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Tillage and Crop Residue Management Practices for Sustainable Dryland Farming Systems

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Abstract: Dryland crop production is limited by precipitation and by soil factors such as texture and profile depth that affect water storage capacity, pH, fertility, and salinity. When prevailing precipitation and soil factors are not in balance, crops will not yield at their potential and productivity may be impaired because soil degradation processes outweigh conservation practices. Sustainable crop production is possible through use of appropriate tillage and crop residue management practices. When adequate crop residues are available, conservation tillage is highly effective for conserving soil and water, achieving favorable crop yields, maintaining soil organic carbon contents, and soil and water quality. Other tillage methods along with appropriate conservation practices may be needed when crop residues are limited.

Key words: Clean tillage, conservation tillage, crop residue management, cropping systems, erosion control, soil conservation, soil organic carbon, soil quality, water conservation, water quality, weed control.

"Dryland agriculture is a dynamic and highly complex system in which the major limitation on food and fiber production is a deficiency of water" (Willis and Dregne, 1983). Dryland agriculture is practiced in semi-arid and subhumid regions where the water deficiency results from low and erratic precipitation and generally inefficient precipitation storage as soil water during noncrop periods. Besides the precipitation limitations, crop production is limited also by soil factors such as texture and profile depth that affect water storage capacity, pH, fertility, and salinity. When prevailing precipitation and soil factors are not in balance, crop yields will be below their potential, and soil productivity may be impaired because degradation processes outweigh conservation practices (Fig. 1). To halt or avoid soil degradation, practices that positively influence productivity must be used. Two practices that strongly influence soil conservation are tillage and crop residue management. When appropriate tillage (e.g., conservation tillage) and residue management (e.g., residue retention on the soil surface) practices are used, sustainable crop production is possible. Our emphasis will be on conservation tillage and residue management, but we will also discuss other related practices.

Tillage and Related Practices

Under most conditions, conservation tillage is highly effective for conserving soil and water resources when adequate crop residues are available to cover much of the soil surface. For example, when 30%

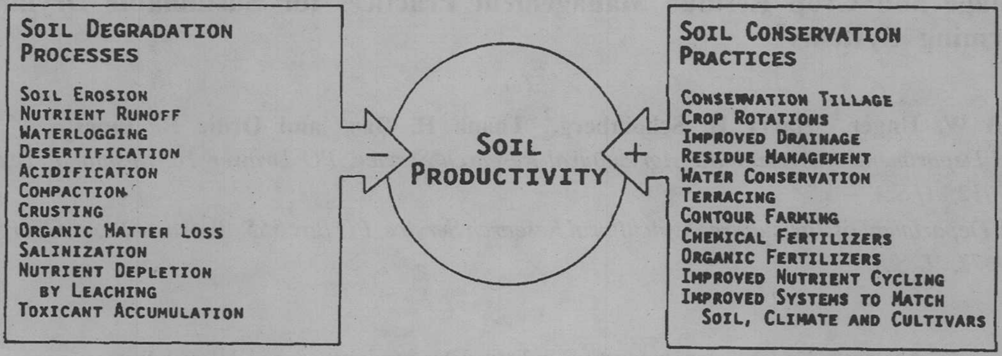

Fig. 1. Relationship of soil productivity to soil degradation processes and soil conservation practices (from Parr et al., 1990).

of the soil surface is covered by crop residues, the amount specified in the definition for conservation tillage (CTIC, 1990), soil losses by erosion due to wind or water are reduced to about 0.25 to 0.30 of the losses from surfaces without residues (Fig. 2). Under dryland conditions, however, crops sometimes do not produce enough residues to provide 30% cover of the surface, or the crop residues may be harvested for animal feed, fuel, or other purposes. When residues are limited or removed, use of other tillage methods in conjunction with other cultural practices often is required to conserve soil and water, which is essential for sustainable crop production.

Conservation tillage

Conservation tillage, as per the definition (CTIC, 1990), is a crop residue management system. Provided sufficient residues are available and retained on the surface, conservation tillage can range from disturbing the entire soil surface by tillage (e.g., with a sweep, chisel, or disk) to disturbing only a small portion of the surface for crop seeding (with no-tillage). Because surface residue retention is a major goal for use of conservation tillage, the most suitable tillage method for a given situation depends largely on the amount of residues present at crop harvest. When relatively large amounts are present, as sometimes is the case even under dryland conditions, disk tillage that incorporates some residues can be used for the first operation. Disk tillage, however, should not be used repeatedly because about 50% of surface residues are incorporated with each disking operation. When full-width tillage is desired and surface residues amounts are relatively low, as frequently is the case under dryland conditions in semiarid regions, stubble mulch tillage usually is more appropriate.

Stubble mulch tillage was developed to control wind erosion in the U.S. Great Plains and Canadian Prairie Provinces, primarily as a result of the severe erosion that occurred in that region during a major drought in the 1930s (Allen and Fenster, 1986). With stubble mulch tillage, sweeps or blades undercut the entire soil surface at a depth of 5 to 10 cm to control weeds and prepare

Table 1. Effect of tillage machines on small grain residues remaining on the soil surface after each operation (adapted from Anderson, 1968)

Tillage machine	Approximate amount remaining (%)
Subsurface operating: Wide-blade cultivator, stubble mulch plow, rodweeder	90
Mixing type: Heavy-duty cultivator, chisel, other similar machines	75
Mixing and partially inverting: One-way flexible disk harrow, one-way disk, tandem disk, offset disk	50
Inverting: Moldboard plow, disk plow	10

a seedbed for the next crop, but most crop residues are retained on the soil surface.

Stubble mulch tillage, although developed primarily for wind erosion control, also helps control water erosion. This benefit results from retaining residues on the surface and from loosening the soil. Surface residues dissipate the energy of falling raindrops, thus reducing soil aggregate dispersion, particle movement and rearrangement, and surface seal development. As a result, water infiltration remains at favorable rates and particle movement across the surface is decreased. Also, surface residues retard water flow across the surface, thus providing more time for water infiltration and reducing soil particle transport. For soils with dense surface layers, stubble mulch tillage loosens the soil, roughens the soil surface, creates surface depressions, and increases soil porosity. These conditions result in temporary water storage, more time for infiltration, reduced water flow and sediment transport, and less erosion by water. Reduced soil water evaporation due to surface residues also contributes to greater water conservation when using stubble mulch tillage.

In general, soil and water conservation benefits with chisel tillage are intermediate between those achieved with disk and stubble mulch tillage because surface residue retention with chisel tillage is intermediate between that with disk and stubble mulch tillage (Table 1). In some cases, soil conservation may be greater with chisel tillage because it results in a rougher soil surface than disk or sweep tillage, which is especially beneficial for wind erosion control when surface residues are limited. Water conservation may be greater with chisel tillage if it loosens the soil to a greater depth, thus providing for greater temporary storage of water and more time for infiltration.

The ultimate type of conservation tillage is no-tillage for which soil is not disturbed, except for a narrow zone for seed placement. With no-tillage, most crop residues are retained on the soil surface, with the resultant surface cover percentage being related to the type, amount, and orientation of crop residues. For example, wheat (*Triticum aestivum* L.) straw at 1.0 Mg ha^{-1} provides about 50% surface cover (Van Doren and Allmaras, 1978), but about 3 of grain sorghum [*Sorghum bicolor* (L.) Moench] stover and 9 of cotton (*Gossypium hirsutum* L.) stalks are needed for the same amount of surface cover when these materials are placed flat on the surface (Unger and Parker, 1976). In general, upright residues provide less surface cover than flat residues. Sal-

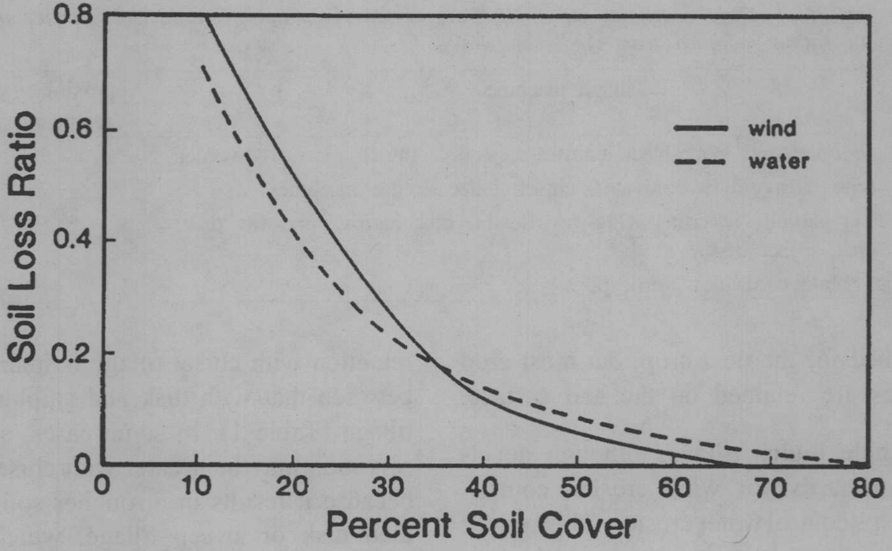

Fig. 2. Relationship between soil loss ratio (SLR is soil loss with cover divided by soil loss from bare soil) and percentage cover (from Papendick et al., 1990).

laway *et al.* (1988) showed that surface cover (%) could be determined from stubble weight according to:

Projected cover = $m(1- e^{-\text{stubble weight}})$ ..1

where, m is 98.1 for wheat, 64.7 for sorghum, and 49.3 for sunflower (*Helianthus annuus* L.), and stubble weight is in kg ha^{-1}

Soil erosion control increases with increasing amounts of crop residues retained on the soil surface. Therefore, use of no-tillage, which results in most residues on the surface, generally provides the greatest erosion control. The effect of differing amounts of surface cover on soil losses due to water and wind erosion are clearly evident from the results shown in Fig. 2.

Water conservation generally also increases with increasing amounts of crop residues retained on the soil surface. Therefore, use of no-tillage generally resulted in soil water contents and/or crop yields similar to or greater than those with other tillage methods (Jones and Popham, 1997; Marley and Littler, 1990; Norwood and Currie, 1996; Nyborg and Malhi, 1989; Pratley, 1995; Rasmussen *et al.*, 1986; Thomas *et al.*, 1995; Unger, 1984a; Unger and Wiese, 1979). Benefits of using no-tillage generally were greatest in years when precipitation was limited. Yield decreases that occurred with no-tillage were attributed to factors such as low nitrogen availability, root disease severity, high soil strength, and possibly allelopathic effects of stubble (e.g., Elliott and Cheng, 1987; Felton *et al.*, 1995; Kirkegaard, 1995). Examples of tillage and residue management effects on soil water contents and/or crop yields are shown in Tables 2 to 9. An example of

Table 2. Effect of fallow management on mean (standard error) wheat grain yields (Mg ha^{-1}) at five sites in Australia, 1981-1990 (adapted from Felton et al., 1995)

Site	Management system		
	No-tillage	Stubble mulch	Straw burned, cultivated
Breeza	2.49±0.25	2.46±0.23	2.88±0.18
Croppa Creek	2.52±0.35	2.72±0.26	3.05±0.26
Gurley	2.02±0.24	2.23±0.27	2.38±0.27
Warialda	3.41±0.17	3.35±0.15	3.53±0.20
Winton	1.96±0.24	2.06±0.26	2.39±0.26
Overall mean	2.48±0.11	2.56±0.10	2.85±0.10

tillage and residue management effects on soil water evaporation under field conditions is shown in Fig. 3. Soil water contents were similar in conventional, minimum, and no-tillage plots one day after rain (14 mm), but were lowest with conventional tillage and greatest with no-tillage after 34 days without additional rain. Surface residue amounts (wheat straw) were 1.2, 2.2, and 2.7 Mg ha^{-1} in conventional, minimum, and no-tillage plots, respectively (Smika, 1976).

Table 3 Progress in fallow systems with respect to water storage and wheat yields, Akron, Colorado (adapted from Greb, 1979)

Year	Fallow tillage	Water storage		
		Amount (mm)	Efficiency (%)	Yield (kg ha^{-1})
1916-1930	Maximum; plow, harrow (dust mulch)	102	19	1070
1931-1945	Conventional; shallow disk, rod weeder	118	24	1160
1946-1960	Improved conventional; begin stubble mulch in 1957	137	27	1730
1961-1975	Stubble mulch; begin minimum with herbicides in 1969	159	33	2160
1976-1990	Estimated; minimum; begin no-tillage in 1983	183	40	2690

Clean tillage

When conservation tillage is not practiced by choice or due to inadequate residues, then soil and water conservation under field cropping conditions usually depends on some other type of tillage that often is supplemented by other practices applied

Table 4. Tillage effects on mean plant-available soil water content and grain yields of grain sorghum and winter wheat, 1984-1993, Bushland, Texas (adapted from Jones and Popham, 1997)

Tillage method	Water content (mm)		Grain yield (kg ha^{-1})	
	Sorghum	Wheat	Sorghum	Wheat
Stubble mulch	195 b[1]	183 b	3400 a	1340 a
No-tillage	214 a	199 a	3390 a	1390 a

[1] Column values followed by the same letter are not significantly different ($P \leq 0.05$).

Table 5. Tillage method and planting date effect on mean plant available soil water content[1] and dryland corn grain yield, 1991-1994, Garden City, Kansas, U.S.A. (adapted from Norwood and Currie, 1996)

Tillage method	Water content (mm)			Grain yield (kg ha^{-1})		
	Early May	Mid May	Late May	Early May	Mid May	Late May
Sweep plow	208	206	224	5110	5130	4560
No-tillage	224	222	241	6210	6130	5360

[1] Determined to a depth of 1.8 m.

to the land. Tillage that incorporates all residues is called 'clean tillage' and the supplemental practices are called 'support practices'.

Appropriate use of clean tillage greatly reduces or eliminates soil erosion under many conditions. A soil surface ridged or roughened by tillage usually is effective for controlling wind erosion, especially when ridges are oriented perpendicular to the direction of prevailing winds. Further erosion reduction is possible by maintaining the soil surface in a roughened, cloddy condition, which can be achieved through the use of a variety of implements (e.g., chisel, sweep, lister, moldboard plow). Implements (e.g., harrows, disks, rotary tillers, drags, etc.) that smooth the surface or breakdown surface clods normally should not be used on soils highly susceptible to wind erosion. A disadvantage of relying on tillage to control wind erosion is that the surface usually must be roughened again after each major rainstorm, especially on sandy soils for which clods often disintegrate during a major storm (Fryrear, 1990). On soils highly susceptible to wind erosion, a combination of surface-roughening tillage, retention of nonerodible soil clods at the surface, and establishment of wind barriers can achieve effective wind erosion control in most cases (Fryrear, 1990).

Water erosion control with clean tillage occurs when water infiltration rates are favorable or excess water is conveyed from land at nonerosive velocities. Often, tillage in conjunction with various other practices [contouring, furrow diking (tied ridges), graded furrows, terracing, etc.] is used to obtain water erosion control. When precipitation rates exceed infiltration rates, runoff and erosion can be reduced by providing temporary storage for water on the soil surface. Ridge-forming tillage on the contour (across the slope of the land) is a proven erosion control and water conservation practice. The ridges hold water on the land, thus providing more time for in-

Table 6. Effect of tillage method on mean wheat grain yield, 1977-1989, Wagga Wagga, New South Wales, Australia (adapted from Pratley, 1995)

Tillage method	Grain yield (kg ha^{-1})
Conventional cultivation, three times with scarifier	2330 a
Reduced cultivation, one time with scarifier, then herbicides	2450 ab
Direct drill (no-tillage), herbicides	2690 b

Table 7. Fallow management effects on mean plant-available soil water contents at planting and grain yield of wheat (1988-1993) and grain sorghum (1989-1991), Billa Billa, Queensland, Australia (adapted from Thomas et al., 1995)

Fallow management[1]	Water content[2] (mm)		Grain yield (kg ha^{-1})	
	Wheat	Sorghum	Wheat	Sorghum
NT-So	117	125	2000	2190
NT-St	138	124	2360	2610
NT-St + gypsum	–[3]	140	2470	2530
RT-B-So	123	126	2290	1920
RT-B-St	130	122	2350	2160
CT-B-So	–	118	2120	1770
CT-B-St	–	120	2080	1920
RT-D-So	–	116	2150	1770
RT-D-St	–	122	2150	1960
CT-D-So	120	117	2070	1680
CT-D-St	120	121	2100	1970
CT-D-St + gypsum	–	130	2420	2250
CT-Ch-St	–	120	2110	2190

[1] Abbreviations: NT, no-tillage; RT, reduced tillage; CT, conventional tillage; B, blade primary tillage; D, disk primary tillage; Ch, chisel primary tillage; So, stubble removal; St, stubble retention.

[2] Determined to a depth of 1.2 m.

[3] Values not available for all years, thus mean not determined.

filtration. Some water, however, may be lost as runoff, which may cause serious erosion when it occurs. The effectiveness of contouring can be enhanced by blocking the furrows, thus reducing the potential for runoff and, hence, erosion. Furrow blocking also helps reduce runoff and erosion on gently sloping land (Fig. 4). All water from a 150-mm rain during a 24-hour period was retained on a slowly-permeable soil (Pullman clay loam, Torrertic Paleustoll) with a surface slope of about 0.5% at Bushland, Texas, U.S.A. (Jones and Stewart, 1990).

Tillage by implements such as plows (moldboard, disk, or sweep), chisels, rotary tillers, and cultivators results in surface depressions and roughness and increased soil pore space, which can provide for temporary storage of water and, therefore, reduce runoff and erosion. Under simulated rainfall conditions, cumulative water infiltration was greater with moldboard plowing than with other treatments (Table 10), apparently because it resulted in the greatest soil pore space and surface roughness. Smoother surfaces with other treatments apparently resulted in more rapid aggregate dispersion and surface sealing, which reduced infiltration.

Support practices

When tillage alone (including contouring and furrow disking) does not provide adequate erosion control and water conservation benefits, support practices used in conjunction with tillage may provide satisfactory results. In general, benefits due to tillage

Table 8. Tillage method effect on mean soil water storage during fallow[1] after irrigated wheat and subsequent grain yields and water use efficiency (WUE) for dryland grain sorghum, 1978-1983, Bushland, Texas, U.S.A. (adapted from Unger, 1984a)

Tillage method	Water storage[2] (mm)	Yield (kg ha^{-1})	WUE[3] (kg m^{-3})
Moldboard plow, disk	89 b[4]	2560 bc	0.71
Disk	109 b	2370 cd	0.65
Rotary	85 b	2190 d	0.61
Sweep	114 ab	2770 b	0.72
No-tillage	141 a	3340 a	0.83

[1] Duration of fallow was 10-11 months.
[2] Determined to a depth of 1.8 m.
[3] Based on grain yield, growing season precipitation, and soil water content changes.
[4] Column values followed by the same letter are not significantly different ($P \leq 0.05$).

and support practices are additive. For this report, support practices are engineering or cultural practices (other than tillage) that provide soil and water conservation benefits.

Strip cropping: To control water erosion, alternate cropped areas and protective strips usually are of equal width, with the protective strip composed of close growing plants in which soil eroded from the cropped area is trapped when transported by runoff water. Strip cropping reduces soil loss from fields, but soil movement from cropped areas to the strips may occur. Water conservation is possible if protective strips reduce runoff from the field and within crop areas.

Strip cropping is used extensively to control wind erosion. In the US Great Plains and other regions, cropped and fallow strips generally oriented perpendicular to the prevailing wind direction, are alternated for the production of crops such as wheat, barley (*Hordeum vulgare* L.), and oats (*Avena sativa* L.). Under such and other similar conditions, use of stubble mulch tillage or no-tillage that retains crop residues on the soil surface helps control wind erosion (Brown, 1970; Fryrear, 1990; Radke and Hagstrom, 1976). Growing specially-planted narrow barrier strips of tall plants also provides protection against wind erosion (Banshaf *et al.*, 1992; Fryrear, 1990; Lamers *et al.*, 1995). The distance between

Table 9. Tillage effects on mean soil water storage during fallow[1] after wheat harvest, sorghum grain yield, and water use efficiency (WUE) in an irrigated wheat-fallow-dryland grain sorghum cropping system, 1973-1977, Bushland, Texas, U.S.A. (adapted from Unger and Wiese, 1979)

Tillage method	Water storage[2] (mm)	Yield (kg ha^{-1})	WUE[3] (kg m^{-3})
No-tillage	217 a[4]	3140 a	0.89 a
Sweep	170 b	2500 b	0.77 b
Disk	152 c	1930 c	0.66 c

[1] Duration of fallow was 10-11 months.
[2] Determined to a depth of 1.8 m.
[3] Based on grain yield, growing season precipitation, and soil water content changes.
[4] Column values followed by the same letter are not significantly different ($P \leq 0.05$).

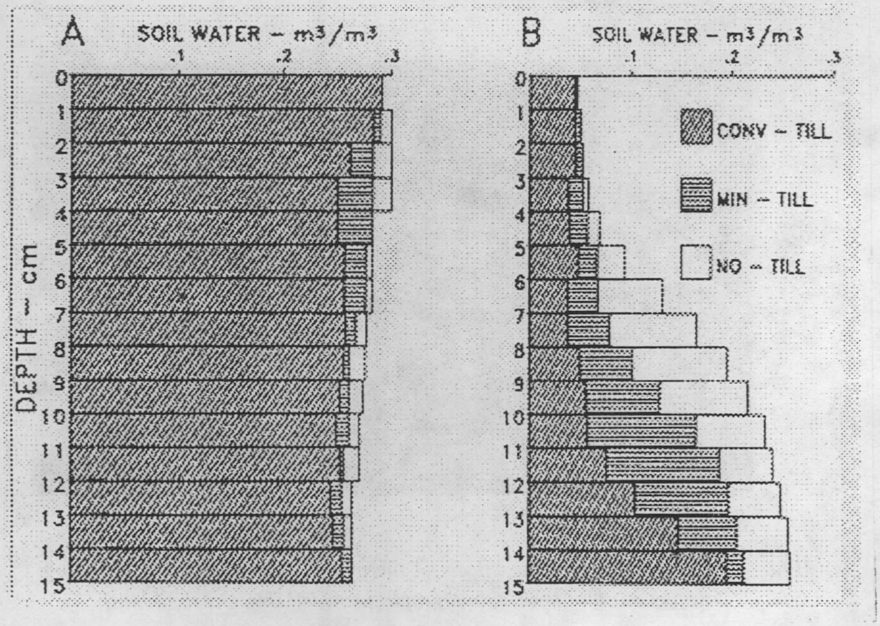

Fig. 3. Soil water content to a 15-cm depth 1 day (A) and 34 days (B) after 14 mm of rain as influenced by tillage treatments (CONV-TILL, conventional tillage; MIN-TILL, minimum tillage; NO-TILL, no-tillage) (adapted from Smika, 1976)

successive barriers should be about 10 times the barrier height to control wind erosion. Snow trapping between barriers provides water conservation benefits where snow occurs (Radke and Hagstrom, 1976).

Terraces: Terraces may be constructed level to hold water on the land or at a slight grade to convey excess water from land at nonerosive velocities. Level terraces may have open ends through which excess water may drain freely or closed ends so that water from most rains is retained on the land. A problem with level terraces is that water retained in the terrace channel often interferes with subsequent cultural operations or crop growth and yields. This problem is reduced by using level bench or conservation bench terraces (CBT). Level bench terraces require leveling all and CBTs require leveling part of the land between adjacent terraces. For the latter, about one-third to one-half of the inter-terrace interval usually is leveled. Leveling distributes runoff water when it occurs over a larger portion of the land, thus allowing more timely performance of cultural operations and generally uninterrupted plant growth. Land leveling, however, is costly. Leveling costs are reduced when narrow CBT or bench terraces are constructed (only wide enough for one or two passes of the equipment being used) (Jones, 1981).

Graded terraces are constructed across the slope, but with a slight grade in the channel to allow water to flow from the land. They generally are used in conjunction

Fig. 4. Photograph showing effects of furrow blocking relative to retaining water on the land (photograph provided by O. R. Jones)

with waterways or underground outlets through which excess water flows from fields at nonerosive velocities.

Graded furrows: In contrast to contour furrows that hold most water on land, graded furrows are similar to miniature graded terraces in that they convey excess water from fields at nonerosive velocities. Some water conservation benefits result from using graded furrows because they slow the rate of water flow from the land, thus providing more time for infiltration than when tillage is with the slope of the land.

Other practices: A number of other practices affect soil and water conservation, but they are suitable for use under rather restricted conditions. Included, but not discussed in this report, are water harvesting, slot or vertical mulching, deep plowing, limited irrigation-dryland farming, row spacing, and land drainage.

Crop Residue Management

Water conservation

Crop residue effects on water conservation were discussed previously in conjunction with conservation tillage. Crop residues, however, also affect water conservation independently of tillage. Laboratory studies showed surface residues greatly influenced soil water evaporation (e.g., Jacks *et al.*, 1955; Unger, 1976; Unger and Parker, 1976). Under field conditions, both greater infiltration (reduced runoff) and subsequent reduced evaporation of the infiltrated water apparently contribute to soil water gains that occur when crop residues are present on the soil surface (Tables 11 and 12). Steiner (1994) showed that reduced evaporation contributed greatly to water conservation when increasing amounts of crop residues were left on the soil surface. Of course, water must infiltrate into the soil

Table 10. Tillage-induced plow layer porosity and surface roughness effect on cumulative infiltration of simulated rainfall[1] (adapted from Burwell et al., 1966)

Tillage treatment[2]	Potential water storage volume (mm) due to		Cumulative infiltration (mm) to		
	Pore space[3]	Surface roughness	Initial runoff	25 mm runoff	50 mm runoff
Untilled	81	8	9	21	24
Plow	137	50	171	217	230
Plow-disk-harrow	124	25	53	73	84
Cultivated	97	29	57	83	91
Rotovated	117	15	24	38	41

[1] Water applied at a rate of 127 mm hour^{-1}.

[2] Plowing and rotovating performed to a 15-cm depth; cultivating to a 7.5-cm depth on untilled soil.

[3] Measured to depth of tillage.

for it to be conserved for subsequent use by plants.

Soil organic matter and carbon contents and dynamics, and soil quality

Organic matter is the major source of N, S, P, and many minor nutrients in soils and is critical for efficient crop production because of its cation exchange and water holding capacity. Soil C pools are important for maintaining nutrient availability, and they depend on the management of residues returned to the system. The organic matter content (OMC) of undisturbed prairie soils is much greater than that of cultivated soils. After cultivation, soil OMC declines exponentially with over half the C loss occurring in the first 10 years (Haas *et al.*, 1957). The loss generally is greater with intensive (e.g., clean) than with reduced (e.g., conservation) tillage, with cropping systems involving fallow than those without fallow, and with row crops than with small grain crops (Bauer and Black, 1981; Beare *et al.*, 1994; Haas *et al.*, 1957; Hobbs and Brown, 1965; Johnson and Davis, 1972; Lamb *et al.*, 1985; Wood *et al.*, 1990 and 1991). Soil erosion by wind and water also contribute to organic matter and C losses by removing them from the field.

Organic C contents (OCC) in the upper soil layer decrease with greater fallow frequency, but most soil C losses due to introduction of fallow occur in the first 20 years (Bremer *et al.*, 1995). Microbial degradation of organic matter increases following cultivation due to increased substrate and O_2 availability. Additionally, removal

Table 11. Straw mulch rate effects on soil water storage efficiency at Sidney, Montana; Akron, Colorado; and North Platte, Nebraska, U.S.A., 1962-1965 (adapted from Greb et al., 1967)

Mulch rate (kg ha^{-1})	Fallow period precipitation (mm)	Storage efficiency (%)
0	355	16
1700	355-549	19-26
3400	355-648	22-30
6700	355-648	28-33
10100	648	34

Table 12. Straw mulch rate effects on mean soil water storage during fallow[1] and grain sorghum yield, 1973-1976, Bushland, Texas, U.S.A. (adapted from Unger, 1978)

Mulch rate (kg ha^{-1})	Water storage[2] Amount (mm)	Water storage[2] Efficiency (%)	Grain yield (kg ha^{-1})
0	72 c[3]	22.6 c	1780 c
1000	99 b	31.1 b	2410 b
2000	100 b	31.4 b	2600 b
4000	116 b	36.5 b	2980 b
8000	139 a	43.7 a	3680 a
12000	147 a	46.2 a	3990 a

[1] Fallow duration was 10-11 months.
[2] Determined to a depth of 1.8 m.
[3] Column values followed by the same letter are not significantly different ($P \leq 0.05$).

of harvested biomass plus reduced organic matter inputs from crop root systems, as compared to native sod or grass root systems, increases organic matter depletion rates (Tate, 1987).

Soil organisms use residues as a source of energy and nutrients, thereby releasing CO_2, inorganic compounds, and recalcitrant molecules, which contribute to the formation of soil humus. Degradation of crop residues releases about 55 to 70% of the C to the atmosphere as CO_2, 5 to 15% is incorporated into microbial biomass, and the remaining 15 to 40% is partially stabilized in soil as new humus (Jenkinson, 1971; Stott and Martin, 1989). Lignin makes up 5 to 30% of crop residue and is an important substrate for soil humus formation due to its resistance to decomposition.

Environmental conditions, initial soil N content, and soil microbial populations also affect residue decomposition rates (Parr and Papendick, 1978). Water and temperature are primary climatic factors influencing microbial activity and residue decomposition (Paul and Clark, 1989), and are directly affected by crop residue management. When clean tillage is used, residues are either buried or incorporated with soil throughout the tillage layer. In contrast, most residues are retained on the soil surface when conservation tillage is used. Decomposition is faster for buried than for surface residues because of greater soil-residue contact, a more favorable and stable microenvironment, and increased availability of exogenous N for microorganisms (Douglas *et al.*, 1980; Parr and Papendick, 1978; Schomberg *et al.*, 1994; Stott *et al.*, 1986; Unger and Parker, 1968). This difference in residue positioning results in differences in organic matter distribution with soil depth. The organic matter accumulates near the surface with conservation tillage while a more uniform distribution with depth occurs with conventional tillage (Doran, 1980; Unger, 1991). No-tillage management also helps retain more residue C in the soil organic matter (Franzluebbers *et al.*, 1994). Greater cropping frequency can increase soil OC, microbial biomass C, and mineralizable C with no-tillage. Seasonal dynamics of C release as CO_2 may not be different once no-tillage or other practices have been in place for a sufficient period (Franzluebbers *et al.*, 1995). Mean soil CO_2 evolution during both fallow and cropped phases was related to soil OC with conventional but not with no-tillage (Franzluebbers *et al.*, 1995). No-tillage soil released as much or more C as CO_2 depending on crop during year 9 and 10 after initiation of the study.

Tillage enhances oxidation of incorporated crop residues and soil organic matter. Enhanced short-term CO_2 flux densities occurred immediately after a tillage operation, but subsided to a basal rate after 2 to 3 days (Dao, 1997; Reicosky and Lindstrom, 1993). Corresponding increases in microbial biomass occurred. Although C loss from each event represented only a small fraction of the total soil OCC, cumulative losses may contribute to the long-term decline in intensively cultivated fields.

Crop residue composition greatly influences N availability to subsequent crops. Legume and non-legume crop residues have different decomposition and N mineralization rates due to different chemical composition, primarily N content. In general, residues with N contents below 1.5% or C:N ratios greater than 30 immobilize inorganic N. Use of critical C:N ratios and initial N contents to determine N immobilization and mineralization, however, can be misleading because of variations in residue chemical constituents (Jansson and Persson, 1982; Reinertsen *et al.*, 1984). Decomposition of residues with low N contents such as wheat, grain sorghum, corn (*Zea mays* L.), rice (*Oryza sativa* L.), and other small grains with high C:N ratios may result in microbial immobilization of soil and fertilizer N, thus reducing N availability to subsequent crops. Availability of residue N to microorganisms may vary because of its presence in highly resistant compounds or due to physical protection from lignin within residues. Patterns of N mineralization also are affected by N fertilization.

Generally, mineralization of N from low-N residues occurs only after 50 to 60% is decomposed or after the C:N ratio is below 30 (Christensen, 1985 and 1986; Cochran, 1991). Placement of residues may play an important role in determining availability of soil N to subsequent crops during the N immobilization-mineralization process. Decomposition can immobilize N for longer periods due to slower decomposition when residues are on the surface than when incorporated. A peak in net N immobilization at 8 months for incorporated barley residues was followed by net N mineralization (Christensen, 1986). Surface-placed residues lost a small amount of N during the first 30 days, probably due to leaching, but little change in residue N content occurred after 30 days. Holland and Coleman (1987) found greater N immobilization and increased fungal abundance in surface than in buried wheat straw in Colorado. Schomberg *et al.* (1994) observed that 10 to 15 kg N ha^{-1} would be immobilized by surface residues in a wheat-sorghum-fallow cropping system during the fallow period. Net N mineralization, however, may not occur during the following cropping season and this would need to be considered when evaluating N requirements of the next crop. Slow N mineralization rates from crop residues may improve the use efficiency of residue N to subsequent crops. Nitrogen mineralization patterns from incorporated residues of continuous wheat and sorghum in Kansas showed that 12 to 15% of wheat and 12 to 33% of grain sorghum residue N was mineralized after one season (Wagger *et al.*, 1985). The low mineralization rate was beneficial because subsequent wheat or sorghum crops recovered 79 and 82% of the mineralized N, respectively. Immobilization of soil N within surface residues may have a positive influence on subsequent crop growth because the N remains near the root zone. However, leaching and denitrification losses of N within the soil profile may increase where surface residues result in increased water infiltration and reduced evaporation rates.

The physical, chemical, and biological properties of a soil influence its ability to function as a medium for plant growth, partition and regulate water flow in the environment, and act as an environmental buffer. Larson and Pierce (1991) defined soil quality as the capacity of a soil to function, both within its ecosystem boundaries and with the environment external to that ecosystem. Management of crop residues impacts many soil characteristics that should be evaluated in determining soil quality (Doran and Parkin, 1994). Changes in these characteristics over time and space are important aspects of management impact on soil quality. Soil quality generally declines when soil OCC declines because soil OCC affects soil structure (aggregate size distribution and stability, bulk density, etc.), which is important for soil water relations (infiltration, retention, conductivity, etc.). The disproportionate accumulation of organic C in the near-surface zone favors development of stable aggregates where water enters a soil (Douglas and Goss, 1982; Perfect and Kay, 1990; Unger, 1984b and 1997) and, therefore, probably contributed to greater water infiltration where conservation rather than clean tillage was used (Potter *et al.*, 1995; Schultz and Malinda, 1994; Unger, 1995; Unger and Jones, 1994). Carbon-stabilized biopores and intact root channels that are preserved in no-tillage soils increased infiltration and soil water storage (Dao, 1993; Edwards *et al.*, 1988). These preferential flow paths allow rapid water by-pass flow and simultaneous recharge of water in multiple soil layers or horizons (Dao, 1993). With greater infiltration, more water potentially is available for use by the next crop, which usually is of major benefit for dryland crop production in subhumid and, especially, in semiarid regions. Greater crop production usually provides more crop residues, which, if returned to the soil, help to maintain or increase soil OCC, thus maintaining or enhancing soil quality. In contrast, if practices are used that reduce the water supply and result in lower yields, less residues generally are produced and the OCC continues to decline, thus resulting in lower soil quality and eventually reduced crop productivity (Stewart *et al.*, 1991).

Appropriate Dryland Crops and Cropping Systems

Many crops can be grown in most dryland regions, but only few are economically viable and they rapidly become the dominant crops for a particular region. These crops are usually drought tolerant and their water use requirements correlate well with precipitation patterns and/or use of stored soil water. The U.S. Great Plains and Canadian Prairies provide good examples of climatic and economic effects on crops and crop rotations. The frost-free period ranges from only 80 days in the Canadian Prairies to 240 days in the southern Great Plains, and precipitation ranges from <400 mm on the western side to >600 mm year^{-1} on the eastern side of these regions.

Cotton, grown on an annual basis, is the major crop in the southern Great Plains south of a line delineating the 210-day frost-free period (Jones and Johnson, 1984). North of this line, grain crops predominate. Winter wheat is the dominant grain crop in the central and southern Great Plains. In the northern Great Plains and Canadian Prairies, both winter and spring wheat are grown, but spring wheat predominates. Much of the wheat historically has been grown in a 2-year wheat-fallow (WF) rotation (one crop in 2 years). In recent years, however, use of improved residue management systems (reduced- and no-tillage) has resulted in reduced evaporation and increased soil water storage, thus allowing more intensive cropping. A 3-year wheat-summer crop-fallow rotation is being used most commonly. Greatly improved precipitation-use efficiencies and profits have resulted from the increased cropping intensity (Dhuyvetter *et al*., 1996; Jones and Popham, 1997; Peterson *et al*., 1996).

Grain sorghum is the summer crop usually grown in the southern Great Plains with its warm temperatures and high evaporation. Both corn and sorghum are used in the central Great Plains with corn or sunflower alternated with winter or spring wheat in the northern Great Plains. Spring barley, flax (*Linum* spp.), safflower (*Carthamus tinctorius* L.), field peas (*Pisum* spp.), and canola (*Brassica* spp.) also are commonly grown in the northern Great Plains and Canadian Prairies. These crops are secondary to wheat, but are grown on substantial areas where they are important components of adapted cropping systems.

Cropping systems can be categorized into (1) continuous cropping, (2) rotations, and (3) multiple cropping (Unger, 1984c). With continuous (annual) cropping, the same crop is grown on the same field for several years in succession. This allows for greatest production of the most desirable or economically favorable crop (e.g., cotton in west Texas). It may, however, lead to increased disease, insect, or weed problems, or increase the wind erosion potential when the crops produce limited amounts of residues.

With crop rotations, different crops are grown in succession or alternated with fallow. Use of rotations, however, does not preclude growing the most desirable or profitable crop two or more times back to back. Alternating high residue producing crops (wheat, sorghum, corn) with low residue crops (cotton, sunflower, safflower) can aid in wind and water erosion control, particularly with reduced or no-tillage management of the residues. Crop rotations can be fixed or flexible. Flexible systems involve fallow, with crop planting depending on the soil water content at planting time. Fixed rotations such as wheat-fallow, wheat-sorghum-fallow, or wheat-corn-fallow are commonly used. Fixed rotations, which usually include some fallow to allow replenishment of soil water, greatly stabilize production; improve weed, disease, and insect control; and allow use of a wide spectrum of herbicides for improved residue management which, in turn, can reduce evaporation and increase soil water storage. Use of fallow may lead to erosion problems where surface residues are limited.

Multiple cropping involves growing more than one crop per year on the same field and includes double or triple cropping and intercropping (two crops growing simultaneously) (Unger, 1984c). Multiple cropping is used to some extent in humid or subhumid climates, but is not common on semiarid drylands.

Weed Control and Herbicide Use

Weeds compete with crops for space, light, nutrients, and water in all climatic regions. Competition for water, however, generally is much more important in semiarid and subhumid regions than in humid regions, especially under dryland farming conditions. Under dryland conditions, crops depend on water stored in soil for survival, growth, and development in the interval between precipitation events. If some of that water is used by weeds, less is available for crop use. Hence, if precipitation is limited and poorly distributed, which often is the case in subhumid and semiarid regions, crop yields may be greatly reduced where weeds have competed with crops for water.

A primary reason for performing tillage is weed control. Tillage aids weed control by (a) burying weed seed and delaying perennial weeds, (b) leaving a rough surface to discourage weed seed germination, (c) providing enough loose soil to permit effective row cultivation, (d) leaving a clean uniform surface for efficient herbicide action, and (e) incorporating herbicides when necessary (Richey *et al.*, 1977). These conditions are achieved through the use of clean tillage. While some herbicides are used under clean tillage conditions, dependence on herbicides increases when conservation tillage is used. For the no-tillage system, herbicides are relied upon totally for controlling weeds.

The effectiveness of weed control operations in conservation tillage systems depends on the system used and, to a large extent, on soil water contents and weed growth stage when the operations are performed. With stubble mulch tillage, soil water content and timing of subsequent precipitation affect the success of the weed control operation. Weed control with stubble mulch tillage generally is good in drier regions, especially if no precipitation occurs soon after the operation. Stubble mulch tillage, however, only cuts the main roots and weeds may survive if secondary roots remain in moist soil or if precipitation occurs before the weeds die. Using a mulch treader in conjunction with the stubble mulch tillage implement improves weed control, especially when the soil is relatively wet at the time of tillage. Use of the treader, however, increases crop residue incorporation, which may reduce the effectiveness of stubble mulch tillage for conserving soil and water.

For effective weed control with herbicides in tillage or no-tillage systems, the material applied must uniformly contact weeds and the exposed soil. Nonuniform herbicide application can result in poor weed control where large amounts of residues cover the soil surface, as often is the case where the no-tillage system is used. Herbicides requiring incorporation with soil are not suitable for no-tillage systems.

Some herbicides control either grassy or broadleaf weeds whereas others (contact herbicides) control all vegetation to which they are applied. Generally good weed control is achieved when appropriate herbicides are applied to susceptible weeds that are small and actively growing. Large weeds often are difficult to control with herbicides. All weeds usually are difficult to control with herbicides when weeds are under stress due to water deficits or low or high temperatures.

For crop growing season weed control, pre- or post-emergence herbicides can be used. Additional weed control in established crops is possible with suitable herbicides. Some herbicides, effective for controlling selected weeds, would damage the crop being grown. Under such conditions, satisfactory weed control with herbicides may be possible by spot spraying, directed spraying, using shielded sprayers, or using a rope wick applicator (Wiese and Lavake, 1980) or similar devices to apply the material to weeds that are taller than the crop. Also, genetic engineering is making it possible to control weeds with broad-spectrum herbicides such as glyphosate[1] [*N*-(phosphonomethyl)glycine] and glufosinate [2-amino-4-(hydroxymethylphosphinyl) butanoic acid] in crops such as cotton and soybean (*Glycine max* L.) without damaging the crops. Genetic engineering of crops such as wheat, corn, and some vegetables for compatibility with herbicides is in progress (Clay Salisbury, Amarillo, Texas, personal communication, 1997). Where effective control of troublesome weeds is not possible or practical by the above methods, it may be necessary to use a rotation for which crops involved have growing seasons different from those of the troublesome weeds. If the problem occurs where conservation tillage is practiced, occasional use of clean tillage may be necessary.

Water Quality

Agricultural materials of primary concern regarding water quality are soil sediments, nutrients (from fertilizers, crop residues, manures, and organic wastes), and pesticides (herbicides, insecticides, etc., and their breakdown products). Soil sediments affect surface water quality, with their transport to streams and reservoirs being dependent on the amount and rate of overland water flow (runoff) from agricultural land. Also, wind-borne soil particles with adsorbed nutrients or other chemicals may be deposited in drainage channels, then directly or later transported in surface waters, or they may settle from the air directly into the surface waters. Runoff usually is less from conservation tillage than clean tillage areas, as discussed previously. In addition to less runoff, conservation tillage with residues present on the soil surface results in lower runoff velocity, which provides more time for sediments to settle from the water before it leaves the field. As a result, water quality based on sediment concentration is better where conservation tillage is used.

Nutrients of concern regarding water quality primarily are phosphorus (P) and

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[1] The mention of trade or manufacturer names is made for information only and does not imply an endorsement, recommendation, or exclusion by USDA-ARS. Mention of a pesticide does not constitute a recommendation for use nor does it imply registration under FIFRA as amended.

nitrogen (N). Because P tends to move in an adsorbed form with sediments, effects of tillage and residue management on P generally are similar to their effects on sediments (Sims *et al.*, 1994). Use of no-tillage, however, concentrates P at the soil surface (Griffith *et al.*, 1977; Guertal *et al.*, 1991; Unger, 1991), which can increase P concentration on sediments transported from no-tillage areas. Greater leaching from large amounts of surface residues also can result in more dissolved P being lost from conservation tillage areas (Unger *et al.*, 1997).

Nitrogen compounds (mainly nitrates) dissolve in water and, therefore, are of major concern regarding surface and ground water supplies. Because use of conservation tillage often reduces runoff relative to that with clean tillage, nitrate-N in surface water generally is less where conservation tillage is used. Greater infiltration with conservation tillage, however, may lead to leaching of N to groundwater. Factors such as crop residue amount, type, and placement affect the amount of N being cycled and, after going through the mineralization-immobilization process, the amount potentially available for uptake by plants and movement with water. Whether or not a crop is growing when the N becomes available and the type of crop grown would influence the amount of N transported with the water (Unger *et al.*, 1997).

Land application of materials such as manures and organic wastes (e.g., materials from animal feeding and slaughtering facilities, food processing plants, and other industries), with factors such as their composition and rate, placement, and timing of application, affect water quality. If properly handled, they often serve as N and P sources for crops, but can lead to water quality problems if they provide more N and P than the amount removed by crops. If retained on the surface, tillage and residue management would affect the movement of these materials in a manner similar to that discussed above. Incorporation of the organic materials by tillage redistributes the N and P throughout the tillage layer, which may enhance their uptake by crops. Incorporation may also reduce N and P movement with water, thus reducing the potential for contaminating water supplies (Unger *et al.*, 1997).

Pesticides applied to crops or cropland may volatilize, photodecompose, leach, adsorb to other materials, be taken up by targeted organisms (plants, microbes), or dissolve in water (Sims *et al.*, 1994). Therefore, those that are not volatilized, degraded, or taken up by plants may affect water quality. In general, the influence of tillage and residue management practices on these materials is similar to their effect on sediments and nutrients, as discussed above. Materials adsorbed on sediments and transported in runoff would affect surface water supplies. Dissolved materials could contaminate surface water and groundwater. A possible negative effect of conservation tillage regarding pesticides is that greater amounts sometimes are used (especially herbicides). Proper herbicide application and formulation can reduce the need for applying more material when large amounts of crop residues are on the soil surface, as when using conservation tillage (Sims *et al.*, 1994). Also, crop residues intercept and adsorb pesticides (herbicides, insecticides, fungicides, etc.), thus maintaining them in the near-surface zone of conservation-tilled soils and minimizing off-the-field water quality impairments (Dao, 1991; Dell *et al*., 1994). Pesticide-adsorption capacity of residues may exceed that of the underlying soil by a factor of eight- to ten-fold. Plant debris adds organic materials to surface soil, thus enhancing its retention capacity for non-ionic pesticides.

Future Challenges

Crop production sustainability is essential to meet the future food and fiber needs of the ever-increasing world population. Production under both dryland and irrigated conditions will be required to meet those needs. Although crop yields generally are much greater with irrigation than on dryland, water for irrigation often is limited and is being depleted in some regions. Hence, crop production on drylands will remain important or become increasingly important in the future.

Presently-available tillage and crop residue management practices can play a major role in sustaining the productivity of drylands. These will be aided by site-specific production techniques and development of herbicide-resistant crops in the future. These practices generally do not adversely affect the environment (air, water, soil, etc.). Because of increasing concerns regarding the environment, however, some materials (pesticides, fertilizers, etc.) presently used for crop production may not be acceptable in the future and weeds may become resistant to herbicides. As a result, modification of present practices or development of new practices may be required. Besides being compatible with goals for the environment, the practices also must be economically and socially acceptable. Cooperative research involving participants from various disciplines will be required to achieve these goals in a timely manner.

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