240 kg ha^{-1} greater than that of sorghum on an adjacent fallowed area where conventional production practices were used.

Unger and Wiese (1979) used no-, sweep-, and disk-tillage methods for managing wheat residues and controlling weeds during fallow in an irrigated winter wheat–fallow–dryland grain sorghum cropping system at Bushland, Texas. Soil water storage averaged 35.2, 22.7, and 15.2% of the precipitation; plant-available water to a 1.8-m depth at sorghum planting averaged 217, 170, and 152 mm; sorghum grain yields averaged 3140, 2500, and 1930 kg ha^{-1}; and water-use efficiencies for grain averaged 0.89, 0.77, and 0.66 kg m^{-3} for the treatments, respectively. All differences were statistically significant. In an irrigated winter wheat–dryland grain sorghum–dryland sunflower (*Helianthus annuus* L.) rotation study at Bushland (Unger, 1984), water storage during fallow after wheat and sorghum grain yields were highest with no tillage (Table 10). The tillage treatments applied during fallow after wheat had no residual effects on yields of sunflower and wheat that followed sorghum in the rotation.

In an irrigated winter wheat–fallow–irrigated grain sorghum study at Bushland, Texas, water storage during fallow averaged 35% of precipitation with no tillage and 21% with disk tillage (Musick *et al.*, 1977). Sorghum grain yields (1970–1971 average) were 5100 and 4080 kg ha^{-1} with no- and disk-tillage treatments, respectively, with 150 mm of irrigation during the growing season. With 300 mm of irrigation, the respective yields were 6460 and 5970 kg ha^{-1}. Because the plots were in level borders and no runoff occurred, differences in water storage during fallow resulted from lower evaporation with the no-tillage treatment. On graded-furrow plots, water storage during fallow averaged 47 and 28% of precipitation with no- and disk-tillage treatments, respectively. During the growing season, 169 mm of irrigation water infiltrated the soil on no-tillage plots, but only 89 mm on disk-tillage plots. The sorghum yielded 5420 and 4260 kg of grain per hectare with no- and disk-tillage treatments, respectively.

The above studies show that surface residues can have a major influence on infiltration of irrigation water as well as on storage of precipitation as soil water. The effects of surface residues on irrigation water infiltration, however, have been variable. For continuous sorghum, infiltration averaged 271 and 300 mm with conventional and no-tillage treatments, respectively. For continuous winter wheat, infiltration averaged 391, 353, and 356 mm with conventional-, limited-, and no-tillage treatments, respectively. Although residues from continuous wheat in the furrows retarded water flow and increased infiltration, loosening the surface soil by tillage also increased infiltration (Musick *et al.*, 1977). In another study with different tillage methods for continuous wheat production (Allen *et al.*, 1976), infiltration differences due to tillage were not significant for two crops, but in the third year, infiltration was higher with clean tillage because the soil was loosened by chiseling.

Sorghum residues in the furrows slowed irrigation water advance with no tillage as compared to that with clean tillage (Allen *et al.*, 1975). For four irrigations in 1971, infiltration was 323 mm with no tillage and 267 mm with clean tillage. A fifth irrigation totaling 82 mm was followed immediately by 63 mm of rainfall. Infiltration for the two events totaled 99 mm with no tillage and 87 mm with clean tillage. Sorghum grain yields, however, were similar for the two treatments, averaging 6180 and 6360 kg ha^{-1} with the no- and clean-tillage treatments, respectively. The no-tillage treatment resulted in an excessive number of volunteer

Table 10. Effect of tillage method on average soil water storage during fallow after irrigated winter wheat and on subsequent rain-fed grain sorghum yields at Bushland, Texas, 1978 to 1983 (Unger, 1984)

	Precipitation			
Tillage treatment	*Fallow*[a] *(mm)*	*Growing season (mm)*	*Water storage*[b,c] *(%)*	*Grain yield*[c] *(kg ha^{-1})*
Moldboard	316	301	29 b	2560 bc
Disk	316	301	34 ab	2370 cd
Rotary	316	301	27 b	2190 d
Sweep	316	301	36 ab	2770 b
No tillage	316	301	45 a	3340 a

[a] Fallow duration of 10 to 11 months.

[b] Based on fallow period precipitation stored as soil water.

[c] Column values followed by the same letter to letters are not significantly different at the 5% level based on Duncan's Multiple Range Test.

sorghum plants, which increased total dry matter yields but which adversely affected grain yields. In subsequent studies with continuous grain sorghum, Allen *et al.* (1980) have found that limited tillage effectively controls volunteer sorghum plants and that irrigation water infiltration and grain yields are higher with limited tillage than with clean tillage.

VII. Residue Effects—Subhumid and Humid Regions

Precipitation reliability is greater in subhumid and humid regions than in arid and semiarid regions. However, water deficiencies that adversely affect crop growth and yields do occur in subhumid and humid regions because of short-term droughts and low water-holding capacities of some soils (Griffith *et al.*, 1977; Reicosky *et al.*, 1977). Where these conditions prevail, additional water for crop use can be provided by increasing infiltration and reducing evaporation by using residue management practices. Subsurface tillage and chisel tillage used for stubble mulch system usually are less effective for increasing soil water storage in wetter regions than in drier regions because weeds often are not effectively controlled by these tillage methods in the wetter regions (McCalla and Army, 1961). Consequently, more intensive tillage methods have been widely used in more humid regions, such as the eastern Corn Belt (Griffith *et al.*, 1977). Intensive tillage, however, frequently leads to excessive soil erosion by water and practices to control this erosion have been evaluated at numerous locations.

To control erosion, runoff must be controlled by reducing the amount and the rate of runoff. Both factors are affected by surface residues because they enhance infiltration, which reduces runoff amount and retards flow across the surface, thus reducing runoff rate. Because infiltration is increased, more water is stored in the soil, provided the soil has capacity to store the additional water.

The amount of surface residues needed to control erosion has been widely researched. Mannering and Meyer (1963), for example, showed that straw mulch applications of 2.2, 4.5, and 9.0 t ha^{-1} to a silt loam on a 5% slope all maintained very high infiltration rates and resulted in essentially no erosion. Mulch rates of 0.6 and 1.1 t ha^{-1} resulted in 6.7 and 2.2 tons of soil loss per hectare, respectively, whereas bare soil lost 26.9 t ha^{-1}. The surface mulch increased the potential for recharging the soil profile with water by retarding runoff, thereby, increasing the opportunity for infiltration.

In recent years, much research has been conducted on conservation tillage systems in subhumid and humid regions. The residues maintained on the surface have resulted in higher soil water contents at many locations, as reported by Bennett (1977), Blevins *et al.* (1971), Jones *et al.*

(1969), Nelson *et al.* (1976) Mannering *et al.* (1975), Mannering and Meyer (1963), Van Doren *et al.* (1976), and others. The additional soil water resulting from maintenance of surface residues resulted in higher yields than with clean tillage, particularly when soil water became limited during the growing season.

VIII. Surface Residue Effects on Evaporation

In the foregoing sections, the increased soil water storage with surface residues resulted from increased infiltration and undoubtedly decreased evaporation. This was indicated by the early work of Duley and Russel (1939) and Russel (1939). The actual contribution of decreased evaporation on water conservation, however is difficult to determine in most field studies, but some studies have clearly shown that lower evaporation with surface residues is a major factor. Bond and Willis (1970) showed that small amounts of plant residue on the soil surface effectively decreased evaporation during the first stage of drying by increasing the resistance of water flow from the soil surface to the atmosphere. First, residues decrease surface temperatures, as shown in Table 11, which results in a decrease in vapor pressure of the soil water; second, the residue layer increases the thickness of the relatively nonturbulent air layer above the soil surface, which decreases vapor transport away from the soil. The latter was demonstrated by Smika (1983) under field conditions where the same amount of wheat residue on soil, but in different positions, resulted in different rates of water loss by evaporation (Figure 2). As the amount of standing straw increased, greater windspeed was needed for initial water loss and the rate of water loss also decreased with increasing amounts of

Table 11. Average daily soil surface temperature as affected by bare soil and wheat straw position during 5-week, August–September period, Akron, Colorado (Smika, 1983)

Straw position[a]	*Soil surface temperature*[b,c] *(°C)*
Bare soil	47.8 c
Flat straw	41.7 b
3/4 flat, 1/4 standing	39.6 b
1/2 flat, 1/2 standing	32.2 a

[a] All straw amounts were 4600 kg ha^{-1}.

[b] Average of measurements at 1000, 1200, and 1500 hr with a radiation thermometer.

[c] Values accompanied by different letters are significantly different at $P = 0.01$ (Duncan's Multiple Range Test).

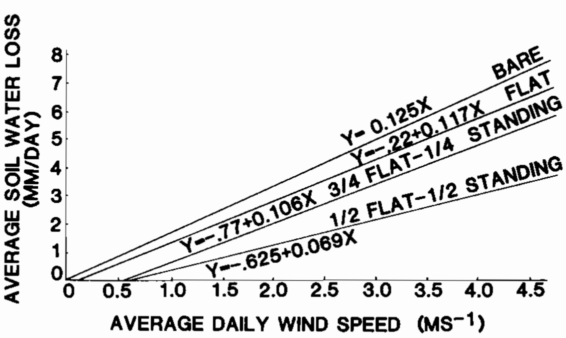

Figure 2. Effect of residue orientation and windspeed on soil water evaporation (Smika, 1983).

standing residue at a given windspeed. This clearly shows that reduced windspeed at the soil surface due to surface residues is a major factor in reducing evaporation, thereby, increasing soil water storage.

After the soil surface dries, water flow to the surface and porosity or air permeability of the surface soil become more important in the evaporation process. This was clearly demonstrated where conventional-, minimum-, and no-tillage treatments were compared for soil water loss during a 34-day period following 165 mm of rainfall and during which time no additional precipitation was received (Smika, 1976b). On the first day after the rain (Figure 3), there was very little difference in soil water content between treatments to a 15-cm depth. After 34 days (Figure 4), soil with the conventional-tillage treatment had dried to less than 0.1 cm cm^{-1} of water to a 12-cm depth and that of the minimum-tillage treatment had dried to that water content level to a 9-cm depth. Both depths are the same at which a blade tillage operation was performed 8 days before the rain. In contrast, soil with the no-tillage treatment dried to that water content level to only a 5-cm depth. For each treatment, some water loss occurred to soil depths greater than those indicated. At the time of this 34-day drying cycle, the conventional, minimum, and no-tillage treatments had 1200, 2200, and 2700 kg ha^{-1} of residue on the soil surface, respectively. The large amount of partly standing residue on the soil surface of the no-tillage treatment was sufficient to limit water loss to the 4-cm depth. However, where the residue amounts were less and the soil had been loosened by tillage, drying occurred to the depth of the tillage.

Decreased evaporation with surface residues is also a factor in greater water storage in more humid regions (Phillips, 1974). For a silt loam in Kentucky, evaporation from May through September was 2.4 times greater with conventional tillage than with no-tillage. This difference provided 18% more water for transpiration by no-tillage corn than for

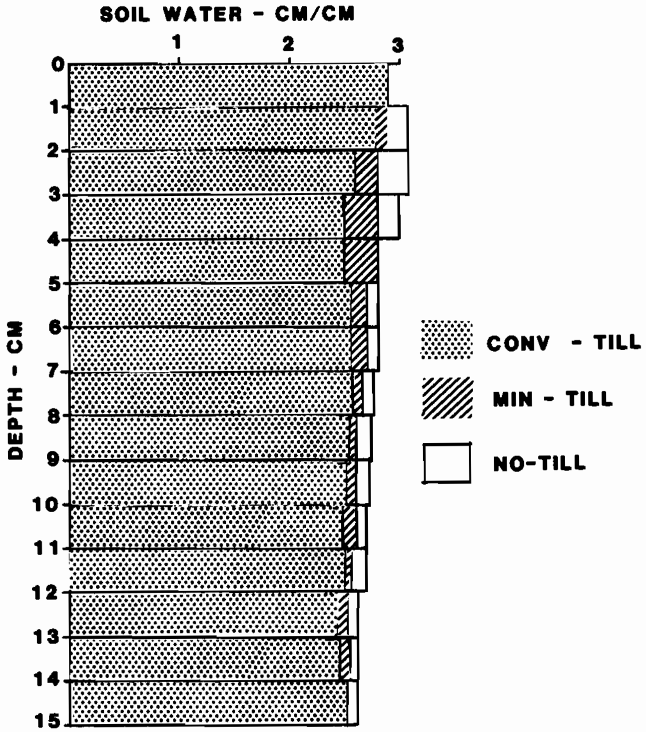

Figure 3. Soil water to a 15-cm depth on day 1 after 165 mm of rainfall as influenced by tillage treatment (Smika, 1976b).

conventional tillage corn (330 vs 280 mm of water during the growing season).

In contrast to field studies where evaporation measurements may be confounded by differences in infiltration, redistribution, and deep percolation due to differences in the amount of residues on the soil surface, the influence of surface residues on evaporation can be better investigated under controlled laboratory conditions. The studies by Bond and Willis (1969, 1970, 1971), which involved soil columns initially wetted to a given water content, showed that increasing amounts of surface residues decreased evaporation, especially during the first stage of evaporation. Because of lower evaporation during the initial stage, water from beneficial precipitation would move deeper into the soil where it was less subject to loss during the latter stages of evaporation. Although differences in evaporation rates between bare and residue-covered soil occur during the initial stage, evaporation rates for mulched soil may be greater during the later stages and, if continued long enough, evaporation from residue-covered soils may eventually approach, equal, or possibly

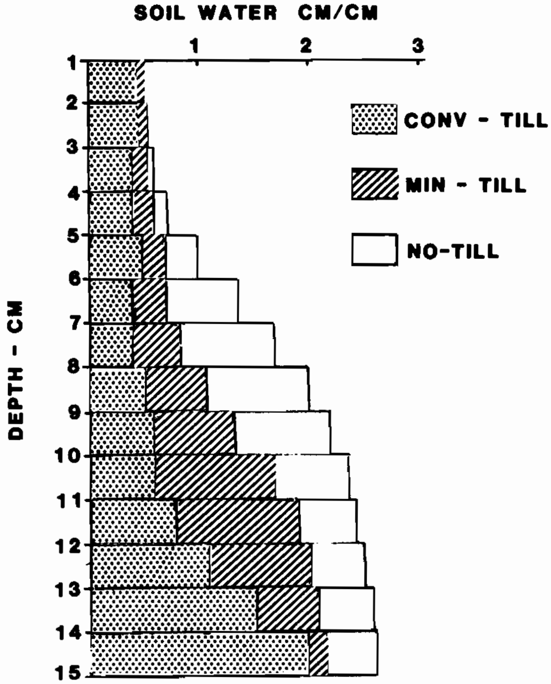

Figure 4. Soil water to a 15-cm depth 34 days after 165 mm of rainfall as influenced by tillage treatment (Smika, 1976b).

exceed that from bare soil. However, until that point is reached, the residue-covered soil will have more stored water than the bare soil that is potentially available for crop use.

Depth of water penetration was shown by Unger (1976) to be a major factor in reducing evaporation and in increasing soil water storage. When 15 mm of water was applied to a clay loam or a sandy loam at 14-day intervals, surface residue rates had little effect on the percentage of water stored. However, with 30-, 60-, or 120-mm water applications, the percentage of water stored in the soils progressively increased with increasing amounts of surface residues. For example, water stored in the clay loam with 30-, 60-, and 120-mm water additions was about 10 and 42%, 26 and 72%, and 48 and 84%, respectively, for the bare soil and 12 tons of residue per hectare treatments.

The foregoing examples in this section involved wheat residues applied at different rates on a surface area basis. Different types of residue have different specific gravities and, consequently, result in different percentages of surface coverage and residue thickness with a given amount of residue by weight. Unger and Parker (1976) used wheat, grain sorghum, and cotton (*Gossypium hirsutum*) (stalk) residues in an evaporation study

Table 12. Characteristics of residues used in an evaporation study (Unger and Parker, 1976)

	Residue type		
	Wheat	*Grain sorghum*	*Cotton*
Center of residues	Hollow	Pithy	Woody
Specific gravity	0.17	0.26	0.49
Thickness (cm) at:			
4 metric tons ha^{-1}	—	1.0	0.5
8 metric tons ha^{-1}	2.9	1.9	1.1
16 metric tons ha^{-1}	—	3.1	1.4
32 metric tons ha^{-1}	—	4.5	3.4
Surface coverage (%) at:			
4 metric tons ha^{-1}	—	66	8
8 metric tons ha^{-1}	100	90	37
16 metric tons ha^{-1}	—	98	80
32 metric tons ha^{-1}	—	100	99

in the laboratory. Characteristics of the residues with respect to specific gravity, thickness, and surface coverage at various rates are shown in Table 12. Effects of the residues at different rates on cumulative evaporation with time when the potential evaporation rate was 6.6 mm day^{-1} are shown in Figure 5. Because of the thickness and surface coverage differences, about 16 tons of sorghum and more than 32 tons of cotton residue per hectare were needed to obtain an evaporation

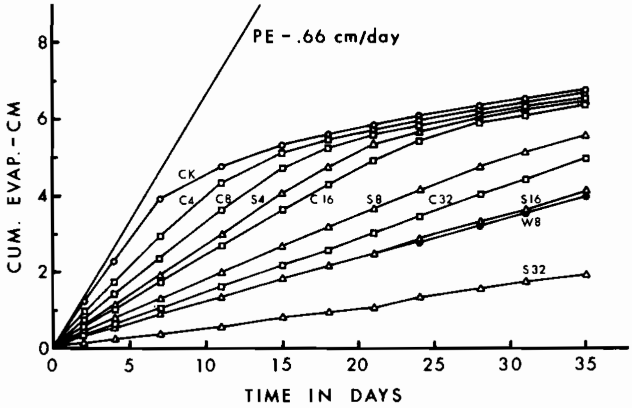

Figure 5. Effects of residue treatments on cumulative evaporation at 0.66 cm day^{-1} potential evaporation. CK = check, C = cotton, S = grain sorghum, W = wheat. Numbers after letters designate metric tons of applied residues per hectare. (Unger and Parker, 1976).

reduction comparable to that obtained with 8 t ha^{-1} of wheat residue. At potential evaporation rates of 9.2 and 12.9 mm day^{-1}, evaporation from the residue-covered soils was only slightly greater than when the potential rate was 6.6 mm day^{-1}. Other characteristics of residues that affect evaporation are rainfall interception; reflectivity, which affects the energy arriving at the soil surface; residue orientation (flat or matted vs standing), which affects thickness and porosity of the residue layer; uniformity of the surface residue layer; and aerodynamic roughness resulting from the residues (Van Doren and Allmaras, 1978).

IX. Surface Residue Effects on Water Conservation from Snow

The effectiveness of crop residues (mainly wheat) for increasing soil water storage during a fallow period increases from south to north. This increase is partially due to the effectiveness of standing residues for trapping and holding snow, providing the potential for increasing soil water storage when it melts.

The contribution of snow to water conservation is greater in the northern locations than in the southern locations because snow comprises a larger percentage of the annual precipitation at the northern locations. For example, water in snow accounts for about 15 to 20% of the average annual precipitation at locations from the central Great Plains in the United States to southern Canada (Saskatchewan) (De Jong and Steppuhn, 1983; Smika and Whitfield, 1966), whereas water in snow accounts for only about 5% of the annual precipitation at Bushland, Texas in the southern Great Plains (weather records, USDA-ARS Conservation and Production Laboratory, Bushland, Texas). In the southern Great Plains, if the snow that falls is held in place, a larger percentage of it is usually stored as soil water than in the northern Great Plains. At southern locations, the soil seldom freezes to inhibit snowmelt water from infiltrating into the soil. At northern locations, however, much of the snowmelt may be lost as runoff because the frozen soil reduces infiltration of the water (De Jong and Steppuhn, 1983).

Snowfall in the Great Plains often is accompaned by high winds, which results in uneven distribution of snow on the landscape. The influence of topography or structures and vegetation on the relative distribution of snow cover (water equivalent) on a watershed in Canada is shown in Table 13. Stubble areas usually had a greater snow cover than fallow areas because the stubble effectively trapped the windborne snow. Bare soil areas retain little or no snow when snowfall is accompanied by wind. Consequently, soil water storage from snow is usually greater in stubble areas than on bare soil areas. Because of snow blown from bare

Table 13. Relative distribution of snow cover (water equivalent) in the Creighton watershed, Bad Lake Basin, in Canada

Land type and use	*Percentage*
Level plains	
Fallow	55
Stubble	71
Pasture	59
Hilltops	
Fallow	20
Stubble	48
Pasture	30
Gradual slopes	
Fallow	68
Stubble	69
Pasture and brush	79
Small draws	
Fallow	132
Stubble, pasture, and brush	138
Steep slopes	
Pasture and brush	253
Farmyards	
Accumulated total snowfall (Niphet shielded gage)	100
Average for entire watershed	77

Reproduced from De Jong and Stepphun, *Dryland Agriculture* pp. 89–104, 1983, by permission of the Am. Soc. Agronomy, Crop Sci. Soc. Am., and Soil Sci. Soc. Am.

soil areas and trapped in stubble areas, soil water storage from snowmelt has exceeded 100% in some stubble areas (Smika and Whitfield, 1966).

The value of surface residues for trapping snow and, consequently, increasing soil water storage is apparent from the foregoing discussion. Surface residues are most effective for trapping snow when they are standing. Other residue management practices for increasing snow trapping and conserving snowmelt include (1) alternating relatively narrow strips of tall (greater than 30 cm) stubble with areas of short (or no) stubble (De Jong and Steppuhn, 1983; Willis *et al.*, 1983); (2) establishing wind barriers of tall stubble, such as rows of corn or sunflower (De Jong and Steppuhn, 1983), sudangrass (Greb, 1983), tall wheatgrass (De Jong and Steppuhn, 1983 Greb, 1983; Willis *et al.*, 1983), and field shelterbelts (Greb, 1983; Willis *et al.*, 1983); (3) seeding winter wheat into standing spring wheat stubble (Willis *et al.*, 1983); and (4) chiseling stubble fields in the fall to below the frost zone (30 cm deep) to enhance water infiltration into nonfrozen soil at the bottom of the chisel furrow (Ramig *et al.*, 1983). Use of rows of trees or bushes are not acceptable as snow barriers in regions where water conservation is required because these plants extend roots into adjacent cropped areas and, therefore, extract soil water that could be used for crop production (Greb, 1983). Also, snow distribution with these plants is seldom uniform.

X. Summary and Conclusions

The value of water stored in soil at planting time for obtaining favorable crop yield in arid and semiarid regions has long been recognized. Early attempts to increase soil water storage involved tillage methods (clean), row spacings, fallowing, crop rotations, etc., and responses of various crops to these practices. The value of crop residues for conserving water was not realized until the late 1930s, and use of residues did not become practical under field conditions until the stubble mulch tillage system was introduced in the 1940s. Even greater emphasis on using surface residues for increasing soil water storage developed when herbicides became available for controlling weeds, thereby reducing the need for tillage to control weeds.

The additional water stored in soil due to maintaing crop residues on the surface has resulted from increased water infiltration and reduced soil water evaporation. In areas where snowfall comprises a significant part of the annual precipitation, maintaining standing residues to trap and hold snow on the land allows snowmelt water to enter the soil and is a major factor in increasing soil water storage where surface residues are present.

The additional water stored in soil where surface residues were maintained on the surface has resulted in increased crop yields at many locations. The surface residues have also provided protection against soil erosion by wind and water. Although water and soil resource conservation has resulted from maintenance of surface residues in most cases, residue production of some crops under rain fed conditions in arid and semiarid regions may not be great enough to have a major impact on soil and water conservation. In other cases, cropping systems necessary for adequate residue production are not yet available. Consequently, additional research is needed to develop suitable systems of water and soil conservation for all soils so that the crop production potential will be maintained or improved. Only by adequately conserving our soil and water resources can we be assured that future generations will have adequate resources for producing the food and fiber that they will require.

References

Allen, R.R., J.T. Musick, F.O. Wood, and D.A. Dusek. 1975. No-till seeding of irrigated sorghum double cropped after wheat. *Trans. Am. Soc. Agr. Eng.* 18:1109–1113.

Allen, R.R., J.T. Musick, and A.F. Wiese. 1976. Limited tillage of furrow irrigated winter wheat. *Trans. Am. Soc. Agr. Eng.* 19:234–236, 241.

Allen, R.R. J.T. Musick, and D.A. Dusek. 1980. Limited tillage and energy use with furrow-irrigated grain sorghum. *Trans. Am. Soc. Agr. Eng.* 23:346–350.

Baker, L.O., J.L. Krall, T.S. Aasheim, and T.P. Hartman. 1956. Chemical summer fallow in Montana. *Down to Earth* 11:21.

Bennett, O.L. 1977. Conservation tillage in the Northeast. *J. Soil Water Cons.* 32:9–12.

Blevins, R.L., D. Cook, S.H. Phillips, and R.E. Phillips. 1971. Influence of no-tillage on soil moisture. *Agron. J.* 63:593–596.

Bond, J.J., and W.O. Willis. 1969. Soil water evaporation: Surface residue rate and placement effects. *Soil Sci. Soc. Am. Proc.* 33:445–448.

Bond, J.J., and W.O. Willis. 1970. Soil water evaporation: First stage drying as influenced by surface residue and evaporation potential. *Soil Sci. Soc. Am. Proc.* 34:924–928.

Bond, J.J., and W.O. Willis. 1971. Soil water evaporation: Long-term drying as influenced by surface residue and evaporation potential. *Soil Sci. Soc. Am. Proc.* 35:984–987.

De Jong, E., and H. Steppuhn. 1983. Water conservation: Canadian prairies. In: H.E. Dregne and W.O. Willis (eds.), *Dryland agriculture. Agronomy Monograph* 23:89–104.

Duley, F.L., and Kelly, L.L. 1939. Effect of soil type, slope, and surface conditions on intake of water. Res. Bull. No. 112 Agr. Exp. Stn., Univ. of Nebraska, Lincoln.

Duley, F.L., and J.C. Russel. 1939. The use of crop residues for soil and moisture conservation. *J. Am. Soc. Agron.* 31:703–709.

Greb, B.W. 1974. Yield response to fall weed control in new wheat stubble in a fallow-wheat rotation. In: B.L. Bohmont (ed.), *Fourth annual Colorado crop Protection Inst. Proc.* Colorado State University, Fort Collins, Colorado, pp. 33–45.

Greb, B.W. 1978. Millet production with limited water. Publ. No. PR-78,Colorado State Univ. Exp. Stn. Ft. Collins, Colorado, pp. 1–3.

Greb, B.W. 1979. Reducing drought effects on croplands in the west central Great Plains. Info. Bull. No. 420, U.S. Dept. Agr., U.S. Governement Printing Office, Washington, D.C., pp. 1–31.

Greb, B.W. 1983. Water conservation: Central Great Plains. In: H.E. Dregne and W.O. Willis (eds.), *Dryland agriculture. Agronomy* 23:57–72.

Greb, B.W., D.E. Smika, and A.L. Black. 1967. Effect of straw-mulch rates on soil water storage during summer fallow in the Great Plains. *Soil Sci. Soc. Am. Proc.* 31:556–559.

Griffith, D.R., J.V. Mannering, and W.C. Moldenhauer. 1977. Conservation tillage in the eastern Corn Belt. *J. Soil Water Cons.* 32:20–28.

Hallsted, A.L., and O.R. Mathews. 1936. Soil moisture and winter wheat with suggestions on abandonment. Bull. No. 273 Kansas Agr. Exp. Stn., 44 pp.

Johnson, W.C. 1964. Some observations on the contribution of an inch of seeding time soil moisture to wheat yield in the Great Plains. *Agron. J.* 56:29–35.

Johnson, W.C., and R.G. Davis. 1972. Research on stubble-mulch farming of winter wheat. USDA-ARS Conserv. Res. Rep. No. 16, U.S. Government Printing Office, Washington, D.C., pp 1–21.

Johnson, W.C., C.E. Van Doren, and E. Burnett. 1974. Summer fallow in the southern Great Plains. *In: Summer fallow in the western United States.* Cons. Res. Rept. No. 17, USDA Agr. Res. Serv., Washington, D.C. p. 97.

Jones, J.N., Jr., J.E. Moody, and J.H. Lillard. 1969. Effects of tillage, no-tillage, and mulch on soil water and plant growth. *Agron. J.* 60:719–721.

Mannering, J.V., and L.D. Meyer. 1963. The effects of various rates of surface mulch on infiltration and erosion. *Soil Sci. Soc. Am. Proc.* 27:84–86.

Mannering, J.V., D.R. Griffith, and C.B. Richey. 1975. Tillage for moisture conservation. Paper No. 75-2523, Am. Soc. Agr. Eng., St. Joseph, Michigan.

McCalla, T.M., and J.T. Army. 1961. Stubble mulch farming. *Adv. Agron.* 13;125–196.

Musick, J.T., A.F. Wiese, and R.R. Allen. 1977. Management of bed-furrow irrigated soil with limited- and no-tillage systems. *Trans. Am. Soc. Agr. Eng.* 20:666–672.

Nelson, L.R., R.N. Gallaher, and R.R. Bruce. 1976. Corn forage yields in double-cropping systems. *Fertilizer Solutions* 20:56–63.

Phillips, R.E. 1974. Soil water, evapotranspiration and soil temperature in no-tilled soil. In: R.L. Blivens and G.L. Thomas (eds.), *Proceedings, no-tillage research conference.* Univ. of Kentucky, Lexington, pp. 6–14.

Phillips, W.M. 1964. A new technique of controlling weeds in sorghum in a wheat-sorghum-fallow rotation in the Great Plains. *Weeds* 12:42–44.

Phillips, W.M. 1969. Dryland sorghum production and weed control with minimum tillage. *Weed Sci.* 17:451–454.

Ramig, R.E., R.R. Allmaras, and R.I. Papendick. 1983. Water conservation: Pacific Northwest. In: H.E. Dregne and W.O. Willis (eds.), *Dryland Agriculture. Agronomy Monograph* 23:105–124.

Reicosky, D.C., D.K. Cassel, R.L. Blevins, W.R. Gill, and G.C. Naderman. 1977. Conservation tillage in the Southeast. *J. Soil Water Cons.* 32:13–19.

Russel, J.C. 1939. The effect of surface cover on soil moisture losses by evaporation. *Soil Sci. Soc. Am. Proc. 4:65–70.*

Smika, D.E. 1976a. Mechanical tillage for conservation fallow in the semiarid Central Great Plains. In: B.W. Greb (ed.), Conservation tillage, Proc. Great Plains Workshop. Publ. No. 77, Great Plains Agr. Council, Fort Collins Colorado, pp. 78–91.

Smika, D.E. 1976b. Seed zone soil water conditions with reduced tillage in the semiarid Central Great Plains. Proc. 7th Conf. Int. Soil Tillage Res. Org. 37.1-37.6, Uppsala, Sweden. June 13–18, 1976.

Smika, D.E. 1983. Soil water change as related to position of wheat straw mulch on the soil surface. *Soil Sci. Soc. Am. J.* 47:988–991.

Smika, D.E., and C.J. Whitfield. 1966. Effect of standing wheat stubble on storage of winter precipitation. *J. Soil Water Cons.* 21:138–141.

Smika, D.E., and G.A. Wicks. 1968. Soil water storage during fallow in the Central Great Plains as influenced by tillage and herbicide treatments. *Soil Sci. Soc. Am. Proc.* 32:591–595.

Unger, P.W. 1976. Surface residue, water application, and soil texture effects on water accumulation. *Soil Sci. Soc. Am. J.* 40:298–300.

Unger, P.W. 1978. Straw-mulch rate effect on soil water storage and sorghum yield. *Soil Sci. Soc. Am. J.* 42:486–491.

Unger, P.W. 1984. Tillage and residue effects on wheat, sorghum, and sunflower grown in rotation. *Soil Sci. Soc. Am. J.* 48:885–891.

Unger, P.W., and J.J. Parker. 1975. No-tillage dryland grain sorghum after irrigated wheat with intervening fallow. Prog. Rep. No. 3330, Texas Agr. Exp. Stn., College Station, Texas, pp. 43–54.

Unger, P.W., and J.J. Parker. 1976. Evaporation reduction from soil with wheat, sorghum, and cotton residues. *Soil Sci. Soc. Am. J.* 40:938–942.

Unger, P.W., and A.F. Wiese. 1979. Managing irrigated winter wheat residues for water storage and subsequent dryland grain sorghum production. *Soil Sci. Soc. Am. J.* 43:582–588.

Unger, P.W., R.R. Allen, and A.F. Wiese. 1971. Tillage and herbicides for surface residue maintenance, weed control, and water conservation. *J. Soil Water Cons.* 26:147–150.

Van Doren, D.M., Jr., and R.R. Allmaras. 1978. Effect of residue management practices on the soil physical environment, microclimate, and plant growth. In: W.R. Oschwald (ed.), *Crop residue management systems.* Spec. Publ. No. 31, Am. Soc. Agron, Madison, Wisconsin, pp. 49–83.

Van Doren, D.M., Jr., G.B. Triplett, Jr., and J.E. Henry. 1976. Influence of long term tillage, crop rotations, and soil type combinations on corn yield. *Soil Sci. Soc. Am. J.* 40:100–105.

Wicks, G.A., and D.E. Smika. 1973. Chemical fallow in a winter wheat-fallow rotation. *J. Weed Sci. Soc. Am.* 21:97–102.

Wiese, A.F., and D.W. Staniforth. 1973. Weed control in conservation tillage. In: A.B. Linford (ed.), *Conservation tillage, the Proceedings of a National Conference.* Soil Cons. Soc. Am., Ankeny, Iowa, pp. 108–114.

Willis, W.O., A.Bauer, and A.L. Black. 1983. Water conservation: Northern Great Plains. In: H.E. Dregne and W.O. Willis (eds.), *Dryland Agriculture. Agronomy Monograph* 23:73–88.